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October 1994
EFI 93-70-Rev

ELEMENTARY PARTICLE PHYSICS IN THE SECOND HALF OF THE 20th CENTURY[1]

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Abstract

A brief history is given of the development of elementary particle physics in the past 50 years, starting from the discovery of a wide variety of new particles and ending with the development of theories of the strong and electroweak interactions.

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[1]To be published as Chapter 6 of *Twentieth Century Physics* (eds. L. M. Brown, A. Pais and B. Pippard) (IOP/AIP, Philadelphia, 1994)

Table 1: The quarks and leptons as of 1994.

Leptons			Quarks		
Symbol	Name	Charge	Symbol	Name	Charge
ν_e	Electron neutrino	0	u	Up quark	2/3
e^-	Electron	−1	d	Down quark	−1/3
ν_μ	Muon neutrino	0	c	Charmed quark	2/3
μ^-	Muon	−1	s	Strange quark	−1/3
ν_τ	Tau neutrino[a]	0	t	Top quark	2/3
τ^-	Tau	−1	b	Bottom quark	−1/3

[a]Not yet directly observed.

1. INTRODUCTION

The past 50 years of elementary particle physics have witnessed an explosion of data, followed by simplifications based on classification and solid theory. Attempts to describe the fundamental interactions from a more unified point of view have borne fruit in a combined theory of weak and electromagnetic interactions based on self-interacting quantum fields, and a similarly-based theory of the strong interactions.

The understanding of the periodic table of the elements bears some similarity to the story of particle physics. An initial systematization of data was followed by firmer theoretical efforts, culminating in the advent of quantum mechanics. The vast variety of atoms and isotopes could be understood in terms of fundamental protons, neutrons and electrons interacting via electromagnetic (well-understood) and strong (poorly understood) forces.

In the 1960's, a scheme for classifying the strongly interacting particles based on the group SU(3) began to make sense of the rapidly proliferating spectrum. Eventually, the success of SU(3) and related symmetries was traced to the existence of a few constituents – the *quarks*. Now we are confronted with a proliferation of quarks and *leptons* (the electron, muon, tau, and their respective neutrinos) for which a deeper explanation is still lacking. These are summarized in Table 1.

As more and more fundamental building blocks of matter were being uncovered, the way in which fundamental forces were described also evolved. The unification of forces has a long tradition, dating from Newton's synthesis of terrestrial and celestial gravity and Maxwell's synthesis of electricity and magnetism. In this century it included a detailed understanding of the weak interactions and their violation of mirror symmetry, and culminated in the unified theory of weak and electromagnetic interactions of Glashow, Weinberg, and Salam, and the discovery of the predicted carriers of the weak force, the W and Z. Still to be understood at the deepest level is the violation of the combined symmetry of charge reversal

Table 2: Carriers of the strong and electroweak forces.

Symbol	Name	Force carried	Mass (GeV/c^2)
γ	Photon	Electromagnetic	0
g	Gluon	Strong	0
$W^{\pm}$	W Boson	Weak (charged)	80.2 ± 0.2
Z^0	Z Boson	Weak (neutral)	90.187 ± 0.007

and mirror reflection, discovered in 1964.

The success of the electroweak theory was particularly heartening because it took place in the context of quantum field theory, previously thought to be useful only for describing electromagnetic processes. A parallel development, also relying on quantum field theory, was the emergence of a theory of strong interactions, now known as *quantum chromodynamics* (QCD). This theory describes why quarks are different from leptons (quarks have a new kind of charge dubbed *color*, while leptons are colorless), and gives quantitative predictions for their interactions with one another via the exchange of quanta known as *gluons*. It explains, through the dependence of interaction strength on distance, why it makes sense to speak of quarks at all, even though they appear to be permanently bound to one another.

A chart of the carriers of strong and electroweak forces is given in Table II. The picture of particle physics as consisting of quarks and leptons interacting via exchanges of photons, gluons, W's, and Z's has come to be known as the "Standard Model".

A symposium has been devoted to the emergence of the standard model[1], and an extensive book[2] treats the whole period with which we are concerned. Specific chapters in particle physics, in the 1930s-1950s[3] and the period 1947-1964[4], are also the subject of excellent historical reviews. In the present article, we touch on some high points of the progress made in this fruitful field in the past 50 years. Our hope is to give some flavor of how far it has come, and where we might expect it to lead in the future.

We do not wish to give the impression that progress in elementary particle physics, any more than in any other field, is an orderly process. In the interest of space, our story omits many blind alleys and wrong experiments. We have chosen to speak of discoveries and ideas that have had some lasting value. At the same time, we cannot claim to be comprehensive in our treatment. There is necessarily some choice of subjects involved, for which we take full responsibility.

We begin in Sec. 2 with a few key points of early 20th-Century particle physics, to set the stage for our later discussion. This period is dealt with more extensively in Ref. 5, which may be consulted for citations. We then (Sec. 3) describe progress in quantum electrodynamics (QED), which until the advent of electroweak uni-

fication and QCD was our only example of a successful, relevant quantum field theory. Except for the treatment of QED, we break our discussion at the mid-1960s, treating properties of matter (Sec. 4) and forces (Sec. 5) before proceeding further.

The description of strongly interacting particles, or *hadrons*, in terms of quarks (Sec. 6) marks a turning point in particle physics in the latter half of this century. With quarks taken seriously, the way was paved for extension of electroweak unification (Sec. 7) from its original province of leptons to the whole range of elementary particles. Moreover, the route was now established for the development of QCD (Sec. 8). New forms of matter, in the form of the third family of quarks and leptons (Sec. 9), could be accommodated without much difficulty in the new framework.

Almost all of the results in particle physics in the past fifty years have been crucially dependent on continued progress in the development of accelerators (Sec. 10) and detectors (Sec. 11). Elementary particle physics has profited immensely from its overlap with other fields (Sec. 12). We mention some puzzles and hopes in Sec. 13, and conclude in Sec. 14.

2. PRELUDES (BEFORE 1940)

The first "elementary particle" identified as such was the electron, whose charge-to-mass ratio was first measured by J. J. Thomson in 1897. The discreteness of the charge itself was demonstrated somewhat later by Millikan.

Experiments by Rutherford in the early part of the 20th century showed that alpha particles underwent scattering from matter at much greater angles than one might have anticipated. A popular model of the atom at that time envisioned material spread uniformly through it, whereas Rutherford's scattering experiments pointed toward an intense concentration of most of the matter over less than 10^{-4} of the atom's linear size. Niels Bohr, a young visitor at Rutherford's laboratory in Manchester in 1911-12, was inspired by Rutherford's experiments to attempt to construct a model of the atom based on negatively charged electrons orbiting a positively charged nucleus. He was forced to introduce new physics, foreshadowing quantum mechanics, in order to keep the orbits from decaying by emission of radiation. He was not initially motivated by data on the spectra of light emitted by hydrogen, but when he learned of the Balmer spectrum, the whole problem became clear to him, and his solution was presented within a month.

The Bohr atom made use of an analogy with previously known ideas, such as orbits. A break with the past occurred in the mid-1920s with the full-fledged develpment of quantum mechanics by Heisenberg, Schrödinger, Born, and others. A crucial aspect of quantum mechanics was the scale set by Planck's constant h, with dimensions of (energy) $\times$ (time) or (momentum) $\times$ (length); another was the identification by de Broglie of the connection between waves and particles: (wavelength) $= h/$(momentum), confirmed experimentally by Davisson and Ger-

mer using electrons. Similarly, though one was accustomed since Maxwell's time to view electromagnetic radiation in terms of waves, Einstein's explanation of the photoelectric effect in 1905 indicated that light could also be regarded as composed of *quanta*, or discrete units, with (energy) = h (frequency). This idea was confirmed by the discovery of the *Compton effect*, the scattering with change of wavelength of electromagnetic quanta (*photons*) on electrons.

The version of quantum mechanics developed in the mid-1920s applied to particles with velocities small compared to that of light. In seeking an equation of motion for particles not subject to this limitation, Dirac introduced new degrees of freedom. His equation applied to a quantity with a total of four components. A two-fold multiplicity allowed one to describe particles such as the electron which have two possible directions of spin. However, an additional two-fold multiplicity was a necessary consequence of invariance of Dirac's equation under the transformations of special relativity. Dirac interpreted this additional doubling to imply the existence of *antiparticles*, with opposite charge and the same mass as particles. Thus, there should exist a positively-charged version of the electron. This particle, the *positron*, was identified by Anderson in cosmic radiation in 1932.

The comparison between the charges and masses of atomic nuclei, and the detailed study of their spins, made it clear that one could not build the nucleus merely out of protons, nor of protons and electrons. A new building block was needed, similar in mass to the proton but electrically neutral. This particle, the *neutron*, was discovered by Chadwick in 1932. Its existence made the picture of atomic nuclei fall into place. The charge (Z) counted the number of protons, while the mass number (A) counted the total number of protons and neutrons. The mass of the nucleus was slightly less than the sum of the masses of individual neutrons and protons (*nucleons*), because of the effects of binding energy.

Radiation from outer space had been identified by V. Hess and others in the early part of the 20th century. By the mid-1930s, cosmic rays were a subject of some experimental interest, and were recognized as providing a useful source of highly accelerated particles, as were products of radioactive decay. However, these sources were soon joined by a number of devices invented for artificially accelerating particles, which were then focused with the help of electric and/or magnetic fields. These devices included the Cockcroft-Walton generator, the Van de Graaff generator, and the cyclotron. The last was pioneered by Ernest O. Lawrence, and was extensively used for particle physics studies until the mid-50s. At that time, various versions became available of the *synchrotron*.

The prediction of infinite quantities, such as the field energy (self-interaction energy) of the electron, meant that a consistent quantum-mechanical description of the interaction of radiation with matter still had not been found in the 1930s. While it was possible during this period to calculate many processes by an approximation valid to lowest order in the interaction strength, a self-consistent description to all orders was lacking.

The continuous nature of the energy spectrum of electrons or positrons emitted in beta decay, and the balance between initial and final particles, implied that an unseen agent was carrying off momentum and angular momentum in the decay. This particle, dubbed the *neutrino*, always accompanied the electron in beta-decay. The fundamental process was then $n \rightarrow pe^-\bar{\nu}_e$, where n is the neutron, p is the proton, e^- is the electron, and $\bar{\nu}_e$ is an antineutrino. In a heavy nucleus with a large proton excess, the process $p \rightarrow ne^+\nu_e$, could occur instead, even though forbidden by energy conservation for a free proton and neutron. Both processes were described by an interaction, postulated by Fermi, which was almost, but not quite, correct. It made no provision for the violation, discovered in the 1950s, of mirror symmetry (*parity violation*) in the beta-decay interaction. In its description of the production of the electron-neutrino pair, the Fermi theory was one of the first applications of *quantum field theory*, which makes provision for the production and annihilation of particles.

The extremely short range of the nuclear force led Yukawa to postulate the existence of a new particle, the *meson*, whose exchange would give rise to a short-range interaction. In 1937, a new type of particle was seen in cosmic radiation. Charged, and with a mass very close to that predicted by Yukawa, this new particle (the *muon*) was initially identified as Yukawa's meson. However, if the muon were really the carrier of the strong nuclear force, it should interact strongly with matter. Its persistent failure to do so led to the gradual realization that the muon was *not* Yukawa's meson. The particle predicted by Yukawa was yet to be discovered, as we shall see in Sec. 4.

The picture of elementary particle physics as of 1940 was fairly simple and self-consistent. The atom consisted of a nucleus built of neutrons and protons, bound to electrons via electromagnetism. Neutrinos were hypothetical particles emitted in beta-decay. The "four forces of nature" were already in place: strong (holding nuclei together), electromagnetic, weak (associated with beta decay), and gravitational. The elements in the periodic table of the elements up to uranium had almost all been seen, and elements heavier than uranium were starting to be discovered. There were few intimations of the rich variety of particles or the progress in understanding of forces that would characterize the next 50 years.

3. QUANTUM ELECTRODYNAMICS

One of the early triumphs of theory in describing elementary particle physics lay in the realm of the purely electromagnetic interactions. This area, *quantum electrodynamics*, or QED, evolved through an interplay of experiment and theory. For many years, its success was regarded as an exception, to be contrasted with much more phenomenological descriptions of the weak and strong interactions. With hindsight, we now know that those theories have followed a route related to that pioneered by QED. Indeed, the weak interactions have now been unified with QED into an *electroweak* theory, and strong forces are described by a theory

which could well be unified in the future with the electroweak interactions. For historical purposes, however, it is appropriate to trace the development of QED in its own right. Even today, progress is continuing to be made in calculations, and some interesting puzzles remain for the hardy experimentalist and theorist.

We shall discuss primarily purely electromagnetic processes, not affected by uncertainties of weak- or strong-interaction physics, taking examples mainly from the interaction of photons with electrons or muons. The calculations we shall describe are organized as a series in increasing powers in $\alpha = e^2/\hbar c \approx 1/137$, the *fine-structure constant.*

3.1. Infinite quantities in the theory

Although the interactions of photons and electrons were described successfully to lowest order in α, as in photon-electron scattering or electron-positron pair production by a photon in an intense external field, it was realized quite early that higher orders in α led to difficulties[6], manifested in a series of calculations which gave infinite answers.

One can see that classical electromagnetic theory is plagued by infinite quantities just by calculating the field energy surrounding a point electron. The energy diverges as $1/r_0$, where r_0 is the minimum distance to the electron taken in the integral over energy density. Could a proper relativistic quantum-mechanical treatment cure this problem?

The description of electrons in a way compatible with special relativity entails also the existence of positrons[7]. With the help of W. Furry, Weisskopf[8] showed that the inclusion of contributions from positrons in the electron self-energy calculation reduced the degree of divergence to $\ln(1/r_0)$, where r_0 again represents a minimum cutoff distance. Thus positrons were a partial, but not sufficient, help.

Another infinite quantity occurring in quantum electrodynamics arises as a result of the production of virtual electron-positron pairs by a photon. Like the electron self-energy, this *vacuum polarization* divergence depends on the logarithm of a cutoff parameter. Despite the infinite nature of vacuum polarization, it was possible to calculate its effect on the Coulomb interaction, for instance in a hydrogen atom, by comparing the interaction at large and shorter distances. The result[9] was a prediction that the $2P_{1/2}$ level of hydrogen should lie 27 MHz above the $2S_{1/2}$ level, whereas the Dirac theory predicts them to be degenerate.

3.2. Early experimental developments

3.2.1. Lamb shift.

The fine structure in the Balmer Series spectrum of the hydrogen atom was first observed in the H_α line ($n = 3 \rightarrow 2$) by Michelson and Morley in 1887. By the time the Dirac equation was available in the later 1920s more than 15 spectroscopic measurements were available for comparison with the theory. Immediately a difficulty was encountered. The intensity ratios of the observed lines were not those expected; even more importantly, the splitting of the lines was different

from that predicted. Already in 1933 a letter was published in Physical Review addressing the issue of this discrepancy[10]. It was entitled *On the Breakdown of the Coulomb Law for the Hydrogen Atom.* Measurements later in the decade on the D_α line by Houston and Williams[11] sharpened the disagreement with the observation of a third line (deuterium shows less Doppler broadening). This work stimulated Pasternack[12] to observe that the observations could be accounted for if the $2S$ level were shifted upwards by about 0.03 cm^{-1} (900 MHz in units used subsequently). The vacuum polarization correction alone[9] was much too small and in the wrong direction to account for the discrepancy. This was the situation until after World War II.

In the U. S. during wartime many physicists worked in one of the Radiation Laboratories devoted to radar development, or on the Manhattan Project concerned with nuclear weapons. Willis Lamb, at Columbia University, was originally denied necessary security clearance to work at the Columbia Radiation Laboratory (CRL) because his wife was not a U. S. citizen. Instead, he taught physics, including atomic physics, to Navy students, thus becoming familiar with the problems associated with the H_α and D_α spectra discussed above. Eventually he was allowed to work at the CRL on high frequency magnetrons in which capacity, though nominally a theoretical physicist, he built one of the first continuous wave magnetrons with his own hands. It operated at 2.7 cm which, not accidentally, was just the frequency of the fine-structure splitting of hydrogen. Immediately after the war, with a graduate student, R. C. Retherford (who had himself developed an expertise in high vacuum techniques as well as in the measurement of tiny currents during the war), Lamb proceeded to mount an experiment designed to definitively answer the questions posed by the hydrogen fine structure. He exploited many of the new techniques and instrumentation developed during the war years. It was a brilliant effort and the experiment succeeded beyond all of Lamb's dreams.

The fine structure splitting between the $2P$ and $2S$ levels in hydrogen was in the range of Lamb's 3 cm magnetron. Nominally, the $2S$ level is metastable with a lifetime sufficiently long to survive a reasonably long path through the apparatus. However, any small stray electric field will mix the $2S$ and $2P$ levels and shorten the lifetime of the $2S$ state, perhaps to the point where no atoms initially in the $2S$ state could survive the trip through the apparatus. To address these and other problems the apparatus was composed of five distinct elements. First, the source was an oven enclosing a hot tungsten surface which dissociated the molecular hydrogen to atoms. On exiting from the oven, a beam of atomic hydrogen was formed by collimation. Second, an electron beam was positioned to cross the beam of hydrogen atoms to excite at least some of the atoms to the $2S$ state. This process was very inefficient; only about 1 in 100 million atoms were so excited, but it was enough. Third, the atomic beam was passed through a radio frequency field to induce transitions from the $2S$ to various $2P$ levels. Atoms in the P states decay

so rapidly to the ground state that they travel less than 10^{-3} cm before they are lost to the beam of metastable atoms. Fourth, a uniform magnetic field enveloped the whole apparatus to remove the (possible) near degeneracy between the $2P$ and $2S$ levels through the Zeeman effect, and thereby minimize the danger of stray electric field which would shorten the lifetime of the beam. Finally, the beam ended with a detector designed to selectively sense the hydrogen atoms in the $2S$ state and reject all others. Following on the work of Massey and Oliphant, Lamb and Cobas had previously calculated that metastable hydrogen atoms impinging on tungsten would de-excite with the emission of electrons from the tungsten and thereby produce a current. Utilizing this fact, the detector consisted of a plate of tungsten connected to the most sensitive current meter available at the time, an FP 54 electrometer.

The experimental measurement consisted of setting the radio frequency and varying the magnetic field until a dip occurred in the detector current. This corresponded to RF induced transitions from the $2S$ to one of the $2P$ states. By extrapolating to zero magnetic field, Lamb and Retherford found that the transitions occurred at a frequency 1000 MHz less than that deduced from theory, just as expected if the $2S_{1/2}$ level was shifted by this amount. They also reported seeing directly the transitions between the $2S_{1/2}$ and the $2P_{1/2}$ levels at this frequency. In the Dirac theory, these levels have exactly the same energy. The results[13] from this very first experiment, obtained April 16, 1947, are shown in Fig. 1. In this one elegant measurement the speculations of Pasternack had been shown to be correct, but the effect was removed far beyond the realm of speculation and now deserved the most serious attention.

Before World War II there had been considerable theoretical effort directed toward the question of the self-energy of the electron. However, because of the war, interest had remained dormant. Now, with the stimulus of the results of Lamb and Retherford the latent interest developed into a major attack by theoretical physicists, and within a few years the problem was solved to the satisfaction of nearly everyone. (To the end of his life, however, Dirac maintained that any theory involving the subtraction of infinities was ugly, unsatisfactory, and surely incomplete.)

Lamb first announced the results which he had obtained only five weeks earlier at a conference held on Shelter Island in Peconic Bay, Long Island, New York, June 2-4, 1947. Sponsored by the National Academy of Sciences and organized by Robert Oppenheimer, it was attended by most of the leading theoretical moguls at the time in the U. S. (see Fig. 2). At that conference, not only were the results of Lamb and Retherford made known, but also R. Marshak first suggested that there were two kinds of mesons, and H. Kramers laid the groundwork for reinterpreting infinite quantities in quantum field theory by means of "renormalization"[14].

Within a few days after the conference, Bethe had calculated the "Lamb shift" to be 1040 MHz using old fashioned non-relativistic methods but with in-

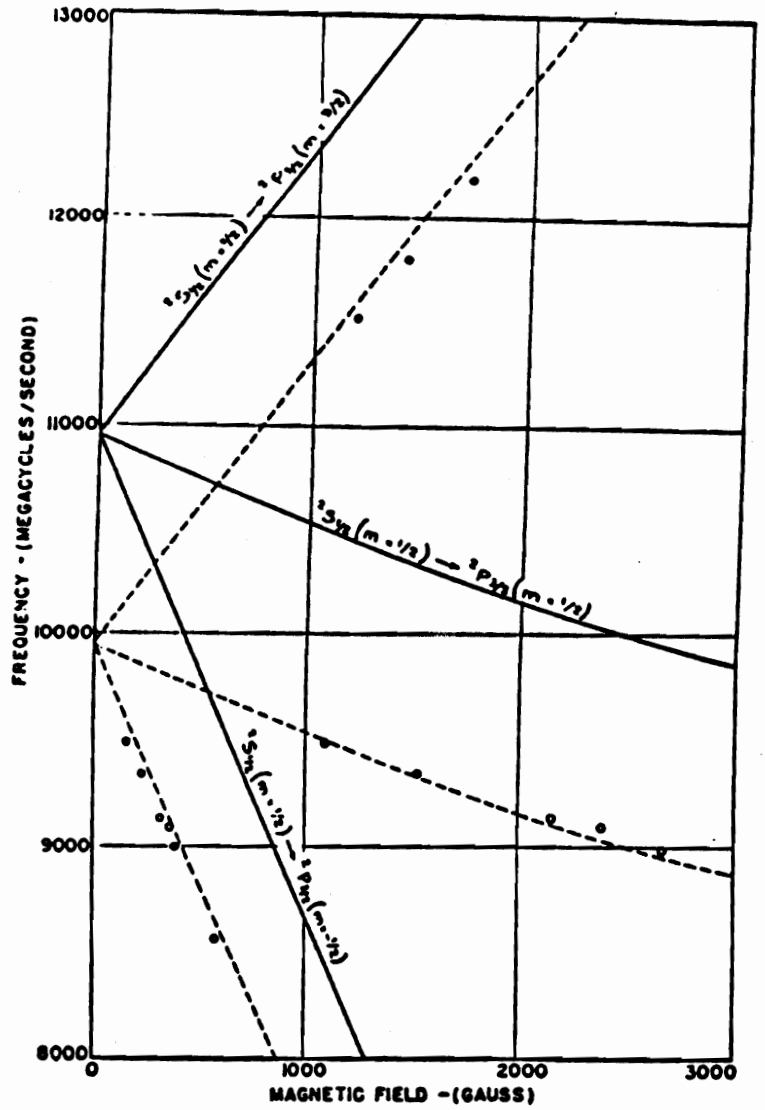


Figure 1: Evidence for the Lamb shift[13]. The solid lines are three of the expected values of level splittings as a function of magnetic field in the absence of a level shift; the dashed lines are those which would be expected in the presence of a 1000 MHz shift.

Figure 2: Participants at the first Shelter Island conference, June 2-4, 1947: 1, I. I. Rabi; 2, L. Pauling; 3, J. Van Vleck; 4, W. E. Lamb, Jr.; 5, G. Breit; 6, D. Mac Innes (National Academy of Sciences); 7, K. K. Darrow; 8, G. E. Uhlenbeck; 9, J. Schwinger; 10, E. Teller; 11, B. Rossi; 12, A. Nordsieck; 13, J. von Neumann; 14, J. A. Wheeler; 15, H. A. Bethe; 16, R. Serber; 17, R. E. Marshak; 18, A. Pais; 19, J. R. Oppenheimer; 20, D. Bohm; 21, R. P. Feynman; 22, V. F. Weisskopf; 23, H. Feshbach. Photo provided by D. Mac Innes, reprinted in second of Refs. 14, p. 380.

genious subtractions of infinite terms[15]. It was a calculation that led to many refinements[16], ending within three years with the fully developed theory of quantum electrodynamics by Feynman, Schwinger and Tomonaga[17].

3.2.2. Electron magnetic moment. The Dirac theory[7] of the electron predicts the factor g in the relation $\vec{\mu} = ge\vec{S}/(2m)$ between the spin $\vec{S}$ and the magnetic moment $\vec{\mu}$ to be exactly 2. Comparison of the fine-structure and hyperfine interactions in sodium and gallium suggested a departure from this value[18] : $g - 2 = 0.00229 \pm 0.00008$. This result was announced at the 1947 Shelter Island conference. Schwinger[19] calculated the effect of the electron self-interaction on this quantity, finding $g - 2 = \alpha/\pi = 0.00232$ in agreement with experiment. The stage was set for a more throrough understanding of such effects. How could one get results in accord with experiment from a theory beset by infinite quantities?

3.2.3. Positronium. We have previously discussed ideas lying dormant during the war and blossoming quickly afterwards. Thus as early as December 1945, a few months after the end of the war, Purcell, Torrey and Pound at Harvard, and Bloch and Packard at Stanford had independently discovered nuclear magnetic resonance. In 1946 Wheeler published a paper[20] on an idea he had developed during the war in which he worked out the details of bound states involving one or more electrons (e^-) and positrons (e^+). The simplest system, the e^+e^- bound state, we now call positronium. He included the rates of annihilation from the singlet and triplet states and the relative polarization of the two photons from the singlet state annihilation. This paper was published in an unlikely journal, the *Annals of the New York Academy of Sciences*, because they were offering a prize for the best paper, which Wheeler won. Experimental confirmation required the development of new tools and instrumentation. The predicted bound state was finally discovered in 1951 by Martin Deutsch[21].

3.3. Advent of renormalization

The banishment of infinite quantities from quantum electrodynamics has been traced in Refs. 14 and 17. Many of the participants in this effort are shown in Fig. 3. Early leaders included Heisenberg, Dirac, Oppenheimer, and Stückelberg. The procedure of reinterpreting infinite quantities in terms of physical ones was proposed by Kramers at the 1947 Shelter Island Conference[14] and developed systematically by Sin-Itiro Tomonaga, Julian Schwinger, and Richard P. Feynman (see box and Fig. 4). The proof that this method was consistent to every order in perturbation theory was due to Dyson and Salam and Ward.

Three major sorts of infinities occur in quantum electrodynamics. The first, associated with the electron's infinite energy of interaction with its own electromagnetic field, is removed by redefining its mass to be the physical value, order by order in perturbation theory. The second can be removed by demanding that a free electron produced at a given point in space be detectable with unit probability at some distant point at a later time. The third, related to the polarization of the vacuum pairs by a test charge, can be removed by redefining the electron's charge as its value as seen by a distant observer.

3.4. Higher-order corrections and experimental confirmation

The successive improvements in theory and experiment in quantum electrodynamics have been a long and mainly happy story[22].

3.4.1. Electron $g-2$ factor. The measurement of the electron's anomalous magnetic moment benefitted greatly from the ability to investigate magnetically confined free electrons[23]. The most recent experiments make use of traps employing both electric and magnetic fields.[24] A single electron has been kept in solitary confinement for nine months in such a trap!

TWELFTH SOLVAY CONFERENCE 1961

Figure 3: Participants in the Twelfth Solvay Conference, Brussels, 1961.

Figure 4: Richard P. Feynman (American Institute of Physics / ESVA Weber Collection).

RICHARD P. FEYNMAN

The contributions of Richard P. Feynman range over wide areas of theoretical physics, from the low temperatures of liquid helium to the highest-energy collisions of elementary particles.

Feynman developed a relativistic theory of quantum electrodynamics using a path integral approach, aided by diagrams that could be identified with actual physical processes. A key element of this language was the identification of positrons as electrons going backward in time. For this work he shared the Nobel Prize in 1965 with Julian Schwinger and Sin-Itiro Tomonaga. Not only have Feynman diagrams become the standard language of elementary particle theory, but they have been widely applied in other areas, such as nuclear physics and condensed matter theory.

Another contribution of Feynman which gave him great pleasure was a description of the weak interactions (the "$V-A$" theory, formulated in collaboration with Murray Gell-Mann and independently by George Sudarshan and Robert E. Marshak) which incorporated the newly-discovered violation of mirror symmetry. Still another was his recognition, along with J. D. Bjorken, that experiments at Stanford were probing pointlike structures (called "partons" by Feynman, but soon to be identified as quarks) in the proton. While few theorists' mathematical skills were the equal of Feynman's, his work was always marked by physical reasoning and appeal to intuition.

Feynman was born in Brooklyn, New York, in 1918 and went to public high school there. He received his undergraduate training at the Massachusetts Institute of Technology and his Ph. D. from Princeton in 1942. During World War II he headed the Scientific Computing division at Los Alamos. After several years on the faculty at Cornell University, he joined the California Institute of Technology in 1950, where was intensely active in physics until his death in 1988.

There were not many physicists bound less by convention than Feynman. Asked to serve on the commission which investigated the explosion of the Challenger Space Shuttle in 1986, he demonstrated on live television that the seals on the spacecraft could not withstand the cold to which they had been subjected at the time of launch.

Although constantly contributing in new frontiers of physics, Feynman loved to share his ideas with others, ranging from undergraduates majoring in physics to the public at large. As a raconteur *par excellence*, he held many generations spellbound with stories of his experiences and insights. The *Feynman Lectures in Physics*, an outgrowth of an introductory course at Caltech, is one legacy of his infinite curiosity and whimsical approach to Nature. This three-volume set, well-thumbed in most physicists' libraries, remains one of the foremost guides to novel and simple ways to view our Universe.

The results for electrons and positrons for $a \equiv (g-2)/2$ are[25] $a(e^-) = (1\ 159\ 652\ 188.4 \pm 4.3) \times 10^{-12}$, $a(e^+) = (1\ 159\ 652\ 187.9 \pm 4.3) \times 10^{-12}$, where the error is a combination of statistical and systematic uncertainties. The theoretical prediction[26] is

$$a(e) = \alpha/(2\pi) - 0.328\ 478\ 965\ (\alpha/\pi)^2 + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + \delta a(e) \quad . \quad (3.1)$$

The first two terms have been calculated analytically, while only numerical evaluations of $C_3 = 1.176\ 11 \pm 0.000\ 42$ and $C_4 = -1.434 \pm 0.138$ have been performed. The term $\delta a(e) = 4.46 \times 10^{-12}$ arises from electroweak interactions and from Feynman graphs involving internal muons, tau leptons, and quarks.

Several determinations of α exist, the most precise of which, $\alpha^{-1}(\mathrm{QHE}) = 137.035\ 997\ 9 \pm 0.000\ 003\ 2$ makes use of the quantum Hall effect[27]. Using this value, one predicts[26]

$$a(e) = (1\ 159\ 652\ 140 \pm 5.3\ [C_3] \pm 4.1\ [C_4] \pm 27.1\ [\alpha]) \times 10^{-12} \quad , \quad (3.2)$$

This result agrees with experiment within errors. Until the uncertainty in α is reduced, one is not really testing the $(\alpha/\pi)^4$ term incisively.

3.4.2. Muon $g-2$ factor. The lowest-order Feynman graphs leading to a difference between $a(e)$ and $a(\mu)$ contribute at second order in α. Instead of $-0.328\ldots$ for the coefficient of $(\alpha/\pi)^2$, one obtains $+0.754\ldots$[28].

The earliest measurement of $a(\mu)$ confirmed that it was within 5% of zero[29]. A pioneering series of experiments was begun at CERN in the late 1950s, involving the containment of muons first in a long dipole magnet and then in storage rings[30]. The most recent results of these last experiments are: $a(\mu^+) = (1\ 165\ 910 \pm 11) \times 10^{-9}$, $a(\mu^-) = (1\ 165\ 936 \pm 12) \times 10^{-9}$, or, combining the two results, $a(\mu) = (1\ 165\ 923 \pm 8.5) \times 10^{-9}$, where the total (statistical and systematic) errors are shown.

The theoretical value contains contributions from QED, intermediate states involving strongly interacting particles ("hadrons"), and weak interactions[31]:

$$a(\mu)|_{\mathrm{QED}} = (1\ 165\ 846.955 \pm 0.046 \pm 0.028) \times 10^{-9} \quad ,$$

$$a(\mu)|_{\mathrm{had}} = (70.27 \pm 1.75) \times 10^{-9} \quad , \quad a(\mu)|_{\mathrm{weak}} = (1.95 \pm 0.10) \times 10^{-9} \quad , \quad (3.3)$$

leading to a total of

$$a(\mu)|_{\mathrm{theor}} = (1\ 165\ 919.18 \pm 1.76) \times 10^{-9} \quad . \quad (3.4)$$

The errors in $a(\mu)|_{\mathrm{QED}}$ reflect the theoretical uncertainty and that due to the measurement of α. The dominant error in $a(\mu)|_{\mathrm{had}}$ and hence in (3.4) comes from uncertainty in hadronic vacuum polarization effects in the $\mathcal{O}(\alpha^2)$ contribution.

An experiment is being mounted at Brookhaven National Laboratory to measure $a(\mu)$ about twenty times more sensitively[30]. Its interpretation will require

reduction of the error in the hadronic vacuum polarization contribution by means of more precise e^+e^- annihilation experiments. With that error reduced, one will then be able to test the weak contribution $a(\mu)|_{\text{weak}}$ to about 20% of its expected value.

3.4.3. Lamb shift. The most recent measurement of the $2S_{1/2} - 2P_{1/2}$ splitting in atomic hydrogen is (1 057 851.4±1.9) kHz[32], to be compared with the theoretical prediction[33] of (1 057 853 ± 14) kHz or (1 057 871 ± 14) kHz, depending on how the proton's structure is described. As in the case of $a(\mu)$, there is satisfactory agreement with experiment, but a hadronic measurement is needed to reduce theoretical uncertainty.

3.4.4. Hyperfine interactions. A history of atomic hyperfine structure experiments is given by Ramsey[34]. The most precise value for the splitting between the $^3S_1$ and $^1S_0$ levels in hydrogen is $\Delta\nu_H$ = (1 420 405 751.766 7 ± 0.000 9) Hz. The theoretical prediction is within about 1 kHz of this value, but is affected by unknown proton structure effects. While experimental accuracy far outstrips theory, the agreement is still impressive.

Purely leptonic systems also exhibit hyperfine structure. The experimental value for muonium agrees satisfactorily with theory within the errors associated with uncertainty in the muon mass. In positronium, the observed hyperfine splitting is $\Delta\nu^{\text{exp}}$ = (203 389.10 ± 0.74) MHz, to be compared with the prediction $\Delta\nu^{\text{theor}}$ = 203 404.5 ± 9.3) MHz, where the dominant source of error comes from uncalculated corrections of order α^2 with respect to the leading result. The calculation of these corrections is a challenge to the most enthusiastic theorist.

3.4.5. Positronium decay: a current puzzle. The annihilation of positronium ground states into photons is governed entirely by QED. The $^1S_0$ (singlet) state decays into two photons, while the $^3S_1$ (triplet) state decays into three. The singlet rate[35] is found to be $\lambda_s = (7.994 \pm 0.011)$ ns^{-1}, to be compared with the prediction[20,35,36] $\lambda_s = (7.986654 \pm 0.000001)$ ns^{-1}, whose error is governed by that on α. The agreement is satisfactory. On the other hand, the value measured in vacuum[37] of the triplet rate, $\lambda_t = (7.0482 \pm 0.0016)$ μs^{-1}, is more than six standard deviations from the calculated value[38] $\lambda_t = (7.03831 \pm 0.00007)$ μs^{-1}. One would need a large $\mathcal{O}(\alpha^2)$ correction to this value to bring theory into accord with experiment. The evaluation of this term represents a frontier of QED.

4. NEW FORMS OF MATTER UP TO THE MID-1960s

The number of known "elementary" particles grew by an enormous factor in the two decades after World War II. In this Section we describe how that growth took place. The penetrating component of cosmic radiation, the muon, was eventually understood as being distinct from Yukawa's particle, the pion. The antiproton, predicted by Dirac's theory, was eventually found. Many "strange" particles were discovered, and evidence was gathered for resonant particles, some living less than 10^{-23} second. Classification schemes during this period made

widespread use of symmetry principles. The understanding of several hundred particles in terms of a few simple constituents came later.

4.1. The 1930s and 1940s: muons, pions, kaons

Modern particle physics starts with the discovery of the deuteron in 1931 by Urey, Brickwedde, and Murphy[39]; the neutron in 1932 by Chadwick[40], the positron in 1932 by Anderson[41] (to be confirmed shortly by Blackett and Occhialini in an experiment discussed below) and what is now called the muon (then, the mesotron or meson) by Neddermeyer and Anderson, Street and Stevenson, and the Nishina group in 1937 [42].

Though Dirac's paper[7] predated the discovery of the positron by three years and Yukawa's meson[43] came before the muon by two years, they played no role in stimulating experimental searches. For example, Anderson observed that a person accepting the Dirac theory at face value could have discovered the positron in an afternoon. "However, history did not proceed in such a direct and efficient manner, probably because the Dirac theory, in spite of its successes, carried with it so many novel and seemingly unphysical ideas, such as negative mass, negative energy, infinite charge density, etc. Its highly esoteric chracter was apparently not in tune with most of the scientific thinking of the day." In addition, while today the Dirac theory is held as a monument to deductive reasoning, a splendid example of the "unreasonable effectiveness of mathematics in physics," it was not accepted for a long time. Leading detractors included the likes of Pauli and Heisenberg. While the discovery of the positron had much to do with the acceptance of the Dirac theory, the theory in no way stimulated the activity leading to the discovery.

In the case of Yukawa's meson theory, Japanese scientific literature was not widely disseminated in the West, and the average physicist simply was unaware of the Yukawa particle. Only after the muon's discovery did Oppenheimer and Serber[44] discuss (with reservations) the possibility of identifying it with the Yukawa particle, making the first reference to Yukawa's paper in Western literature[45].

During the 1930s the only theoretical construct that took hold was the neutrino[46], forced on the community of physicists by energy conservation. This apparent independence of experimental and theoretical work contrasts strikingly with the close communication and interplay that developed between theory and experiment by the 1960s.

Blackett and Occhialini[47] not only beautifully confirmed the observations of Anderson, but gave photographic cloud-chamber evidence of cosmic-ray induced showers of particles. In addition, their experiment initiated one of the most important new techniques of the decade, the use of counter-controlled cloud chambers. The previous practice was to expand the cloud chamber and, after an optimum time, take a photograph. Consequently, most of the photographs were of an empty chamber, or showed old tracks fuzzed out by diffusion. With counter-controlled expansions, more than 75% of the pictures showed ionizing tracks. Never again, relative to the passage of particles, would cloud chambers be expanded randomly

in time. The neutral pion excepted, for the next twenty years all of the new particles were discovered through the study of cosmic rays via visual techniques: by the use of counter-controlled cloud chambers and, after World War II, photographic emulsions.

The Yukawa meson theory[43] (1935) and the Fermi theory[48] (1934) of beta-decay were patterned on electrodynamics, where the force between charges is viewed as arising from photon exchange. In the case of radiation from atoms, the photons did not previously exist in the atom but were created at the moment of radiation. Likewise, in Fermi's beta-decay theory, the electron and neutrino did not pre-exist in the nucleus but were spontaneously created. This enormous conceptual advance immediately resolved many questions, including the nature of the neutron. From its discovery until the advent of the Fermi theory, a hotly debated topic had been whether the neutron was a particle with the same status as the proton or whether it was an electron-proton composite. With the Fermi theory, beta-decay was simply the transmutation of the neutron to proton, electron, and neutrino. The lifetime of the neutron was not measured until 1948 but in 1934 the Fermi theory estimated it to be $\sim 10^3$ sec. (It is now known to be very close to 15 minutes: 887 ± 2 seconds[48a]).

In the case of the Yukawa theory the particles mediating the interaction were given mass to produce a short-range "Yukawa potential," $V(r) \sim \exp[-r(mc/\hbar)]/r$. Choosing a range then known to be characteristic of nuclear forces, $\approx 10^{-13}$ cm, one gets a mass around 200 MeV. Oppenheimer and Serber asked whether this was the same particle as the mu meson (which they prophetically referred to as a heavy electron). However, this association almost immediately ran into conflict with experiment.

If the meson were to account for nuclear forces it should interact strongly with nuclear matter, so that the cross section for interaction should approach the geometric cross section with a mean free path of about 100 grams/cm^2. It quickly became apparent that the penetrating component of the cosmic radiation interacted with a much smaller cross section. Furthermore, Rossi and Nereson[49] showed in 1940 by studying the flux of this component as a function of altitude that the attenuation through the atmosphere could only be accounted for by including a decay component as well as nuclear interactions. They were able to measure the lifetime to be $(2.15 \pm 0.07) \times 10^{-6}$ s, roughly 100 times longer than the lifetime of the Yukawa particle estimated on theoretical grounds. Shortly afterwards, a meson was seen to decay to an electron plus neutral particles in a cloud chamber[49a].

Early on it became apparent that positively- and negatively-charged mesons could be expected to behave quite differently on coming to rest in matter. The positive particle would very quickly come to thermal energies and decay at its natural rate. The negative particle would come to rest, find itself attracted to a positive nucleus, cascade down through the various atomic levels by emitting

radiation or Auger electrons, and then, depending on the nature of the particle, either decay or interact with the nucleus. The whole process, stopping and atomic transitions to the $1S$ state, was estimated to take less than 10^{-11} s, a time much shorter than the expected decay times.

The experiment which definitively showed that the meson discovered in 1937 was not Yukawa's particle was performed by Conversi, Pancini, and Piccioni[50] (1945). Using magnetized iron as a charge selector, they showed that both positive and negative mesons appeared to decay when coming to rest in carbon, while if the particles came to rest in iron only the positive ones decayed. Since negative mesons with Yukawa-like properties would be expected to interact even in elements as light as carbon, the evidence was unmistakable that the mesons could not be the strongly interacting Yukawa type.

In the meantime, significant advances were taking place in the production of photographic emulsions sufficiently sensitive to detect lightly ionizing particles. Following initial applications in nuclear physics, in 1946 Perkins at the Imperial College in London and Powell and his group at Bristol first exposed the new emulsions to cosmic rays[51]. (The history of the photographic emulsion technique and its contributions to particle physics has been beautifully recorded in Ref. 52.)

Though the first emulsions were not sensitive to minimum ionizing particles, the technique almost immediately showed its value. Perkins found an example of a meson coming to rest and depositing its rest energy into a "star" of heavily ionizing fragments in an emulsion exposed in an airplane flown at 30,000 feet. The Bristol group exposed their emulsions at the Pic du Midi laboratory in the French Alps (Fig. 5), quickly finding examples of pi mesons decaying to mu mesons with characteristic tracks 600 microns long. (This group first labelled the two kinds of mesons as π and μ, the only two Greek letters on Powell's typewriter.) The pi meson decay was clearly two-body. (The emulsions were not yet sufficiently sensitive to see the electron track from the subsequent mu decay.)

The paper of the Powell Group at Bristol, generally marked as announcing the discovery of the π meson or pion[53], appeared in Nature's issue of May 24, 1947. The existence of two types of meson had been anticipated by Sakata's group in Japan, whose work only became known after several years, and was discussed in the West by R. E. Marshak and H. Bethe[54].

Seven months later in the same journal appared a paper "Evidence for the Existence of New Unstable Elementary Particles" by C. D. Rochester and C. C. Butler[55], reporting on the first two examples of "strange" particle decay in a cloud chamber. We would now call them beautiful examples of K mesons, the neutral K_S and a charged K^+. Elementary particle physics would be occupied for the next quarter century with the properties of pions, muons and the "strange" particles.

4.2. Pion properties

Nuclear forces were expected to be *charge-independent*, obeying a symmetry which amounted to invariance under rotation in an abstract *isotopic spin* or *isospin*

Figure 5: The Pic-du-Midi, site of early cosmic ray experiments. From first of Refs. 3, p. 65.

space[5]. As a consequence, Yukawa's theory entailed not only charged but also neutral pions[55a], first seen around 1950 in various accelerator and cosmic ray experiments[56].

4.2.1 Spin and parity. The spin of charged pions was established by comparing the rates for $p + p \rightarrow \pi^+ + d$ and $\pi^+ + d \rightarrow p + p$. The ratio of the rate for the first process to that for the second is proportional to $2S_\pi + 1$, where S_π is the spin of the pion. The result of measurements of both reactions[57] led to the conclusion that $S_\pi = 0$.

Particles can be characterized by an intrinsic *parity*, describing the behavior of their fields under space inversion. The negative parity of charged and neutral pions was deduced by comparing[58] rates for the process $\pi^- + p \rightarrow n + \gamma$ with $\pi^- + p \rightarrow n + \pi^0$, and $\pi^- + d \rightarrow 2n$ with $\pi^- + d \rightarrow 2n + \gamma$ and $\pi^- + d \rightarrow 2n + \pi^0$, and by comparing[58a] the yields of neutral and charged pions in proton collisions on light nuclei. An early test of charge-indepdence by comparing the cross sections for $n + p \rightarrow d + \pi^0$ and $p + p \rightarrow d + \pi^+$ was performed by R. Hildebrand[58b].

4.2.2 Charged and neutral pion decays. The lifetime of the charged pion was first measured using pions produced artificially at an accelerator[59]. Within a couple of years, precise electronic timing techniques had yielded a result[60] very close to that known at present (26 ns), and considerably shorter than that of the muon. The dominant channel is $\pi^\pm \rightarrow \mu^\pm \nu$.

The nature of the neutral pion was still open to question. It was seen to decay to two photons, but direct measurements of its spin, parity, and lifetime were needed. S. Sakata, L. D. Landau and C. N. Yang[61] showed that a spin-1

particle could not decay to two photons, and showed how to determine the parity by comparing the linear polarizations of the two photons. Parallel polarizations implied even parity, while perpendicular polarizations implied odd parity. Later measurements[62] showed the parity to be odd, in agreement with the result of Ref. 58.

The lifetime of the neutral pion was determined by direct measurements[63] to be less than 10^{-13} s. Estimates[64] by J. Steinberger suggested the possibility of an even shorter lifetime than this upper bound, outside the reach of direct detection methods at the time. It was proposed by H. Primakoff[65] to use the rate of neutral pion photoproduction in the Coulomb field of a nucleus to measure the decay rate indirectly. This method was first applied a number of years later, yielding values slightly below 10^{-16}s [66]. Direct methods, now the most accurate, also evolved for measuring such short lifetimes using sandwiches of foils[67].

4.3. Antiprotons

The Dirac theory of antiparticles, so stunningly confirmed by the positron's discovery, also predicted a negative version of the proton, the *antiproton* or $\bar{p}$. The antiproton and proton were expected, though not unanimously, to have equal masses. The energy of a new accelerator under consideration at Berkeley was chosen to lie above the threshold for the reaction $p + p \rightarrow p + p + p + \bar{p}$. This accelerator, the Bevatron, not only discovered the antiproton, but a wealth of other particles, ushering in a new era of high energy physics.

Several groups were searching for antiprotons at the Bevatron. Key players included O. Chamberlain, O. Piccioni, E. Segré, W. Wenzel, C. Wiegand, and T. Ypsilantis. The construction of a beam of antiprotons was a crucial feature of the discovery. Protons in the machine struck an internal target, and the resulting negatively charged particles were focused into a well-collimated external beam with a narrow momentum range. Antiprotons were distinguished from the much more abundant negative pions by precise time-of-flight measurements and with the help of focusing Čerenkov counters, a tool that contributed greatly to the experiment's success. Knowing both the momentum and the velocity of particles in the beam, one could measure their masses. A clear signal was seen of negatively charged particles with the mass of a proton[68]. Their identity as examples of antimatter was confirmed by the observation of their annihilations in nuclear emulsions[69].

4.4. Strange Particles

The story of the discovery and classification of "strange particles," as they were called, affords a lovely example of order emerging from chaos[70].

4.4.1 Discoveries in cosmic rays. Two techniques for studying cosmic rays were in use during the 1940s: nuclear emulsions, in which the passage of particles exposed a three-dimensional photographic image, and cloud chambers, in which

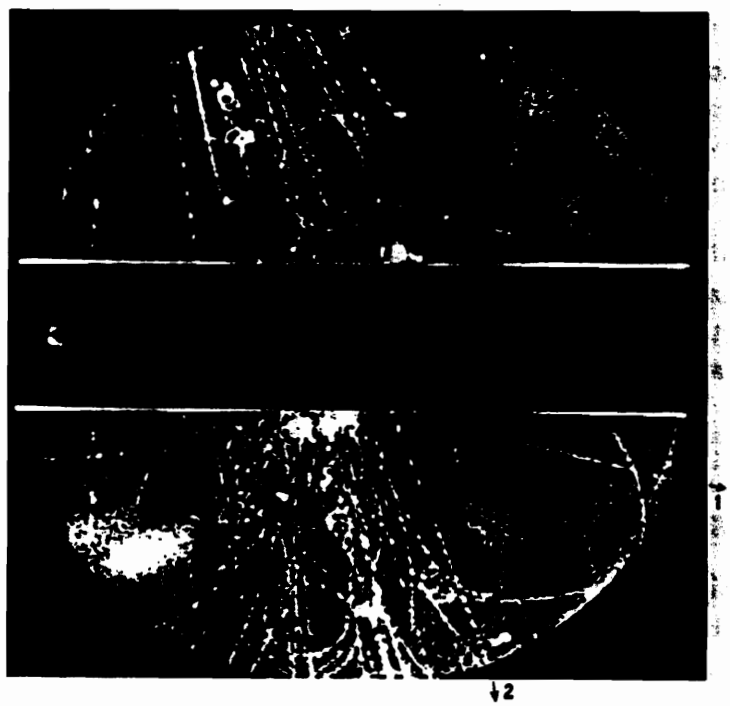


Figure 6: First evidence for a neutral strange particle, from the cloud chamber experiment of Rochester and Butler[55]. The particle was produced in a lead plate (shown at center) and decayed to two charged particles (1 and 2).

charged particles left a trail of droplets in a supercooled vapor. Both yielded evidence for new particles besides the positron, muon, and pion.

By studying elastic scattering of charged particle tracks on electrons in emulsions, Leprince-Ringuet and Lhéritier[71] deduced the existence of a new particle of mass about 990 times the electron's mass. In retrospect, this appears to have been the first measurement of the mass of the charged *K meson*, or *kaon*.

Using a cloud chamber at Manchester, Rochester and Butler[55] saw two events which we would now characterize as decays of kaons, as mentioned in Sec. 4.1. The neutral particle led to the emergence of a "forked" pair of tracks (Fig. 6), while the charged one was seen decaying to an electron and one or more missing neutral particles. A long "dry spell" for the Manchester group followed, during which an emulsion experiment[72] saw the decay of a charged kaon to $\pi^+ + \pi^+ + \pi^-$, permitting a decisive measurement of its mass. Meanwhile confirmation of the existence of Rochester and Butler's events came from a cloud chamber operating primarily at high altitude in California[73]. The Manchester group then set up operation on the Pic du Midi in the Pyrenees, where many more events were found.

The neutral kaon was seen to decay to $\pi^+ + \pi^-$. Because of the equal masses of the two pions, the momentum distributions of their tracks were equal, and so were the typical angles they made with the direction of the incident kaon. However, in

1950, an event was seen in which the positive track appeared to be a proton[74]. In the decay of a neutral particle to $p + \pi^-$, the proton, because of its larger mass, tends to carry most of the momentum, leading to an asymmetric configuration. The Pic du Midi group[75], led by R. Armenteros, and a cloud chamber group at Indiana[76] led by R. Thompson resolved the decay $K^0 \to \pi^+ + \pi^-$ from what we now understand to be $\Lambda \to p + \pi^-$. The Λ was the first example of a *hyperon*, a particle heavier than the proton. Cosmic-ray studies also yielded the first evidence for charged hyperons, the Ξ^- and the Σ^+. The Ξ^- was called the "cascade" particle because it was seen[77] to decay to $\Lambda + \pi^-$, with the subsequent decay of the Λ. The Σ^+ was seen[78] decaying to $n + \pi^+$ and $p + \pi^0$.

In contrast to the neutral kaon, the charged kaon was found to have many different decay modes. Sorting out all these results took some time and effort, in which emulsion studies were of tremendous help.

4.4.2 Discoveries in accelerators. The Brookhaven Cosmotron, which began operation in 1952, belonged to a new generation of accelerators constructed to study fundamental interactions at unprecedented energies[79]. Its attention was quickly turned to strange particles. In a series of experiments performed with a hydrogen cloud chamber, Ralph Shutt and his group[80] were able to demonstrate what cosmic ray experiments had been unable so far to reveal: the new heavy particles were produced in pairs, as in the reaction $\pi^- + p \to \Lambda^0 + K^0$, confirming earlier hypotheses by several groups in Japan[81] and by A. Pais[82]. In addition to the associated production of Λ's just mentioned, Shutt's group was the first to produce and observe neutral and negative Σ hyperons.

4.4.3 Associated production and strangeness. The new heavy particles were produced fairly copiously (in about 1% of all cosmic-ray events), but decayed very slowly (with lifetimes about a trillion times longer than one might expect if their production and decay were governed by the same interaction). A clear statement of this paradox was given very early by Nambu, Nishijima, and Yamaguchi in their second paper of Ref. 81:

"... production and decay are not inverse processes and/or some kind of selection rules (in a very general sense) are at work in the decay reaction)."

One option for such a rule was a quantum number ("isotopic parity") taken to be $+1$ for the nucleon, pion, and muon and -1 for the new ones (corresponding to what we now call the K and Λ). This quantum number was taken to be conserved *multiplicatively* in production processes, but could be violated in the much weaker decay processes. Thus, a kaon always had to be produced in association with a Λ, a rule that came to be known as "associated production."

Associated production as formulated required one to assign an odd isotopic parity to the Σ hyperons, but did not prohibit reactions like $p + p \to \Sigma^+ + \Sigma^+$ or $n + n \to \Lambda + \Lambda$ that were not seen. Moreover, associated production ran into difficulty with the negative cascade particle, Ξ^-, which decays to $\Lambda\pi^-$ with a typical "slow" lifetime of the order of 10^{-10} s. By the above scheme we would

then assign even isotopic parity to the Ξ^-. But then what would prohibit the decay $\Xi^- \to n + \pi^-$, a process that has not been seen to this day?

The strong interactions of pions and nucleons conserve isospin symmetry, mentioned at the beginning of Section 4.2. Pions have isospin $I = 1$ and nucleons have $I = 1/2$. The charge of a pion is the third component of its isospin, while that of the nucleon is displaced by half a unit. For both particles, one can write $Q = I_3 + B/2$, where the ***baryon number*** B is 0 for pions and 1 for nucleons.

M. Gell-Mann[83] and K. Nishijima[84] generalized this relation to the new particles by postulating "displaced" isotopic spin multiplets, with $I = 0$ for the Λ, $I = 1$ for the Σ^+ and Σ^- (thereby predicting the Σ^0), and $I = 1/2$ for charged and neutral kaons. The conservation of charge and I_3 in strong interactions then required every multiplet to be characterized by an additional quantum number, called ***strangeness***, also conserved in the strong interactions.

The relation between the charge and the third component of isospin could now be written $Q = I_3 + Y/2$, where the ***hypercharge*** $Y = B + S$, with a new additive quantum number S assigned to every strongly interacting particle, described the displacement of the isospin multiplet. The K^0 and K^+ were taken to have $S = 1$ and the Λ and Σ were assigned $S = -1$. The reactions $p + p \to \Sigma^+ + \Sigma^+$ and $n + n \to \Lambda + \Lambda$ were forbidden by this scheme. Decays such as $K^0 \to \pi^+ + \pi^-$ and $\Lambda \to p + \pi^-$, violating S by one unit, were allowed to proceed, but only weakly.

In order that $\Xi^- \to \Lambda + \pi^-$ be a weak decay violating strangeness by one unit, but to prevent the occurrence of $\Xi^- \to n + \pi^-$, one had to take $S(\Xi^-) = -2$. Then $K^- + p \to K^+ + \Xi^-$ should proceed strongly, as was later confirmed. Moreover, $I_3(\Xi^-)$ should equal $-1/2$, entailing the existence of a neutral partner Ξ^0 with $I_3 = +1/2$, a particle eventually seen in a bubble chamber[85].

4.4.4 Neutral kaons and their lifetimes. The existence of kaons with both signs of charges had been known for some time before Gell-Mann and Nakano and Nishijima proposed that these mesons had isospin 1/2. But that proposal implied the existence also of two kinds of ***neutral*** kaons, the K^0 (with strangeness $S = 1$ like the K^+) and the $\bar{K}^0$ (with strangeness $S = -1$ like the K^-). How could one tell them apart? This question was raised by Fermi in June of 1954 at a seminar by Gell-Mann describing the strangeness scheme.

The resolution of this problem[86] provided a beautiful application of quantum mechanics. The K^0 and $\bar{K}^0$ are two degenerate states; nothing specifies what combination of them corresponds to states of definite mass and lifetime. However, if invariance under charge reflection is assumed in the K decay process (as it was in the mid-1950s), one linear combination of K^0 and $\bar{K}^0$ could decay to $\pi^+ + \pi^-$, while the other could not. These two states were denoted K_1^0 and K_2^0, respectively. The K_1^0 had already been seen; the K_2^0 was a newly predicted particle that should live much longer than the K_1^0, since its decay to $\pi^+ + \pi^-$ was forbidden.

An experiment at the Brookhaven Cosmotron[87] soon confirmed the existence of the predicted neutral kaon with its characteristic long lifetime and dominant

three-body decay mode. Supporting evidence came from four events which, most plausibly, originated from interactions of K_2's in photographic emulsions[87a].

4.5. Resonances

4.5.1 Pion-nucleon scattering. The isospin of a combined pion-nucleon system can only be 1/2 or 3/2, entailing simple relations among pion-nucleon scattering amplitudes[88]. (Other early applications of isotopic spin are noted in Refs. 89.) As artificially produced pions began to be available in the late 1940s because of increased cyclotron energies, attention was turned to the properties of pion-nucleon scattering. The development of electron synchtrorons capable of reaching energies of several hundred MeV led to production of high energy photons, also useful in producing pions[90]. A crucial result of these experiments was the discovery of the first *isobar*, an excited nucleon state.

4.5.2 Nucleon isobars. With increasing pion and photon energies, the cross sections for pion-nucleon elastic scattering and single pion photoproduction grew in a very specific pattern[91]. Theorists[92] proposed that this pattern might signal the existence of a short-lived excited state of the nucleon with $I = J = 3/2$. With still higher energies[93], the cross sections traced out a well-defined pion-nucleon resonance, called the (3,3) resonance because of its spin and isospin. Its current appelation is $\Delta(1232)$, where the number (here and later) denotes the mass in MeV/c^2. The phase shift in the corresponding channel was seen to pass through 90° as appropriate for a resonance.

Still higher energies led to the discovery of additional peaks in cross sections, corresponding to states with well-defined spins and isospins. By the late 1950s, several of these pion-nucleon resonances had been identified[91].

4.5.3 The resonance explosion. Invention of the bubble chamber[94] permitted the study of particle interactions in much greater detail during the mid-1950s. Several groups, including Luis Alvarez and collaborators[95], introduced automated methods to scan photographs of interactions. Pions, nucleons, and strange particles all were found to participate in the formation of resonant states with well-defined masses and spins. Widths of these states were typically tens of MeV, as expected for states formed and decaying via the strong interactions[96].

Some of the earliest resonances had been anticipated from spin and isospin properties of nuclear forces. A "mixture of mesons," not just Yukawa's proposed particle, appeared to be needed[97]. Experiments on the *form factors* of nucleons[98], to be discussed in Sec. 6.2.1, could be interpreted as though the photon coupled to nucleons through a spin-1, isoscalar particle[99], decaying to three pions. An $I = J = 1$ resonance decaying to $\pi^+ + \pi^-$ also was suggested[100] on the basis of form factor experiments. This resonance, the $\rho(776)$, was the first meson resonance to be discovered[101]; the three-pion isoscalar resonance $\omega(783)$ followed shortly thereafter[102].

Resonance searches utilized two major techniques: "formation," or varying the beam energy and observing a peak in the cross section as in the discovery of

the (3,3) resonance, and "production," or grouping particles in the final state into combinations whose "effective mass" spectrum could be studied for enhancements. We already noted that formation experiments in pion-nucleon and photon-nucleon collisions led to a fertile yield of resonances. The advent of beams of negatively charged kaons revealed many resonances of negative strangeness formed in K^-p and K^-n reactions. Excited states of the Λ and Σ hyperons thus began to be uncovered. The production experiments had unique ability to see meson resonances, but also were the first to detect several excited baryon states. By the early 1960s, the $\rho(776)$, $\omega(783)$, another three-pion resonance, the $\eta(547)$ (Ref. 103), a $J = 1$ "excited kaon," $K^*(892)$, and a $J = 3/2$ version of the Σ at 1385 MeV had appeared. The "elementary particles" had thus progressed from a handful to a veritable zoo in the course of twenty years[96].

4.6. Unitary symmetry

4.6.1 Preludes. By 1960, a wide variety of baryons with spin 1/2 had been identified. Isospin had proved a successful guide to the classification of all the strongly interacting particles, but the existence of particular multiplets and the masses of the baryonic states remained a mystery. Similarly, it appeared that kaons were strange versions of pions, with the same spin and intrinsic parity.

4.6.2 SU(3). Initial efforts to unify non-strange and strange particles[104] included a "global symmetry" of the strong interactions, composite models of mesons, and searches for various Lie groups containing isospin [SU(2)] as a subgroup. The group SU(3) was proposed[105] as a symmetry of strongly interacting particles in 1959, with the proton, neutron, and Λ assigned to a triplet representation. The mesons π, K, and an as yet undiscovered eighth meson (now known as the η), all composites of p, n, Λ, and their antiparticles, were to form an octet.

Murray Gell-Mann had been searching for several years for higher symmetries containing isospin which could unify the baryons. In 1960 he realized that the octet representation of SU(3) was a perfect home for the spin-1/2 states N, Λ, Σ, and Ξ. His conclusions on this "eightfold way" were originally published only in preprint form[106]. Independently, Yuval Ne'eman, an Israeli military attaché in London working for his Ph. D. in physics, was asked by his supervisor, Abdus Salam, to find an appropriate group containing isospin to classify the observed hadrons. He generalized the work of Yang and Mills[107] on self-interacting fields to higher symmetries, and realized the importance of SU(3). He, too, suggested that the spin-1/2 baryons belonged to an octet[108]. Gell-Mann's approach was part of a larger scheme in which *currents* (such as the electromagnetic current) played a crucial role[109]. We shall return to that aspect of SU(3) in Chapter 5.

4.6.3 Consequences for masses; verification. The SU(3) scheme, when combined with an assumption about the nature of symmetry breaking, led Gell-Mann and Okubo[110] to mass relations among the baryons and among the mesons:

$$M(N) + M(\Xi) = [3M(\Lambda) + M(\Sigma)]/2 \quad ; \quad M(K) = [3M(\eta) + M(\pi)]/4 \quad .$$

The relation for the baryons is well satisfied: with the observed masses, we have 2257 MeV $\approx$ 2270 MeV. For the mesons, the symmetry breaking is greater, and we have 495 MeV $\approx$ 446 MeV. The success of the mass formula for baryons and the discovery[103] of the predicted η were notes of encouragement for the SU(3) scheme. Another higher symmetry, based on the group G_2, had room for only seven mesons and seven baryons.

When SU(3) was proposed, an isospin-3/2 nonstrange multiplet [the $\Delta(1232)$] and an isospin-1 strange multiplet [the $\Sigma(1385)$] were known. At the 1962 International Conference on High Energy Physics in Geneva an excited state of the Ξ at 1530 MeV/c^2, decaying to $\Xi + \pi$, was announced. The SU(3) scheme and another contender, the G_2 group mentioned above, had very different predictions for the remaining particles if the $\Delta(1232)$, $\Sigma(1385)$, and $\Xi(1530)$ all belonged to the same multiplet.

A 10-dimensional SU(3) representation was the smallest which could accommodate the Δ and its partners. The Gell-Mann – Okubo mass relation predicted equal spacings between the masses of its members. The $\Xi(1530)$ obeyed this prediction. It was expected to have isospin 1/2. Nine states of the ten would then have been seen: four Δ's, three Σ's, and two Ξ's. The missing tenth state was expected to have strangeness –3 and a mass of about 1675 MeV. With this mass, it would be *stable* with respect to the strong interactions, decaying instead weakly to such channels as $\Lambda + K^-$. The members of the lowest octet and decimet of baryons are shown in Fig. 7.

The next largest representation of SU(3) which could decay to a pair of octets and could hold a Δ is 27-dimensional. It contains resonances of positive strangeness, decaying to such states as $K^+ + p$ and $K^+ + n$. However, no such resonances had been seen[111].

The smallest G_2 multiplet accommodating the Δ was 14-dimensional. Although it had room for a state of strangeness –3 [like the 10-plet of SU(3)], it had an isoscalar positive-strangeness resonance. The absence of such a resonance thus weighed against the G_2 scheme, and favored the 10-plet (rather than the 27-plet) assignment of the multiplet within SU(3).

The SU(3) prediction of a strangeness -3 state was stressed by Gell-Mann and Ne'eman at the 1962 Geneva Conference[112]. Shortly thereafter, a new 80-inch bubble chamber at Brookhaven was exposed to a beam of K^- mesons. The story of how the predicted particle, the Ω^-, was discovered[113] in 1964 is one of the exciting chapters in the history of particle physics. Its mass was almost exactly the predicted value, and the first event (Fig. 8) was a particularly clean signature in which all the decay products revealed themselves.

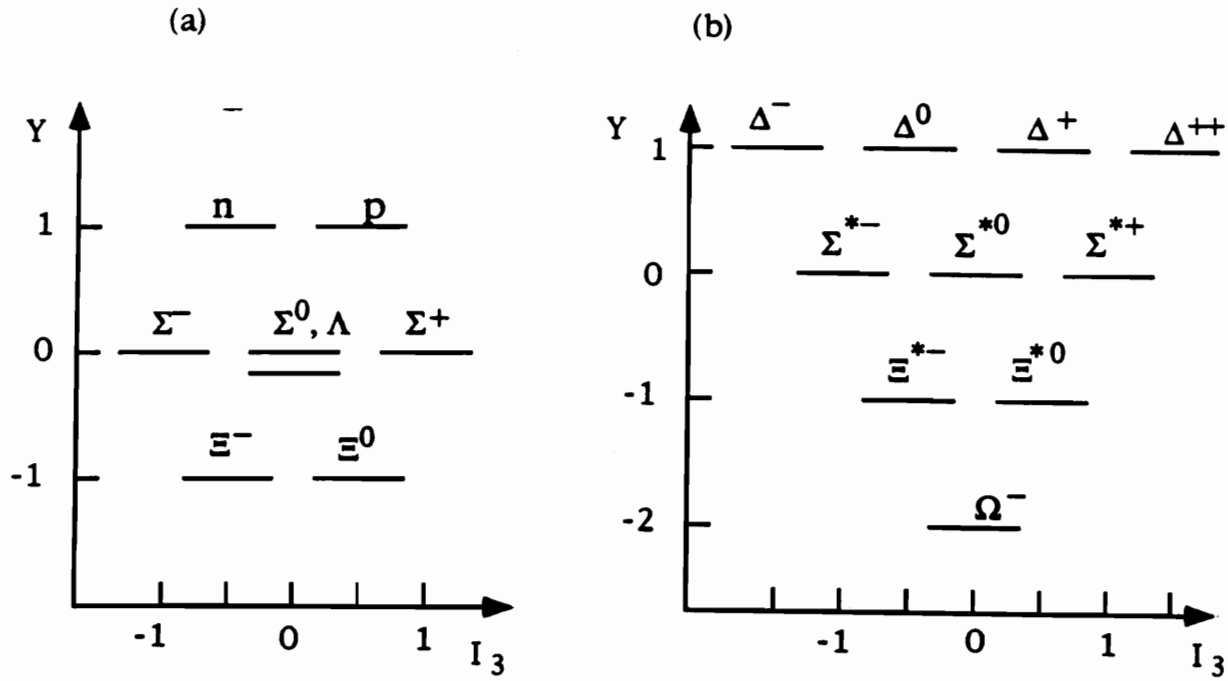


Figure 7: Low-lying baryonic states as classified in SU(3). (a) octet; (b) decimet.

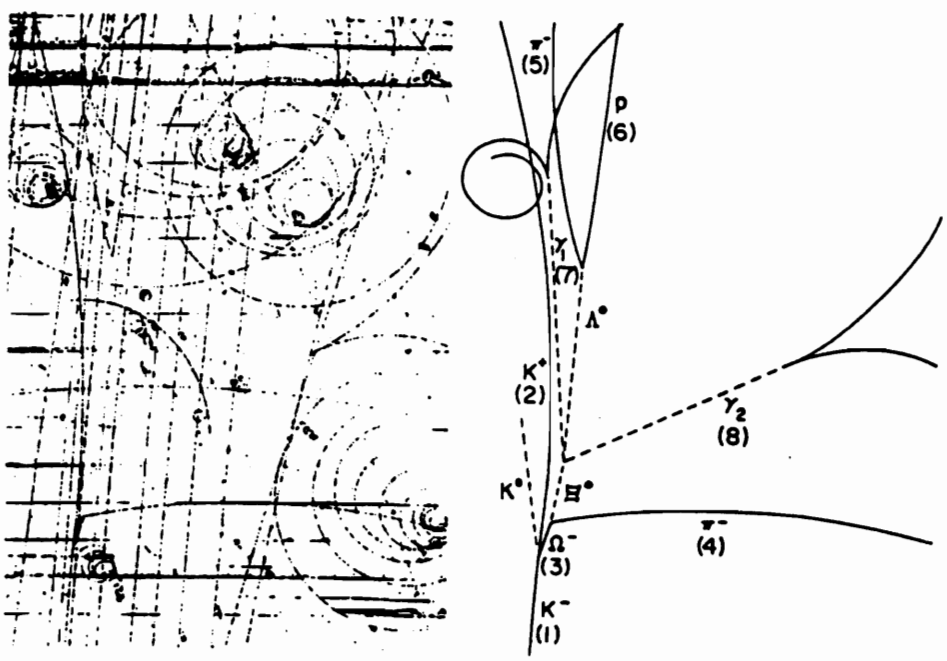


Figure 8: First evidence for the Ω^- baryon[113]. (a) Bubble chamber photograph; (b) interpretation.

5. INTERACTIONS UP TO THE MID-1960s

5.1 Weak interactions and V-A theory

5.1.1 Observation of the neutrino. The neutrino was postulated in the early 1930s to carry off the unseen energy and momentum in the beta-decay process $n \to p + e^- + \nu$ (see Sec. 2). However, no direct evidence for it had been found. After World War II, F. Reines and some of his colleagues considered using a nuclear explosion as a copious source of neutrinos[114]. Eventually he and Clyde Cowan decided to use neutrinos produced at a nuclear reactor, eliciting an approving letter from Fermi that the new method should be much simpler to carry out and had "the advantage that the measurement can be repeated any number of times."

The inverse of the beta-decay reaction, the process $\bar{\nu}+p \to n+e^+$, was studied. A very large target, well shielded against accidental interactions, was required to observe this process, which is about a billion billion times less frequent than a proton-proton interaction.

The initial experiment was performed at the Hanford reactor in 1953. Signals with the reactor on and off were compared. The large reactor-off signal, eventually traced to cosmic-ray interactions, prevented a definitive observation[115]. The experiment was then moved to Savannah River, yielding a signal sufficiently convincing[116] for Reines to send a telegram to Pauli in June of 1956 informing him that the particle he predicted more than 25 years earlier had been found.

The observation of the reaction $\bar{\nu} + p \to e^+ + n$, without any examples of $\bar{\nu} + n \to e^- + p$, was the first proof of *lepton number conservation* in the weak interactions. The electron and the neutrino, by convention, are assigned lepton number $L = 1$. The neutral lepton accompanying an electron in beta decay (the source of reactor neutrinos) must then be an antineutrino with $L = -1$, giving rise only to positrons (with $L = -1$).

5.1.2 Early classification of beta decay. Fermi's 1934 theory of beta decay[5], mentioned in Sec. 2, was based on an interaction of the *vector* (V) type between pairs of fermions, one of five possibilities consistent with Lorentz invariance and mirror symmetry. The others are scalar (S), tensor (T), axial vector (A), and pseudoscalar (P), whose names refer to each fermion pair's properties under Lorentz transformation.

The nonrelativistic limit of the S and V interactions corresponds to a unit operator evaluated between spinors. Beta-decay transitions of this type were called *Fermi* transitions; many were identified experimentally. The nonrelativistic limits of the T and A interactions involve instead the Pauli matrix σ. Transitions of this *Gamow-Teller* type[117] also were identified quite early, through their characteristic change of one unit of nuclear spin, suggesting complements to Fermi's hypothesis.

The energy dependence of the beta-decay spectrum depends on the form of couplings. When S and V or T and A interactions coexist, terms arise of the form m_e/E_e, where m_e and E_e are the electron's mass and energy. Such *Fierz interference* terms[118] were not seen, restricting the allowed interactions.

Electron-neutrino correlations in beta decay experiments allow one to sort out different interaction types, with distributions proportional to $1 + b\hat{p}_e \cdot \hat{p}_\nu$, with[119] ($b = -1,\ 1,\ 1/3,\ -1/3$) for pure ($S,\ V,\ T,\ A$) interactions, respectively. In the mid-1950s, experiments on ^{6}He $\rightarrow^6$ Li $+ e^- + \bar{\nu}$, ^{19}Ne $\rightarrow^{19}$ F $+ e^+ + \nu$, and ^{35}Ar $\rightarrow^{35}$ Cl $+ e^+ + \nu$ gave conflicting results, which were soon to be sorted out.

5.1.3 Universality hypothesis. The weak interactions, though initially involved only in nuclear beta decay, were soon seen to participate with equal strength in $\mu \rightarrow e\nu\bar{\nu}$ and muon capture by nuclei. This observation led to the hypothesis[120] of *weak universality*, according to which any of the pairs (p, n), (e, ν), and (μ, ν) would interact equally with itself or any other pair. The charged pion's decay proceeds at a rate consistent with weak universality if dominated by a nucleon-antinucleon intermediate state. The decays of strange particles appeared to be due to an interaction similar to but somewhat weaker than the beta-decay interaction.

5.1.4 Overthrow of parity conservation. As decays of charged strange mesons were identified in the early 1950s, the masses of particles decaying in various modes all clustered more and more closely about a single value, now known to be $m(K) =$ 493.6 MeV/c^2, with lifetimes showing a similar approach to a common value[121]. However, two distinct decays, called $\theta^+ \rightarrow \pi^+ + \pi^0$ and $\tau^+ \rightarrow \pi^+ + \pi^+ + \pi^-$, could not correspond to the same particle if the weak interactions were invariant under mirror symmetry.

An examination[122] of the kinematic distribution of the three-pion ("τ^+") decays favored zero relative angular momentum between the two like pions and between them and the unlike pion. In that case, the τ^+ had to have spin J equal to zero and negative intrinsic parity P (since the parity of each pion was identified as negative; see Sec. 4.2.1). A mixture of internal relative angular momenta leading to $J^P(\tau^+) = 2^-$ was also possible.

The two-pion ("θ^+") decay can only occur for a particle with $P = (-1)^J$. Thus, since the above analysis favored $J^P(\tau^+) = 0^-$ or possibly 2^-, the τ^+ and θ^+ could not be the same *if parity was conserved in weak decays.*

The possibility of parity violation in the weak interactions began to be debated informally in seminars early in 1956. At the Sixth International Conference on High Energy Physics in Rochester, New York, in the early spring of that year, Feynman quoted a question by Martin Block asking whether the τ and θ could be different parity states of the same particle with no definite parity, implying that parity is not conserved[123]. Returning from the conference and reviewing all the evidence, T. D. Lee and C. N. Yang (Fig. 9) realized that no conclusive test had yet been performed of parity conservation in the weak interactions; such a test should measure the expectation value of an operator odd under spatial reflection, such as the scalar product of a momentum and a spin vector. They suggested several such tests[124]. (For two complementary historical accounts, see Refs. 125.)

Before Lee and Yang's paper was published, R. Oehme pointed out to them[126] that one could not see the effects of parity(P) violation in a beta-decay experi-

Figure 9: T. D. Lee (left) and C. N. Yang in 1957. Photo by Alan W. Richards. (Courtesy of Niels Bohr Library, American Institute of Physics.)

ment if charge-conjugation invariance (C) and time-reversal symmetry (T) were preserved. Moreover, in the absence of significant final-state interactions, even C invariance alone prevented the observation of a P-violating asymmetry. Thus, Lee and Yang's suggestion of P violation in beta-decay implied as well the violation of C. The published work incorporated this suggestion, and was followed by a joint paper[127] which also pointed out that the equality of masses and lifetimes for particles and antiparticles followed just from CPT invariance, a consequence of Lorentz invariance and local field theory[128]. Thus, for example, the observed equality of positive and negative muon lifetimes could not be used as evidence of invariance under charge conjugation since it followed from much weaker assumptions.

The Lee-Yang suggestion was taken up by C. S. Wu at Columbia and her collaborators at the National Bureau of Standards in Washington, and by V. L. Telegdi at Chicago and his student J. I. Friedman. Wu and her colleagues found that parity was indeed violated[129] in the beta decay of polarized ^{60}Co. Friedman and Telegdi began a search, which ultimately bore fruit[130], for parity violation in the decay $\pi \to \mu \to e$ in emulsions.

Mme. Wu returned to Columbia early in 1957 with the preliminary news of her results. Within a weekend Garwin, Lederman, and Weinrich[29] were able to devise and perform an experiment searching for parity violation in $\pi \to \mu \to e$. The story is told in Ref. 131 by one of the participants.

Lee and Yang suggested that one parity-violating observable could be an up-down asymmetry in the weak decays of polarized Λ hyperons. The observation of this asymmetry[132] was a further confirmation that, indeed, parity was violated in the weak interactions.

The weak interactions as now written down could be described by a theory which violated spatial reflection (P) and charge conjugation (C) symmetries, but was invariant under time reversal (T) and the product CP, thereby satisfying the requirement of a CPT-invariant theory. The conservation of T by the weak interactions as newly formulated explained why the neutron did not appear to have an electric dipole moment. Experiments placed quite stringent limits on such a moment[133]. Its absence had been thought to be evidence against parity violation, but it was now realized that T invariance alone would forbid an electric dipole moment for any elementary particle.

5.1.5 $V - A$ theory and conserved vector current (CVC). In the initial experiment demonstrating parity violation in beta decay, the electrons were found to be emitted in a direction correlated with the spin of the initial nucleus. Soon thereafter, a number of experiments found that the spins of beta-decay electrons and positrons were correlated with their own velocities. Electrons were emitted spinning in a predominantly left-handed manner, or with left-handed *helicity*, while positrons emerged primarily with right-handed helicity.

Before the observation of parity violation in the weak interactions, Salam and Landau had proposed that a neutrino could exist in a single helicity state[134].

Indeed, Weyl had considered spinors with two components much earlier, but this possibility was rejected by Pauli in the 1930s for the neutrino because it did not conserve parity[134a]. The ordinary spin-1/2 particle satisfying the Dirac equation has four degrees of freedom – two for each spin of both particle and antiparticle. When the rest mass is zero, however, the four-component solution breaks apart into two two-component ones, the first describing a left-handed particle and a right-handed antiparticle and the second describing a left-handed antiparticle and a right-handed particle.

A two-component neutrino was tailor-made for the large degree of parity violation observed in beta-decay experiments[135]. If a neutrino had one helicity and its antiparticle the opposite helicity, an electron released with velocity v in beta decay had to have polarization equal to $\pm v/c$, while a positron with the same velocity had to have the opposite polarization. This was indeed verified. Electrons always had polarization $P(e^-) = -v/c$, while positrons had polarization $P(e^+) = v/c$.

In view of the apparent two-component nature of the neutrinos participating in beta decay and the beauty and simplicity of the two-component formalism, Feynman and Gell-Mann and Sudarshan and Marshak proposed[136–138] that *all* particles participate in the weak interactions in the same two-component manner. As a consequence, each particle pair [such as (e, ν), (μ, ν), and (n, p)] had to participate in the weak interaction with a definite combination of vector (V) and axial (A) strengths, by convention called $V - A$. The scalar (S), tensor (T), and pseudoscalar (P) interactions vanish under the two-component hypothesis.

The universal $V - A$ interaction agreed with many results at the time it was proposed. In addition to predicting the polarizations of electrons and positrons in beta decay, it reproduced the observed the muon lifetime and the electron-neutrino correlations in most beta-decay processes. However, it seemed incompatible with some observations, including the apparent dominance of S and T interactions in ^{6}He beta decay[138a] and the apparent absence[138b] of the decay $\pi \to e\nu$. In due course, a new ^{6}He experiment[139] confirmed the $V - A$ prediction, and the $\pi \to e\nu$ decay was eventually found at the predicted level[140]. The theory also predicted parity violation in purely *nonleptonic* processes, thus resolving the $\tau - \theta$ puzzle mentioned earlier. It implied that the neutrino emitted in beta decay was left-handed, as was verified in an elegant experiment (see box) by M. Goldhaber, L. Grodzins, and A. Sunyar[141] using the apparatus described in Fig. 10. A more detailed discussion of these and other tests of the $V - A$ theory appears in Ref. 142.

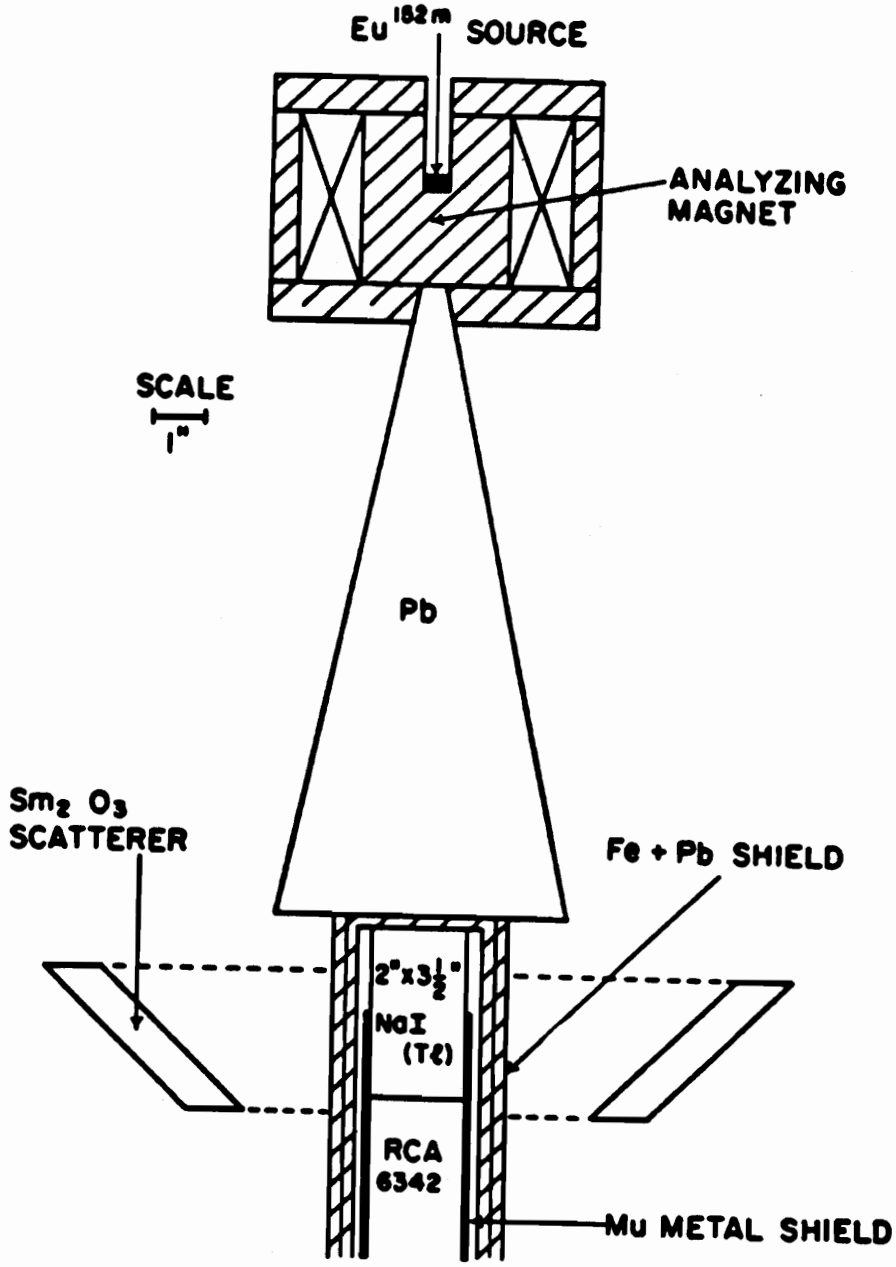


Figure 10: Apparatus in the experiment of Goldhaber, Grodzins, and Sunyar[141] to determine the neutrino helicity by measuring circular polarization of resonant scattered γ-rays.

THE HELICITY OF THE NEUTRINO

Everyone knows that the neutrino is a most elusive particle requiring tons of material just to detect. Who then would have the daring to even contemplate measuring its spin direction relative to its direction of motion, its helicity? M. Goldhaber, L. Grodzins, and A. Sunyar (GGS) (Ref. 141) succeeded in doing this in an ingeniously conceived and executed experiment. It was an experiment that required encyclopedic knowledge of nuclear isotopes as well as cunning experimental technique.

Consider ^{152}Eu which decays to ^{152}Sm by electron capture from the K–shell with the emission of a neutrino with energy 0.840 MeV. The ^{152}Eu has spin zero but the ^{152}Sm which accompanies the neutrino is in an excited state, Sm* with spin 1. It decays in 3×10^{-14} sec to the spin zero ground state with the emission of a gamma ray. How did GGS put all this together to measure the helicity of the neutrino? First, by conservation of angular momentum, the spin of the neutrino plus the Sm* must equal the spin of the captured electron. This forces the spin of the Sm* to be opposite to that of the neutrino and since the Sm* nucleus is recoiling away from the neutrino, the ***helicity of the Sm* must be the same as the neutrino.*** Measuring the helicity of the neutrino has been reduced to measuring the helicity of the recoiling Sm*.

The angular momentum of the Sm* will be carried away by the emitted gamma ray. It is possible to measure the direction of the (circular) polarization of gamma rays by passing them through magnetized iron since the absorption cross section is sensitive to the spin direction of the scattering electrons. But to get the helicity of the Sm* it is still necessary to determine its direction of travel relative to the direction of the gamma. GGS pull still another trick out their bag. They note that the gamma ray energy is 0.960 MeV, not far from the neutrino energy. If the gamma ray is emitted in the direction the Sm* is traveling, the energy will be boosted a bit; indeed, just enough so that the gamma will be scattered resonantly (hence, with a large cross section) from Sm in its ground state if the scattering angle is about 90 degrees. This then determines that the gamma ray has been emitted in the direction of motion of the Sm*.

This brilliant, complex scheme was implemented in the apparatus shown schematically in Fig. 10. Note that the apparatus has cylindrical symmetry about the vertical axis. By measuring the gamma ray intensity in the NaI crystal as a function of the direction of the magnetization of the iron, the neutrino was found to be *left handed*!

A general test for Lorentz structure of couplings in muon decay had been proposed in 1950 [143]. The electron energy spectrum in muon decay could be described in terms of a parameter ρ and the ratio x of the electron energy in the muon rest frame to its maximum value. Normalized to unit integral over the range $0 \leq x \leq 1$, the spectrum has the form $N(x) = 6x^2[2(1-x) + (4/9)\rho(4x-3)]$. The $V-A$ theory implied that labeling electrons as particles but muons as antiparticles yields $\rho = 0$, while labeling both muons and electrons as particles yields $\rho = 3/4$. Experiments eventually converged on the latter value.

The universal $V-A$ interaction was also generalized to strange particles. Notable among the results[136] was the linkage of strangeness S and charge Q in beta-decay interactions, represented by the empirical rule $\Delta S = \Delta Q$. If $\Delta S = -\Delta Q$ transitions also had been allowed, they would have led to unobserved processes such as $\Xi^- \to \pi^- + n$.

The universal weak (current) $\times$ (current) interaction, where each $V-A$ current carries unit charge, implies that all Fermi-type interactions in beta decay stem from the nucleon's V current, while all Gamow-Teller transitions arise from A. A remarkable feature of these currents, particularly of the vector current, is their universal strength. For example, in Fermi transitions between nuclei of zero spin, as in ^{14}O beta decay, the coupling strength appears to be almost identical with that in muon decay, despite the presence of strong interactions which in principle could modify the nucleon's current.

To explain the niversality of the weak vector current, Feynman and Gell-Mann[136] and Gershtein and Zel'dovich[144] suggested that the charged weak vector current belonged to an isotopic spin *triplet* of conserved vector currents. This *conserved vector current* hypothesis identified the vector weak current with the generator of the isotopic spin symmetry, whose matrix elements are set by simple isospin considerations, independently of strong interaction details. For example, the rate for the decay $\pi^+ \to \pi^0 + e^+ + \nu_e$ was predicted precisely[136]; the process was observed, with the predicted rate, several years later[145].

5.1.6 Two-neutrino hypothesis and its confirmation. The current-current form of the weak interactions, with a Fermi coupling strength $G_F \approx 10^{-5} m_p^{-2}$, leads to cross sections which violate the unitarity of the S-matrix at high energies. One cure of this problem was the proposal, first appearing in Yukawa's theory of the meson and in various forms thereafter[146], that the weak interactions arose from the exchange of a meson, in analogy with the pion for the strong force and the photon for electromagnetism. The $V-A$ nature of the weak interaction required this particle to have spin 1, i.e., to be a *vector* boson. The modern name for this boson is W.

The vector boson proposal predicted the process $\mu \to e\gamma$ to occur with a branching ratio far above the upper limits set in the early 1960s. The process involved a virtual transition of the muon to some charged intermediate state and a neutrino. The charged intermediate state would then radiate a photon and

reabsorb the neutrino to become an electron. However, the predicted decay would not occur if the muon and electron coupled to *separate* neutrinos.

An experiment was performed at Brookhaven National Laboratory by the participants shown in Fig. 11 to study the interactions of neutrinos produced in the decay of pions in the process $\pi^{\pm} \rightarrow \mu^{\pm}\nu$. Neutrinos distinct from those emitted in beta decay would produce only muons, not electrons, in reactions such as $\nu + n \rightarrow \mu^- + p$ and $\bar{\nu} + p \rightarrow \mu^+ + n$. The result was conclusive: the muon and electron neutrinos were different[147].

The history of the two-neutrino experiment is told in Ref. 148. The development of neutrino beams had been first proposed by B. Pontecorvo and M. Schwartz[149], with resulting physics anticipated in a prescient paper by Lee and Yang[150].

One goal of early neutrino experiments was the search for the W boson mentioned above. The results in experiments on both sides of the Atlantic[151] were negative, placing a lower limit of 2 GeV/c^2 on the mass of the W, which is now known to be much heavier. Neutrino interactions were so rare in those early days (1963) that a bottle of champagne was opened each time an interaction was seen at the European experiment, performed at CERN.

5.2 CP violation

5.2.1 Implications of P and C violation for neutral kaon systems. The $V - A$ theory of weak interactions violated both parity (P) and charge-conjugation invariance (C), while preserving time-reversal invariance and the product CP. Now, the original prediction of two types of neutral kaons, the short-lived kaon decaying to $\pi\pi$ and the long-lived one forbidden from doing so[86], was based on the assumption of C invariance of the weak interactions. Similar results were shown to follow[152] from combined invariance under the product CP. Hence, the K_2^0, mentioned in Sec. 4.4, was still expected not to be able to decay to $\pi\pi$ if CP invariance was valid in the weak interactions.

5.2.2 Initial experiments. Searches for the decay $K_2^0 \rightarrow \pi^+\pi^-$ during the late 1950s and early 1960s failed to find any signal at a level of a part in 300. With the advent of spark chambers permitting selective triggering on events of a given type, a more sensitive search was mounted by J. Christenson, J. Cronin, V. Fitch, and R. Turlay at Brookhaven National Laboratory. The early history and motivation for this experiment are described in Ref. 153. A signal was indeed seen (Fig. 12), corresponding to one event for every 500 decays[154].

Theoretical analyses[127,155] had set the stage for a description of CP violation in decays of neutral kaons. After its discovery, Wu and Yang suggested further experiments[156], establishing many conventions still in use today. Since both K_1^0 and K_2^0 were now seen to decay to pairs of pions, their names were changed to denote states of definite lifetime: K_S for the short-lived neutral kaon, with lifetime 0.09 ns, and K_L for the long-lived neutral kaon, with lifetime 52 ns.

The presence of the decay $K_L \rightarrow \pi^+\pi^-$ indicated CP violation in the weak

Figure 11: Participants in the two-neutrino experiment at Brookhaven[147]. From left to right: J. Steinberger, K. Goulianos, J.-M. Gaillard, N. Mistry, G. Danby, W. Hayes, L. Lederman, M. Schwartz. Top: then; bottom: recently. Courtesy of Brookhaven National Laboratory.

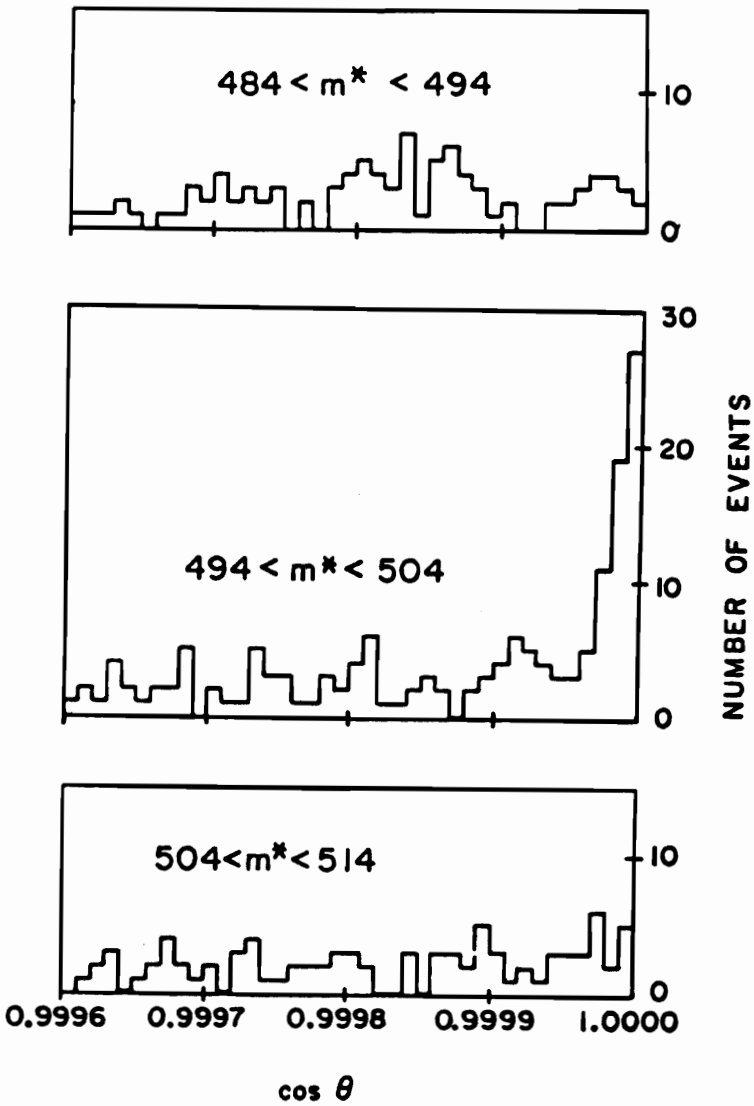


Figure 12: Evidence[154] for the decay $K_L \to \pi^+\pi^-$. The angular distribution of the two-pion system with respect to the beam is shown for three mass ranges, of which the middle range corresponds to the signal.

interactions. Assuming the validity of the CPT theorem, this implied also T violation, a result not to be taken lightly. The experimenters spent more than six months analyzing their signal before concluding that their data were indeed evidence for CP violation. Detailed analyses (see, e.g., Ref. 157) without the assumption of CPT invariance later showed that indeed the data were also signalling T violation.

A crucial test confirming that the $\pi^+\pi^-$ final state indeed originated from the long-lived kaon was the observation[158] of interference between the decays $K_L \to \pi^+\pi^-$ and $K_S \to \pi^+\pi^-$. The K_S was produced by *coherent regeneration*[159]. As a K_L beam passes through matter, the phase and magnitude of the beam's K^0 and $\bar{K}^0$ components change in different ways, inducing a mixture of K_S. As a result, one can measure not only the magnitude but also the phase of the ratio of $K_L \to 2\pi$ and $K_S \to 2\pi$ amplitudes.

The evidence for CP violation has so far been confined exclusively to the system of neutral kaons. Reviews of major results since the discovery of CP violation can be found in Refs. 157 and 160.

5.2.3 Decays to charged and neutral particles. The origin of CP violation in neutral kaon decay still is not understood in terms of a fundamental theory. A question arose immediately whether the observed effect results entirely from mixing, or stems in part from direct CP violation in the decay process.

The states $K^0_{S,L}$ of definite mass and lifetime can be regarded as mixtures of states $K^0_{1,2}$ with even and odd CP. In a CPT-conserving theory[127], one can write

$$|K_S\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}(|K_1\rangle + \epsilon|K_2\rangle) \quad , \quad |K_L\rangle = \frac{1}{\sqrt{(1+|\epsilon|^2)}}(|K_2\rangle + \epsilon|K_1\rangle) \quad ,$$

where the complex parameter ϵ denotes the effect of the mixing. The amplitudes for the decays of K_L to $\pi^+\pi^-$ or $\pi^0\pi^0$ may be characterized by their ratios to the corresponding K_S decay amplitudes:

$$\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \equiv \eta_{+-} \quad , \quad \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \equiv \eta_{00} \quad ,$$

where $\eta_{+-} = \eta_{00} = \epsilon$ if the only CP violation takes place through mixing. In general one can write $\eta_{+-} = \epsilon + \epsilon'$ and $\eta_{00} = \epsilon - 2\epsilon'$. Here ϵ' describes the effect of direct CP violation (i.e., that not due to mixing) in the decay amplitude leading to a final state with isospin 2.

The leading candidate for a theory of CP violation in the neutral kaon system, the presence of phases in the Cabibbo-Kobayashi-Maskawa matrix (Sec. 9), predicts that ϵ' should have a phase very close to that of ϵ, with $\mathrm{Re}(\epsilon'/\epsilon)$ a few parts in 10^4. However, a model with $\epsilon' = 0$, in which CP violation in neutral kaons is due entirely to a $\Delta S = 2$ "superweak" interaction[161] mixing K^0 and $\bar{K}^0$, still is not conclusively excluded by present data.

One experiment[162] finds $\mathrm{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}$, consistent with zero, while another[163] finds $\mathrm{Re}(\epsilon'/\epsilon) = (23 \pm 6.5) \times 10^{-4}$, nonzero at the level of more than three standard deviations. There is not a serious contradiction between the two results if $\mathrm{Re}(\epsilon'/\epsilon)$ is around 14×10^{-4}. Improved versions of both experiments are planned. The theory can also be tested by studies of B mesons (Sec. 9).

5.2.4 Asymmetries in semileptonic decays. By comparing rates for neutral kaons to decay to states such as $\pi^- e^+ \nu_e$ and $\pi^+ e^- \bar{\nu}_e$, one can learn the relative admixture of K^0 and $\bar{K}^0$ in each neutral kaon's wave function[164]. The $\Delta S = \Delta Q$ rule of strangeness-changing weak interactions mentioned above implies that only negative pions emerge from K^0 and only positive from $\bar{K}^0$. CP violation implies an asymmetry proportional to 2 Re ϵ in rates of K_L decay to these final states. This asymmetry was searched for and found; the results[165] are in perfect accord with expectations.

5.2.5 CP violation and baryon asymmetry in the Universe. Shortly after CP violation was discovered, Sakharov[166] pointed out that it was a key ingredient in understanding why the observed Universe contains more baryons than antibaryons. Other crucial features were interactions which violate baryon-number conservation, and a period in the early Universe when reactions governed by these interactions were out of thermal equilibrium. Those conditions have been realized in subsequent models[167], to which we shall return in Secs. 12 and 13.

5.3 Current algebras

5.3.1 The role of the pion. In the newly proposed $V - A$ theory, the weak interactions of strongly interacting particles remained mysterious. While the vector weak current of nucleons seemed to be nearly unaffected by the strong interactions, the axial vector coupling strength, parametrized by $G_A \approx 1.25$, deviated significantly from the value $G_A = 1$ expected if nucleons behaved like leptons. Moreover, decays of strongly interacting particles to purely leptonic final states were characterized by arbitrary constants, such as the pion decay constant f_π for $\pi \to \mu + \nu$.

Armed with experience in both strong and weak interactions, M. L. Goldberger and S. B. Treiman[168] embarked on a calculation of f_π. Their result involved a crucial role for the nucleon-antinucleon intermediate state and hence for the pion-nucleon coupling constant $g_{\pi NN}$. They obtained the relation $f_\pi = m_N G_A / g_{\pi NN}$, which is accurate to a few percent. Here m_N is the mass of the nucleon.

The vector current's time component, when integrated over all space, is the *isotopic charge*, or generator of isotopic spin transformations. The conservation of vector current is thus associated with isotopic spin invariance. The space integral of the *axial* current's time component also performs isotopic spin transformations, rotating left-handed and right-handed fermions oppositely in isospin space. Invariance under separate isospin rotations of left-handed and right-handed fermions is known as *chiral invariance.*

But is the axial current conserved? Apparently not; the divergence of the matrix element of the axial current between one-nucleon states is proportional to m_N, and so cannot vanish unless the nucleon is massless. Under such circumstances, one indeed would have a chiral invariance. Chiral symmetry would be realized in the *Wigner-Weyl* sense, by manifest invariance of both the equations of motion and their solution. One implication of manifest chiral symmetry is the prediction that for every particle with a given parity, there should be a degenerate particle with opposite parity. This certainly did not seem to be so.

In a sequel to their first paper on the pion decay constant, Goldberger and Treiman[169] showed that the requirement of a conserved axial current entails a zero-mass pole in beta-decay amplitudes. Inspired by this result and by an analogy with superconductivity, Y. Nambu[170] discovered another mode in which chiral symmetry could be realized. If the *vacuum itself* were not chirally symmetric, so that the part of the symmetry generated by the axial current was *spontaneously broken*, there was no need for parity doubling in the spectrum of states like the nucleon. Instead, a massless pseudoscalar particle, the pion, miraculously appeared; the parity partner of the nucleon was then a state with a nucleon and a pion. This behavior illustrated a general theorem of J. Goldstone[171]: spontaneous breakdown of a global, i.e., space-independent symmetry (such as chiral symmetry) necessarily leads to massless particles in the spectrum. For systems of pions and nucleons, chiral symmetry is said to be realized in the *Nambu-Goldstone* sense: via spontaneous symmetry breaking. In Nambu's approach, the pion satisfied the Goldberger-Treiman relation as a natural consequence of its role in the breakdown of chiral invariance. The zero-mass pole which Goldberger and Treiman had discovered could be, in fact, identified with the pion in the limit of exact chiral invariance.

M. Gell-Mann and M. Lévy were motivated to understand the deviation of the axial coupling constant G_A from unity by identifying the divergence of the axial current with the pion field itself[172]. They constructed several field-theoretic models in which this was so. The Goldberger-Treiman relation was a welcome consequence. The fact that the divergence of the axial current was nonzero, but identified with the pion field, was called *partial conservation of axial current* (PCAC).

5.3.2 Gell-Mann - Lévy discussion of universality. Although the vector current was not expected to be renormalized by the strong interactions, the Fermi constant G as measured in ^{14}O beta decay appeared to be about 3% lower than G_μ as measured from muon decay. Gell-Mann and Lévy proposed[172] that the missing "strength" was made up by the beta-decay coupling of the proton to the Λ: in modern notation, the hadronic beta-decay current then involved the charge-changing transitions $p \leftrightarrow n\cos\theta + \Lambda\sin\theta$. With $\sin^2\theta \approx 0.06$, one was then able to understand both $G/G_V \approx 0.97$ and the relative suppression of strangeness-changing weak decays (particularly notable for the process[173] $\Lambda \to pe^-\bar{\nu}$).

5.3.3 Gell-Mann's algebra of currents. In search of a dynamical principle underlying the success of unitary symmetry, Gell-Mann[174] (Fig. 13) realized that both isotopic spin [the group SU(2)] and its generalization to SU(3) were generated by *charges* – space integrals of time components of vector currents. These charges F_i ($i = 1, \ldots, 8$) obeyed an algebra of the form $[F_i, F_j] = if_{ijk}F_k$, where the f_{ijk} are totally antisymmetric *structure constants.*

The spatial integrals of time components of axial vector currents give rise to charges F_i^A, which necessarily transform as vectors under the symmetry: $[F_i, F_j^A] = if_{ijk}F_k^A$. The existence of an octet of light pseudoscalar mesons is the reason the axial charges are not conserved; when acting on the vacuum, they produce a pion, kaon, or η.

When one has a set of generators of a symmetry, it is natural to ask for the behavior of *all* commutators. Gell-Mann postulated that the algebra was completed by the simplest possibility for the commutator of two *axial* charges: $[F_i^A, F_j^A] = if_{ijk}F_k$. This is indeed the case for the leptons. It could be true for strongly interacting particles as well if they were made up of more fundamental entities – at least, one could conceive of interactions not affecting the basic relations. These entities could be identified with *quarks*[175] – members of the triplet representation of SU(3). We shall discuss them in Sec. 6.

The combinations $(F_i + F_i^A)/2 \equiv F_i^R$ and $(F_i - F_i^A)/2 \equiv F_i^L$ then would obey two independent SU(3) algebras. This SU(3) $\times$ SU(3) structure has led to successful predictions for many quantities previously regarded as the province of intractable strong interaction physics.

5.3.4 Cabibbo theory of strange particle decays. If vector and axial vector currents transformed as generators of SU(3), their matrix elements between various states of SU(3) multiplets could be related to one another. By 1963, data on beta decays of various hyperons in the baryon octet had been accumulating, and the time was ripe for such an analysis.

N. Cabibbo[176] postulated that the charge-changing weak current behaved as a member of an SU(3) octet, consisting of a linear combination of a piece transforming like a charged pion (with coeffient $\cos\theta$) and a charged kaon (with coefficient $\sin\theta$). While the angle θ is the one Gell-Mann and Lévy proposed for rescuing universality of the weak hadronic current, we shall henceforth refer to it as θ_C.

The conservation of vector current specifies uniquely the vector current's matrix element between baryon states. However, the nonconservation of axial current allows for two types of matrix elements for the axial current. In SU(3) there are two ways to couple an octet current to initial and final octet baryons, called F (totally antisymmetric) and D (totally symmetric).

One combination of F and D coupling for the axial current is the axial charge of the nucleon, $F + D = G_A \approx 1.25$. The Cabibbo theory described decays such as $K \to \pi e\nu$, $\Lambda \to pe\nu$, $\Sigma^- \to ne^-\nu$, and $\Sigma^- \to \Lambda^0 e^-\nu$ with a single value of θ_C and a self-consistent value of F/D. In modern fits, which also include data on

Figure 13: Murray Gell-Mann (left); Yuval Ne'eman, at First International Meeting on the History of Scientific Ideas, Sant Feliu de Guíxols, Catalonia, Spain, September 20-26, 1983. (Universitat Autònoma de Barcelona; distributed by World Scientific Publishing.)

several other hyperon beta-decays (and on the ratios of axial to vector couplings in some of them) one finds[177] $\sin\theta_C \approx 0.22$ and $F/D \approx 2/3$. This last value turns out to be close to what one expects in a quark picture of baryons.

5.3.5 Adler-Weisberger relation. The PCAC hypothesis permitted calculations of soft pion emission[178] in a manner analogous to calculations of soft photon emission using general principles of electromagnetism[179]. Stephen Adler, a skilled practitioner of this technique, used it to study a series of processes, including low-energy pion-nucleon scattering[180]. Hearing of the proposal by Murray Gell-Mann and his student Roger Dashen to apply the commutator of two axial isospin generators to obtain a relation between the axial-vector coupling constant and pion-nucleon scattering, Adler realized that his experience was ideal for the problem. In very short order he related G_A to the difference in total cross sections of positive and negative pions on nucleons, integrated over energy[181]. At the same time, W. I. Weisberger produced a similar calculation, and subsequently generalized the result to relate $|\Delta S| = 1$ transitions to kaon-nucleon scattering[182].

The Adler-Weisberger relation in the zero-pion-mass limit may be written

$$G_A^2 = 1 - 2\frac{f_\pi^2}{\pi}\int_0^\infty \frac{d\nu}{\nu}[\sigma^{\pi^- p}(\nu) - \sigma^{\pi^+ p}(\nu)] \quad ,$$

where ν stands for the laboratory energy of the pion. Its prediction for G_A depends to some extent on the treatment of corrections for massive pions, but the resulting value $G_A \approx 1.2$ was sufficiently close to experiment that the power of current algebra was immediately recognized.

5.3.6 Other current algebra relations. The Adler-Weisberger relation exploits the nonlinearity of the current commutation relations to normalize axial charges. The commutator between axial and vector charges also contains useful information, providing a relation[183] between the semileptonic process $K \to \pi e \nu$ and the purely leptonic decay $K \to \mu\nu$. Even purely hadronic processes such as pion-pion scattering could be attacked by such methods, as shown by Weinberg[184]. Many other successes of current algebra were chronicled in contemporary texts and reviews[185].

5.4 Strong-interaction schemes

While the theory of weak interactions enjoyed tremendous progress during the 1950s, the strong interactions remained a mystery. Symmetry arguments sufficed for many results, but the underlying forces were not understood until the advent of quantum chromodynamics in the 1970s. Still, the efforts to understand strong forces bore fruit in a number of areas even in the absence of a fundamental theory.

5.4.1 S-matrix theory and dispersion relations. A unitary matrix relating outgoing to incoming scattering states was introduced by Wheeler in the 1930s[186] in the context of nonrelativistic nuclear reactions, with a fully relativistic treatment developed independently by Heisenberg[187]. The scattering matrix, or S-matrix, as it came to be called, had an interesting history during World War II[188]. News

of Heisenberg's work was brought to Japan by German submarine in the form of a letter from Heisenberg to Nishina. A unitary S-matrix appeared in Japanese literature of the 1940s in analyses of microwave junctions by Tomonaga and his group[189]. The U. S. wartime microwave work also employed the S-matrix in description of junctions[190]. Around this time Stückelberg independently introduced an analog of the S-matrix[191]. In the physics of antenna impedance matching, a transformation very similar to Stückelberg's had been proposed even earlier, forming the basis of the frequently used *Smith chart*[192]. The development of the relativistic S-matrix in the post-war years owed much to the work of Moller[192a].

As the strong coupling of pions to nucleons became clear in the 1950s, physicists despaired of describing the strong interactions by quantum field theory, so successful for QED. It was hoped[193] that by characterizing the singularities of the S-matrix, a theory could avoid expanding amplitudes as a perturbation series, which fails because of the large pion-nucleon coupling constant. Thus began a period of intense study of analytic properties of scattering amplitudes and of "bootstrap" theories in which the known particles were all viewed as composites of one another. An early success of this program was the development of dispersion relations for scattering amplitudes[194], relating the real parts of amplitudes to integrals over total cross sections. Precise measurements of pion-nucleon total cross sections and of real parts of amplitudes[195] provided one impressive verification of these relations . Dispersion relations could also be written simultaneously in variables corresponding to relativistic generalizations of energy and momentum transfer[196], providing insight into parameters governing the range of strong forces.

5.4.2 Chew-Low theory and isobars. The first pion-nucleon resonance, the $\Delta(1232)$ mentioned above, was described by Chew and Low[197] in a theory that viewed the force between a pion and a baryon (the nucleon or Δ) as due primarily to baryon exchange. Indeed, the singularities in the scattering amplitude most important for its low-energy behavior are just those associated with baryons in the crossed channel.

5.4.3 Pion-pion scattering and the bootstrap program. The idea that strongly interacting particles could all be viewed as composites of one another (encouraged by Chew and Low's result for the Δ, nucleon, and pion) grew in the 1950s into a full-fledged "bootstrap" program, dealing only with the self-consistent singularities of the S-matrix actually found in Nature. The key ingredients in this program were the unitarity of the S-matrix and the analyticity and *crossing symmetry* of the scattering amplitude. This last feature relates such processes as $A + B \to C + D$ to *crossed reactions* such as $\bar{C} + B \to \bar{A} + D$.

A simple test of the bootstrap program was provided by pion-pion scattering. Since pions are not available in the laboratory, how would one employ them as targets? The answer was provided by Chew and Low[198]: Use virtual pions (see Fig. 14). In the reaction $\pi + p \to X + n$, for example, the scattering amplitude has a pole in the invariant momentum transfer, corresponding to exchange of a pion,

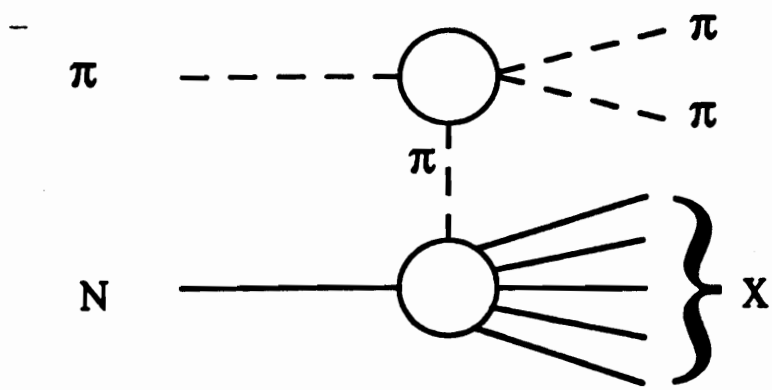


Figure 14: Diagram describing the Chew-Low proposal[198] for studying pion-pion scattering.

which dominates the scattering for small enough values of momentum transfer.

Many bootstrap calculations of pion-pion scattering were performed[193], with varying degrees of success in reproducing the dominant low-energy features. These included a prominent P-wave resonance in the $I = 1$ channel, the $\rho(770)$ (the number refers to the mass in MeV/c^2), and a slow increase of the S-wave phase shift in the $I = 0$ channel. Once the low-energy behavior predicted by current algebra[184] was specified, successful bootstrap calculations were indeed displayed[199]. However, analyticity, unitarity, and crossing symmetry proved inadequate to specify scattering amplitudes uniquely.

5.4.4 Regge poles. A paper by Tullio Regge[200] dealing with scattering in a nonrelativistic potential provided an important step in the description of scattering in particle physics. The S-matrix has poles in complex angular momentum which *change their position as a function of energy*, solving a knotty problem that had plagued field-theoretic descriptions of scattering amplitudes.

Unitarity and the short-range nature of the strong force allowed Froissart to show[201] that total cross sections can grow no more rapidly at high energy than $\sigma_T \sim (\log s)^2$, where s is the square of the center-of-mass energy. For exchange of any particle of spin J, the total and elastic cross sections should grow as $\sigma_T \sim s^{J-1}$ and $\sigma_{\rm el} \sim s^{2J-2}$, respectively, exceeding the Froissart bound (and violating $\sigma_{\rm el} \leq \sigma_T$) for $J > 1$. Particles of high spin had been observed, but cross sections showed no sign of violating the Froissart bound.

Adapting Regge's result to relativistic scattering, Chew and Frautschi proposed[202] that particles lie on *Regge trajectories*, with specific states corresponding to integer or half-integer values of angular momentum $J = \alpha(s)$. Since all the known trajectories had values of $\alpha(t)$ less than or equal to 1 for the scattering regime $t \leq 0$, where t represents the invariant momentum transfer variable, there was

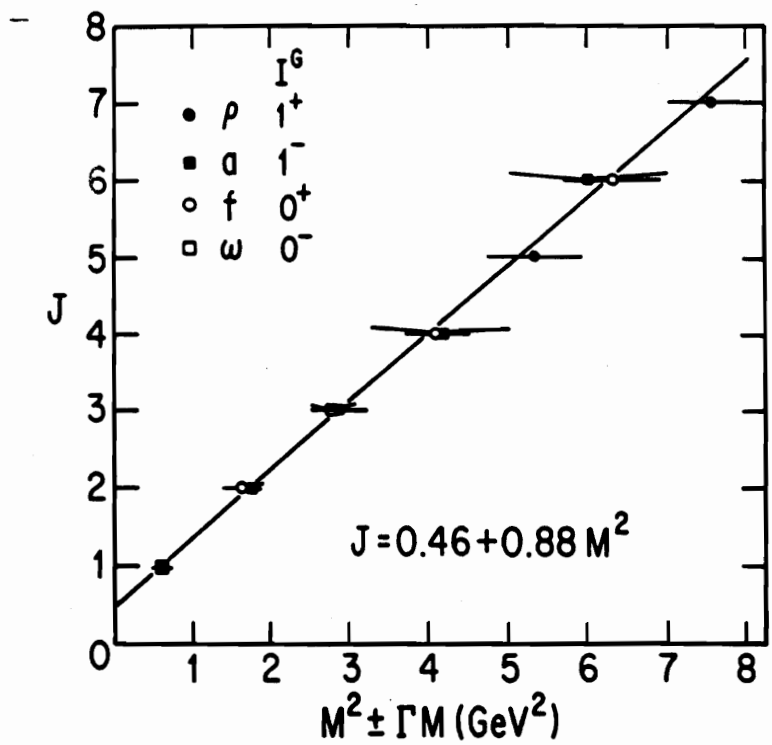


Figure 15: Example of Regge trajectories for nonstrange mesons. Points denote values of (squared) mass; error bars denote effects of natural widths. The trajectories for isospins $I = 0$ and 1 and for positive and negative G-parities (charge-conjugation eigenvalue of the neutral member of the isospin multiplet) are seen to coincide in this case.

no conflict with the Froissart bound. Understanding the approach of total cross sections at high energy to an approximately constant value required the introduction of another trajectory with $\alpha(0) = 1$, called the *Pomeranchuk trajectory* in honor of Pomeranchuk's description[203] of the high-energy behavior of total cross sections.

The derivation of singularitities in the complex angular momentum plane from field theory using dispersion relations was performed by Gribov; Bardakci; Barut and Zwanziger; Oehme; and Oehme and Tiktopoulos in 1962[203a].

The hypothesis of Regge pole exchange also implies a definite phase of the scattering amplitude. Evidence for this phase confirmed the hypothesis. The result relies on the asymptotic energy dependence of the scattering amplitude and its properties with regard to analyticity and crossing. Regge trajectories, an example of which is shown in Fig. 15, display a high degree of linearity in $s = m^2$, a feature to be discussed in Section 8.3.

5.4.5 Duality and forerunners of string theory. Progress in one area of theory

frequently leads to results in another. Thus, attempts to understand the strong interactions eventually led to a candidate theory for quantum gravity.

During the 1960s, it was popular to describe scattering processes at high energies by sums of Regge pole exchanges. For processes with no exchange of quantum numbers, the Pomeranchuk trajectory, or *Pomeron*, for short, plays the dominant role. Differences between various such processes are governed by contributions of the nonleading trajectories. If quantum numbers are exchanged, the Pomeron cannot contribute. For example, in pion-nucleon charge exchange, $\pi^- + p \to \pi^0 + n$, the dominant trajectory is the one on which the ρ meson lies (see Fig. 15), with energy dependence at high energy well described by ρ trajectory exchange. But what about the behavior at low energies, when resonances lead to rapid oscillations of the amplitude?

R. Dolen, D. Horn, and C. Schmid[204] found that Regge and resonance descriptions of pion-nucleon charge exchange are not to be added to one another, but instead are complementary descriptions of the same physics, the Regge trajectory providing an *average description of the resonant behavior*. Moreover, the average description of the resonances entails a phase of the scattering amplitude similar to that expected at higher energies from Regge pole exchange. This *duality* between resonances and Regge behavior applies only to non-Pomeranchuk trajectories[204a], and can be visualized in terms of quark graphs[204b].

M. Ademollo, H. Rubinstein, G. Veneziano, and M. Virasoro studied the Dolen-Horn-Schmid duality result for the process $\pi + \pi \to \pi + \omega$, which is particularly simple under crossing symmetry. Over the course of a year they hammered together a model scattering amplitude with increasing features of duality[205]. Finally Veneziano, en route by boat from Israel to Italy and his first postdoctoral job at CERN, found a remarkable formula for a scattering amplitude with both poles and Regge behavior in two kinematic variables[206]:

$$A(s,t) \sim B[1-\alpha(s), 1-\alpha(t)] \equiv \frac{\Gamma[1-\alpha(s)]\,\Gamma[1-\alpha(t)]}{\Gamma[2-\alpha(s)-\alpha(t)]} \quad .$$

The Veneziano amplitude created quite a stir among physicists accustomed to the intractability of the strong interactions. C. Lovelace and J. Shapiro[207] proposed a model pion-pion scattering amplitude very similar to the one just quoted, with many attractive features including a low-energy limit in agreement with current algebra results[184]. Attempts to construct a theory yielding the Veneziano amplitude led to the forerunners of string theory[208] and of supersymmetry[209].

String theories of the hadrons were originally viewed as models of the strong interactions, perhaps valid in some limit. One of their seemingly unattractive features was their need to exist in twenty-six space-time dimensions, rather than the usual four. In 1974 J. Scherk and J. Schwarz[210] realized that these theories possess a massless spin-2 particle – a good candidate for the graviton – and, together with a few other devotees, began to study them as possible versions

quantum gravity. Then, in 1984, M. Green and J. Schwarz[211] discovered that supersymmetric versions of certain string theories could exist in ten, rather than twenty-six, dimensions, and the extra six dimensions began to be interpreted in terms of internal symmetries of particles. These *superstring* theories became the subject of intense theoretical activity, which we shall describe further in Sec. 13.

All in all, despite the absence of a fundamental theory, much was learned in the 1950s and 1960s from the study of the strong interactions. We shall return to them in Sec. 8 in the context of quantum chromodynamics.

6. THE QUARK REVOLUTION

During the 1960s and early 1970s, particle physics underwent a transformation. Hundreds of strongly interacting resonances and a bewildering hodgepodge of interactions were gradually understood in terms of a few basic building blocks interacting via Yang-Mills fields (to be described in Section 7). Thus was the physics of quarks and gluons born. In this Section we describe the building blocks; we return to the interactions in Sections 7 and 8.

6.1 The quark model.

6.1.1 Triplets as a basis for SU(3). A good deal of the behavior of a symmetry group such as SU(2) or SU(3) may be learned from its action on its *fundamental* representation, corresponding to a triplet of particles for SU(3). One can build any SU(3) representation out of sufficently many triplets or antitriplets.

A fundamental triplet, consisting of the proton, neutron, and Λ as building blocks, was employed by Sakata[212] for constructing models of elementary particles, and by his colleagues[105] whom we have mentioned earlier in the context of SU(3). However, with the advent of the eightfold way (Sec. 4.6.2), the proton, neutron, and Λ no longer could be regarded as fundamental; they belonged instead to an *octet* of particles, along with three Σ's and two Ξ's. Moreover, there appeared to exist a 10-plet of baryons of spin 3/2, including the $\Delta(1238)$, $\Sigma(1385)$, the $\Xi(1530)$, and the predicted $\Omega(1675)$. Triplets were employed quite early to construct such states by Goldberg and Ne'eman[213].

Could one regard all the baryons (and the emerging multiplets of spin-0 and spin-1 mesons) as composites of more fundamental entities? During a visit to Columbia University in 1963, Murray Gell-Mann proposed taking SU(3) triplets seriously as fundamental subunits of the hadrons[175,214]. Calling the subunits *quarks* (as in the passage "Three quarks for Muster Mark" from *Finnegans Wake*[215]), he found that all baryons could be identified with states of three spin-1/2 quarks, while mesons could be represented as quark-antiquark pairs. The members of the SU(3) triplet were an isospin doublet (u, d) and a (strange) singlet s. They had to have fractional charges: $Q(u) = 2/3$, $Q(d) = Q(s) = -1/3$ – a heavy price, since fractionally charged entities had never been observed in Nature. Working independently at CERN, George Zweig developed a picture of the same fraction-

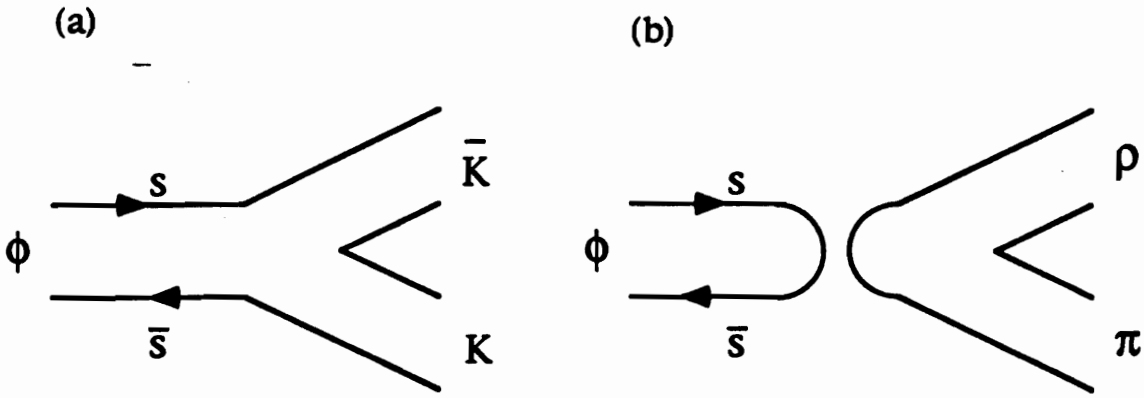


Figure 16: Diagrams illustrating Zweig's rule. (a) Allowed decay; (b) forbidden decay.

ally charged constituents of matter[216], which he called "aces." In the choice of a name, quarks won out over aces, poetry over poker.

Zweig wished to understand why some decays were allowed and others were forbidden. A spin-1 meson known as the ϕ, conjectured to exist[217] as a mixture of a singlet and octet in SU(3), had been observed[218] decaying to K^+K^- and $K^0\bar{K}^0$. Its decay to $\rho\pi$, though allowed by the combined symmetry of charge conjugation and isospin known as *G-parity*[219], seemed suppressed. This fact was hard to appreciate group-theoretically but could be apprehended immediately through quark diagrams. (See Fig. 16.) The suppression of decays in which the initial quarks must annihilate one another rather than appearing in the final particles is now known as *Zweig's rule.*

The quark picture immediately explained why baryons appeared only in singlets, octets, and 10-plets of SU(3), since these are the states that can be formed of three triplets. Mesons occurred only in singlets and octets, states that can be formed of a triplet and antitriplet. For states without orbital angular momentum, one could make positive-parity baryons of spin 1/2 and spin 3/2, and negative-parity mesons of spin 0 and 1. These coincided exactly with the lowest-mass observed families of strongly interacting particles. Additional orbital angular momentum would yield states of higher spin and even or odd parity.

6.1.2 The spectrum of resonant particles. The rules for combining quarks into hadrons are simple. For mesons, a quark and antiquark can form states of spin $S = 0$ or 1. For baryons, three quarks can form states of spin $S = 1/2$ or 3/2. These quark spins combine vectorially with an orbital angular momentum L to form states with various total angular momenta J. The intrinsic parities P of these states are also well-defined in terms of orbital configurations. Since the relative parities of a quark and antiquark are opposite, the mesons should have

parities $P = (-1)^{L+1}$. Indeed, the lowest-lying mesons have $J^P = 0^-$ and 1^-, as predicted for $L = 0$ states. The next-lowest mesons have $J^P = 0^+$, 1^+, and 2^+, as predicted. The lowest-lying baryons (the octet and decimet shown in Fig. 7) indeed have $J^P = (1/2)^+$ and $(3/2)^+$, as expected for $L = 0$ states, while their first excitations appear to have negative parity and $J = 1/2$, $3/2$, and $5/2$ as expected for $L = 1$ states.

The quark model allowed one to describe masses and magnetic moments of elementary particles with remarkable success[220]. A more algebraic formulation embodying many successes of the quark model was based on the group SU(6) (formed from the product of SU(3) and an SU(2) for quark spin)[221].

There is evidence for a substantial number of orbital excitations, and some radial excitations as well. However, the nature of the baryon ground states posed a problem best visualized by referring to the Δ.

6.1.3 The quark statistics problem. The $\Delta(1232)$ multiplet has isospin $I = 3/2$ and spin $J = 3/2$. It is a natural candidate for an S-wave state of three quarks. It is symmetric in isospin (containing, for example, the Δ^{++} with three u quarks). In the absence of orbital angular momentum among the quarks, it is symmetric in spin (containing, for example, the $J_z = 3/2$ state with all three quarks aligned along the $+z$ axis). It is symmetric in space if it is the spatial ground state, as is likely. But this behavior is unacceptable for a state composed of three identical fermions, which must obey the Pauli exclusion principle.

It was shown under certain assumptions[222] that particles of integral spin should obey Bose-Einstein statistics, while particles of half-integral spin should obey Fermi-Dirac statistics. These properties are expressed in terms of commutation relations for boson field operators and anticommutation relations for fermion fields. In 1953, H. S. Green[223] discovered a generalization of these rules, known as *parastatistics*, based on the assumption of new internal degrees of freedom of the fields. In 1964, Greenberg[224] suggested that quarks obeyed Green statistics, behaving as parafermions of order 3.

The parafermion hypothesis for quarks was equivalent to imagining quarks to occur in three versions, baryons consisting of one of each. A wave function antisymmetric in this new degree of freedom was symmetric in all the remaining ones. Greenberg was then able to classify the symmetry of all three-quark wave functions, finding a close correspondence with many known baryon states.

A more concrete proposal of an extra degree of freedom for quarks was made by Han and Nambu[225]. The quarks' apparent fractional charges arose from averaging over three species with *integral* charges. Thus, two u quarks would have charge 1 and one would have charge 0, making an average of 2/3, while two d quarks would have charge 0 and one would have charge -1, making an average of $-1/3$. Again, baryons would have one quark of each type.

We shall see the eventual outcome of the quark statistics problem when discussing quantum chromodynamics in Section 8. The internal "triplicity" proposed

by Greenberg and by Han and Nambu has come to be known as "color." Whereas more "flavors" of quarks are now known than the u, d, and s of the 1960s, the number of colors has remained three. Thus, the quote "Three quarks for Muster Mark" remains as appropriate as ever.

6.2 Deep inelastic scattering

6.2.1 Elastic scattering and form factors. The advent of new electron accelerators and sensitive detection techniques after World War II enabled the study of electron elastic scattering on protons and neutrons at momentum transfers large enough to probe nucleon structure[98]. The proton and neutron were found to be structures with radii of the order of 1 fm (10^{-13} cm). Their *form factors* (the Fourier transforms of their charge and magnetic moment distributions[226]) were found to fall off at large momentum transfers q roughly as q^{-4}.

6.2.2 Design and operation of SLAC. In the 1950s, planning began for a large linear accelerator to be located west of the Stanford University campus. The persistent efforts of W. K. H. Panofsky and others eventually led to the construction of the Stanford Linear Accelerator Center (SLAC) (see Fig. 17), which began operation in 1967.

Opinion was divided as to whether the SLAC accelerator was worth the cost and effort[227]. When the machine was conceived, many people thought that the proton form factor would continue to drop with increasing momentum transfer. A similar behavior was anticipated for each form factor for excitation of specific resonances like the Δ. If true, this behavior would mean that the high-energy scattering of electrons on protons would prove a barren desert.

6.2.3 Discovery and interpretation of scaling. An experiment to study the *inelastic* scattering of electrons on protons was mounted by an MIT-SLAC collaboration. One simply detected the scattered electron, inferring some properties of the final hadronic state from the direction and energy of the electron alone.

The results[228] were as surprising as those obtained by Rutherford more than half a century earlier. The number of high-angle scatterings was far in excess of what one expected on the basis of rapidly decreasing form factors, as if the proton itself contained pointlike constituents. A 1966 paper by Bjorken[229], predicting such behavior on the basis of current algebra, had anticipated this viewpoint.

Two relativistically invariant quantities characterize the deep inelastic scattering of a lepton on a target of mass M: the square of the invariant momentum transfer, Q^2, and the product $2M\nu$, where $\nu = E - E'$ is the difference between the initial and final lepton energies E and E' in the laboratory system. Bjorken's result predicted that, aside from well-defined kinematic factors, the scattering could be described in terms of a *scaling* variable $x \equiv Q^2/2M\nu$, i.e., in terms of the *ratio* of the two quantities just mentioned. Observations confirmed this behavior. The decrease of form factors for elastic scattering and for excitation of specific resonances with increasing Q^2 was compensated by the ability to excite more and more states of high mass.

Figure 17: Aerial view of the Stanford Linear Accelerator Center in 1969. (Courtesy of Physics Today collection, Niels Bohr Library, AIP.)

6.2.4 Initial neutrino experiments. In the early plans for Fermilab, it was recognized that deep inelastic scattering of neutrinos on protons and neutrons could play a role complementary to that of the SLAC experiments. Whereas deep inelastic electron scattering is governed by the electromagnetic interactions, and hence is sensitive to charges of the nucleon's constituents, the neutrino reactions known to occur at the time were sensitive to the presence of constituents able to change their charges by ± 1 unit.

Two experiments were mounted to study deep inelastic scattering of neutrinos on nucleons in the earliest days of operation of Fermilab: a Harvard-University of Pennsylvania-Wisconsin collaboration[230] (E-1) and a Caltech-Columbia-Fermilab-Rockefeller collaboration[231] (E-21). Experiments at CERN with bubble chambers such as Gargamelle[232], using neutrinos produced at the lower energies of the CERN Proton Synchrotron (PS), also made early studies of deep inelastic neutrino scattering. As in the SLAC experiments, scaling was dramatically confirmed. Moreover, a comparison of the electromagnetic and weak scattering experiments made it possible to determine the charges of constituents[233], confirming the hypothesis advanced several years earlier that the constituents of protons and neutrons had charges of $\pm 1/3$ and $\pm 2/3$.

6.2.5 Parton hypothesis and its successes. Bjorken noted that his current algebra results, which had predicted the scaling behavior observed at SLAC and in inelastic neutrino interactions, could be interpreted in terms of pointlike objects in the proton. Feynman[234] took the idea of pointlike constituents seriously, interpreting the scaling variable $x = Q^2/2M\nu$ as the fraction of a proton's momentum carried by the constituent, or *parton*, that absorbs the momentum and energy from the scattered lepton. A test for the spin of the constituents proposed by C. Callan and D. Gross[235] soon supported the idea that the pointlike objects in the proton indeed were quarks.

A systematic exploration of the parton hypothesis, undertaken by Bjorken and Paschos[236], developed a consistent description of the momentum distributions of partons in protons and neutrons for all deep inelastic scattering data known at the time. Those distributions are parametrized by *structure functions*, an example of which is shown in Fig. 18.

Structure functions are also probed when a parton in one hadron annihilates an antiparton in another to produce a lepton pair. That process, first proposed by Drell and Yan in 1971[237], still plays a major role today in the study of parton distributions and in tests of QCD, and is central to the production of W and Z bosons to be discussed in Sec. 7. Another effect of pointlike constituents in hadrons, predicted by Berman, Bjorken, and Kogut[237a] in 1971 and observed in a series of experiments at CERN and Fermilab[237b], was the production of hadrons at high transverse momenta as a result of parton-parton collisions.

6.3 Electron-positron annihilation.

The cross section for $e^+ + e^- \rightarrow$ hadrons can be normalized by defining a

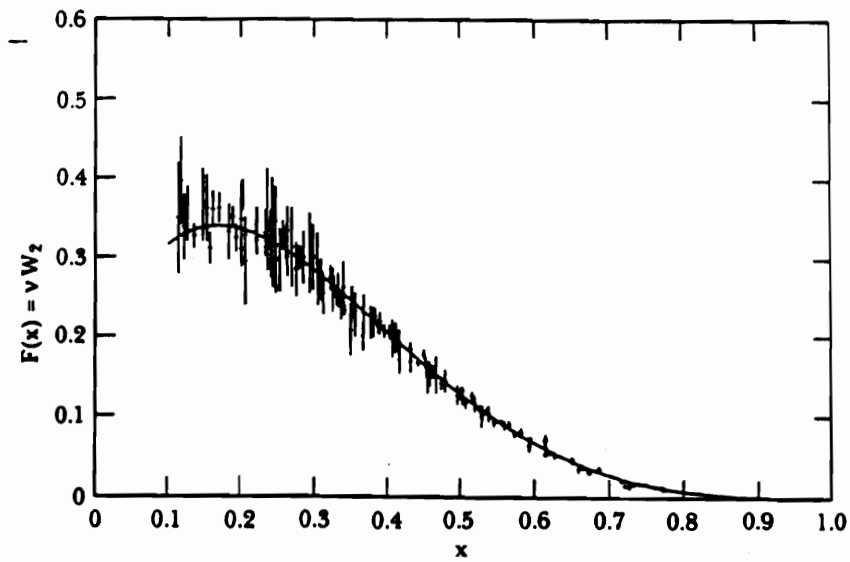


Figure 18: Proton structure function versus the scaling variable x. From Ref. 227, p. 152.

ratio $R \equiv \sigma(e^+ + e^- \to \text{hadrons})/\sigma(e^+ + e^- \to \mu^+ + \mu^-)$. In the quark model this ratio measures just the sums of the squares of the produced charges, and would be expected to increase when the energy crosses the threshold for new kinds of quarks. For example, just above the threshold (about 300 MeV) for the production of pairs of pions which are composed of up and down quarks, this ratio should be $R = 3(q_u^2 + q_d^2)/q_\mu^2$, where q_u, q_d and q_μ (the charge of the up quark, the down quark, and the muon) are $+2/3$, $-1/3$, and 1, respectively. The factor "3" represents the number of quark "colors", while the muon occurs in only one variety. R should equal 5/3 if these daring conjectures are correct, i.e., if the assigned quark charges are correct and if quarks have three colors. (The presence of sharp resonances in the cross section prevents this average behavior from being realized in practice.) As the energy of the colliding particles crosses the threshold for strange quark production as manifested by pairs of kaons, about 1 GeV, the ratio R should rise to 2. As resonances become broader and start to overlap at higher energies, this average behavior should be observable.

The study of electron-positron collisions was pioneered by several groups starting in the late 1950s (see Sec. 10.9), leading to the construction of machines at Stanford, Orsay (France), Frascati (Italy), and Novosibirsk (U.S.S.R.). In the late 1960s, a group at Frascati brought into operation the ADONE collider, with a center-of-mass energy of up to 3 GeV, the first capable of studying the process $e^+ + e^- \to$ hadrons above the region where prominent resonances led to fluctuations in the cross section. This machine, with an energy sufficient to produce pairs of u, d, and s quarks, should have yielded $R = 2$. Results were consistent

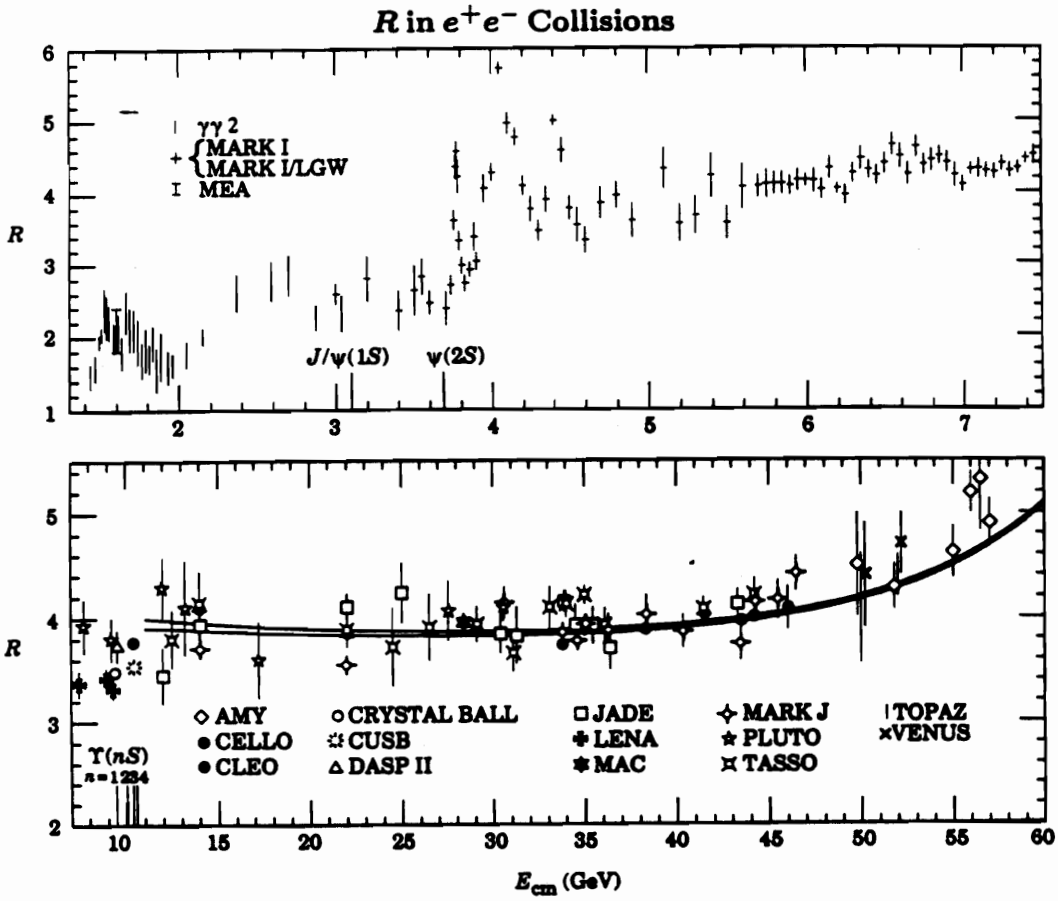


Figure 19: Behavior of the ratio $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of center-of-mass energy E_{cm}. From Ref. 48a, p. 1334.

with this, though with wide errors[238], as shown in Fig. 19.

In an attempt to reach higher collision energies, the Cambridge Electron Accelerator, or CEA, was adapted for electron-positron collisions in the early 1970s (see Sec. 10.9). Above the threshold (slightly below 4 GeV) for "charmed" quark production ($q_c = +2/3$) , the quark model predicted that R should rise to $3\frac{1}{3}$. However, when higher energies of 4 and 5 GeV were reached at CEA, the value of R was found[239] to rise to around 5! These results were eventually confirmed by the Stanford electron-positron collider SPEAR (Secs. 9.1, 10.9). New physics in the form of a τ lepton (Sec. 9) had unexpectedly appeared, the decay products of the τ being counted as hadrons. (The values of R in Fig. 19 have this contribution subtracted out.) It took some years to straighten out this initially confusing situation[240], but eventually quark counting by means of the ratio R proved a very useful technique.

6.4 Searches for free quarks.

The absence of free quarks was a continuing source of concern to many. Searches

for fractionally charged particles (for a review, see Ref. 241) were mounted as soon as proposed; even the early observations of Millikan were examined with quarks in mind. Claims for detection of free quarks in cosmic rays[242] were not supported by further evidence[241]. Physicists looked in such diverse places as oysters (where substances with odd chemical properties might be concentrated[243]) and samples from the Moon[244]. Excitement over free quarks peaked in the late 1970s with experiments of Fairbank and collaborators[245] which seemed to show fractional charges on niobium balls heated on a tungsten substrate. However, other experiments[241,245a] failed to see the effect, which was eventually understood to result from inhomogeneities on the surfaces of the balls.

To this day, free quarks have not been observed. Quantum chromodynamics provides a plausible reason why they should be permanently confined in hadrons, as we shall see in Section 8.

7. ELECTROWEAK UNIFICATION

7.1. A theory of leptons

7.1.1 Yang-Mills fields. As mentioned in Sec. 5.1.6, Yukawa[43] and subsequent authors[146] suggested that the weak interactions stem from exchange of a spin-1 boson, in analogy with the exchange of photons in electromagnetism. A crucial step laid the ground for a self-consistent theory based on this idea. In 1954 C. N. Yang and R. L. Mills proposed[107] that isotopic spin symmetry arises in the same way as electromagnetic gauge invariance. Their theory of fields which interact with *one another* as well as with external matter turned out to serve not only to unify electromagnetic and weak interactions, but also to describe strong forces. (In this context see also Ref. 245b.)

The following discussion owes much to an exposition by Yang[245c]. In electromagnetism, consider a slowly moving test charge undergoing a virtual displacement by a four-vector dx_μ. The change in the phase of its wave function (aside from any $p \cdot x$ contribution, where p is its four-momentum) is $eA^\mu(x)dx_\mu$ (in units with $\hbar = c = 1$), where $A^\mu(x)$ is the vector potential, and e is the electric charge of the particle in question.

According to *local gauge invariance,* the phase convention for the particle can be set independently at each space-time point x, corresponding to changing the vector potential by the divergence of a scalar quantity which depends on x. This *local gauge transformation* changes only the difference in phases at the endpoints when a particle is taken along a path from one point to another. When the endpoints coincide, so that the particle is taken on a voyage along a *closed path* in space-time, this phase difference vanishes.

Every experiment corresponds to either taking a particle on a closed path in space-time, or comparing the results of two *different* paths from a point x_1 to another x_2. Thus, one can take a particle through either of two slits or around either side of a solenoid (as in a classic experiment proposed by Aharonov and

Bohm[246]). One measures not $A^\mu(x)$, but the spatial integral of the *field strength* $F^{\mu\nu} \equiv \partial^\nu A^\mu - \partial^\mu A^\nu$ over an area enclosed by the particle's closed path in space-time (or by the area between the two paths from x_1 to x_2). The field strength is invariant under a local gauge transformation. Since changes of phase commute with one another, such a gauge theory is said to be *Abelian*. The group of phase changes is U(1), the unitary group in one dimension.

Yang and Mills' generalization of local gauge invariance involves not only transformations of phase, but local rotations in isotopic spin space. Thus, the quantity $A^\mu(x)$ induces isotopic spin transformations, and acts as a matrix in isospin space. Its dimension depends on the representation chosen for isotopic spin: two-dimensional for proton and neutron, three-dimensional for π^+, π^0, and π^-, and so on. Since rotations about different axes do not commute with one another, the corresponding field strength has an additional term:

$$F^{\mu\nu} \equiv \partial^\nu A^\mu - \partial^\mu A^\nu + g[A^\mu, A^\nu] \quad .$$

Here g is the gauge coupling strength, analogous to the electric charge e. Such a theory, said to be *non-Abelian*, has fields which interact with one another as a result of the additional term in $F^{\mu\nu}$. The isotopic spin group is denoted by SU(2); the 2 stands for the dimension of its smallest non-trivial representation.

7.1.2 Glashow's model. The first attempts[146] to unify the charge-changing weak interactions with electromagnetism assumed that charged intermediate bosons (the W's, mentioned in Sec. 5.1.6) together with the (neutral) photon formed an SU(2) triplet. However, the W's couple only to left-handed fermions, while the photon couples to both left- and right-handed fermions. In order to allow for this difference, Glashow[247] extended the SU(2) to an SU(2) $\times$ U(1) group. Gauge bosons corresponding to SU(2) would consist of W^+, W^-, and a neutral W^0, while an additional neutral boson (B^0 in today's notation) would correspond to U(1) gauge transformations. The W^0 and B^0 would be mixed by an interaction also giving rise to masses of charged W's. Two linear combinations of fields then emerged: the massless photon γ, with field $A^\mu(x)$, and a *massive* neutral vector boson Z with field $Z^\mu(x)$:

$$A = B\cos\theta + W^0\sin\theta \ , \quad Z = -B\sin\theta + W^0\cos\theta \quad .$$

The mass of the Z was predicted in terms of θ and the mass of the W : $M_Z = M_W/\cos\theta$. Weak processes involving exchange of a Z ("neutral-current interactions") were thus predicted by this theory.

7.1.3 Symmetry breaking and the Higgs mechanism. The origin of W and Z masses remained unexplained in Glashow's theory. In an electroweak theory based on a *renormalizable* Yang-Mills theory (one in which divergent quantities could be defined away by redefinitions of fundamental parameters like masses and coupling constants), it appeared that gauge bosons had to remain massless. The *ad hoc* introduction of gauge boson masses destroys renormalizability, gauge invariance,

or both. How could one break the SU(2) × U(1) symmetry without spoiling the attractive properties of the theory?

It became apparent in the late 1950s and early 1960s that symmetries could be manifested in two ways. (See Sec. 5.3.1.) In the *Wigner-Weyl* realization, symmetry is manifest through degeneracies in the spectrum. In the *Nambu-Goldstone* mode[170,171], the vacuum breaks the symmetry but the equations of motion retain it. In this mode, each broken symmetry operation corresponds to a massless, spinless particle, known as a *Nambu-Goldstone boson.*

In a theory with massless vector bosons, such as electromagnetism, only two polarization states are allowed: the two directions transverse to the boson's direction of propagation, or, equivalently, left and right circular polarization. A massive spin-1 particle has, in addition, a longitudinal polarization state. It was noted by J. Schwinger, P. W. Anderson, Peter Higgs and others[248] that in a gauge theory containing Nambu-Goldstone bosons, such bosons could act as the needed third component of a massive vector boson. One can describe the massless scalar particles as being "eaten" by the gauge bosons, which then become heavy. This process is now known as the *Higgs mechanism.*

7.1.4 The Weinberg-Salam Model. The Higgs mechanism was soon employed in the service of electroweak unification by Weinberg and Salam[249,250] (see Fig. 20). The simplest version of the theory introduced only an SU(2) doublet (ϕ^+, ϕ^0) and its complex conjugate $(\phi^-, \bar{\phi}^0)$. With an appropriate self-interaction of the fields, the combination $\eta \equiv (\phi^0 + \bar{\phi}^0)/\sqrt{2}$ would acquire a non-zero vacuum expectation value v, thereby breaking SU(2) × U(1) down to U(1) of electromagnetism as desired. The fields $\phi^\pm$ and $(\phi^0 - \bar{\phi}^0)/\sqrt{2}$, corresponding to the Nambu-Goldstone bosons of the broken symmetry, would be "eaten" by the $W^\pm$ and Z, while the difference $H \equiv \eta - v$, often referred to as "the" Higgs boson, would remain in the spectrum as a massive particle.

7.1.5 Renormalizability. The Weinberg-Salam theory remained a curiosity for several years, referred to very little even by its inventors. It predicted unobserved *neutral weak currents*, such as neutrino interactions in which a neutrino rather than a charged lepton emerged, and strangeness-changing decays such as $K^+ \to \pi^+\nu\bar{\nu}$. Limits on such decays were particularly stringent, lying far below the level of ordinary weak interactions. That is why Weinberg entitled his model "A Theory of Leptons."

It was, furthermore, not clear at the outset that the Higgs mechanism solved the problem of the renormalizability of the electroweak theory, until the proof was supplied in 1971 by Gerard 't Hooft[251], a student of Martinus Veltman in Utrecht (see Ref. 252 for some historical perspectives on this work) and extended by Benjamin W. Lee and Jean Zinn-Justin[253].

The proofs of the self-consistency of the Glashow-Weinberg-Salam electroweak theory were a major factor in its acceptance, and sent the particle physics community into a state of excitement. Weinberg immediately realized the significance

Figure 20: Clockwise, from upper right: S. Glashow (courtesy of Harvard University and AIP Emilio Segrè Visual Archives); S. Weinberg (courtesy of Fermilab); A. Salam (courtesy of AIP Emilio Segrè Visual Archives, Weber Collection).

of the result[254]. Early calculations of rates for neutral-current processes began to appear[255]. Discussions with experimentalists began in earnest: had neutral currents been overlooked? Variants of the model without neutral currents but with new particles were proposed[256]. Attempts were renewed to extend the theory to hadrons; these will be discussed in Sec. 7.3.

7.2. Experimental confirmation of neutral currents

With the growth of interest in the Glashow-Weinberg-Salam theory in the early 1970s, the search for weak neutral currents entered a more serious phase[257]. Previous upper bounds on such effects were reexamined in many processes. Particularly stringent bounds appeared to exist for reactions initiated by neutrinos.

7.2.1 Neutrino scattering. The Gargamelle collaboration at CERN had been investigating deep inelastic neutrino scattering during the late 1960s and early 1970s. Its limits on neutral current events were reported by Perkins at the 1972 International Conference on High Energy Physics[233]. Deep inelastic neutrino scattering was also beginning to be studied by experiments at Fermilab, as mentioned in Sec. 6.2.4.

Neutrinos were produced at accelerators mainly from the decays $\pi \to \mu\nu$ and $K \to \mu\nu$, and hence were of the muonic type. When interacting in matter via the charged current, they gave rise to hadronic showers and to a clearly identified muon in the final state. The presence of a muon rather than an electron was the basis of the claim that the muon and electron neutrinos were distinct. (See Sec. 5.1.6.) Occasional hadronic showers without an accompanying muon, observed even in the earliest neutrino experiments[258], were usually ascribed to contamination of the beam with neutral particles (particularly neutrons). One could check this possibility by studying in detail the distribution of events with respect to distance along the detector or inward from the lateral boundaries. Neutron-induced events would become rarer as either distance increased, while the rate for neutrino-induced events would be independent of distance.

The likelihood that the Gargamelle Collaboration was seeing neutral-current events was discussed informally at CERN in the early months of 1973. First, however, a detailed check of backgrounds had to be made[259]. Once the experimenters were satisfied that neutrons and other backgrounds could not be responsible for their signal, they announced the discovery of neutral currents in weak interactions of neutrinos. The effects were seen both in deep inelastic scattering[260] and in a "golden" neutrino-electron elastic scattering event[261]. The E-1A Collaboration at Fermilab also saw deep inelastic neutral-current interactions of neutrinos[262]. Their signal was present at an early stage, but an attempt to understand it better by reconfiguring the detector led to a temporary loss of the effect[263].

How could neutral-current effects have been overlooked for so long? One source of the difficulty in identifying them can be seen in Fig. 21. Define R_ν and $R_{\bar{\nu}}$ as the ratios of neutral-current to charged-current event for deep inelastic neutrino scattering. The predictions of the Glashow-Weinberg-Salam theory as a function

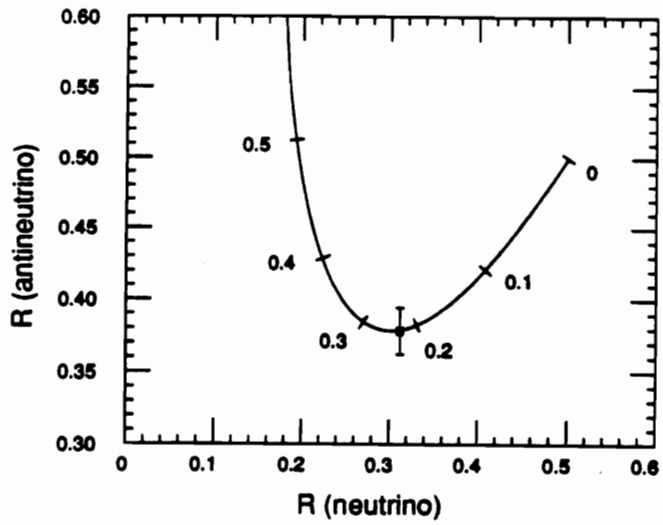


Figure 21: The neutral-current to charged current ratios R for deep inelastic scattering of neutrinos and antineutrions, plotted parametrically as functions of $\sin^2\theta$ (labels on curve). The plotted point shows an average of recent data. From Ref. 264.

of the angle θ (Sec. 7.1.2) yield a nose-like curve relating R_ν and $R_{\bar{\nu}}$. The present data, shown as the plotted point[264], sit at the bottom of the "nose." The ratio R_ν is expected to be quite small for a large range of values of $\sin^2\theta$, while the ratio $R_{\bar{\nu}}$, though larger than R_ν, is about as small as it can be. Neutral currents were also expected (and eventually found[265]) in *elastic* neutrino-proton scattering.

7.2.2 Parity violation in electron-deuteron scattering. The Glashow-Weinberg-Salam theory also predicted neutral-current weak processes involving charged leptons. These processes are normally masked by the much stronger electromagnetic interactions. However, in contrast to electromagnetism, the neutral weak force does not conserve parity. Despite its weakness, its effects can be observed through *interference* of the electromagnetic and weak interactions.

A collaboration led by V. W. Hughes and C. Y. Prescott searched at SLAC for the predicted parity violation in deep inelastic scattering of polarized electrons[266]. A difference in interactions of left-circularly polarized and right-circularly polarized electrons would confirm the predicted effect. It was necessary to prepare a source of polarized electrons, and to arrange their arrival at the target with desired (and known) polarization. The choice of target was also important: The

predicted effect turns out to be much smaller in hydrogen than in deuterium, so both were investigated.

The results were announced in 1978. The electron had neutral weak interactions, just as the theory had predicted. One could observe the interference of photon and Z^0 exchange. This confirmation was a major source of excitement at the 1978 International Conference on High Energy Physics in Tokyo[267].

7.2.3 Parity violation in atoms. A fundamental violation of parity in the electron-nucleus interaction can lead to such effects as optical rotation in atoms[268]. Initial experiments (chronicled in the first of Refs. 266 and the reviews of Ref. 269) did not see the expected effects, leading to some bizarre variations on the simplest version of the theory. Eventually laser stability was brought under control, and calculations of atomic physics effects to high orders were performed. The first experiments to claim the observation of parity violation were performed in atomic bismuth, with other groups who had previously not seen a signal then finding one.

More recent experiments[270] have attained ever-improving accuracy in measuring atomic parity violation. The most recent results in cesium by C. Wieman's group, when taken in conjunction with atomic physics calculations[271], not only confirm the electroweak theory at better than the 3% level, but provide a useful constraint on physics beyond the standard model[272].

7.2.4 Other neutral-current processes. Many other neutral-current effects have been observed over the years since they were first predicted. They include forward-backward asymmetries in electron-positron reactions, parity violation in polarized-electron scattering on nuclei other than hydrogen and deuterium, detailed studies of $\nu_\mu e$ and $\bar{\nu}_\mu e$ elastic scattering, and interference between charged and neutral currents in $\nu_e e$ and $\bar{\nu}_e e$ elastic scattering. An excellent source for tracking how these data have steadily improved is the series of reviews of Ref. 273.

7.3. Extension to hadrons and the charm hypothesis

The Cabibbo theory of strange particle decays, discussed in Sec. 5.3.4, can be re-expressed in terms of quarks and W bosons. A charged W can be emitted or absorbed in transitions between a u quark and the linear combination $d' \equiv d\cos\theta_C + s\sin\theta_C$, with $\sin\theta_C \approx 0.22$. The charge-conjugate couplings also exist.

The charged currents carrying a left-handed u quark into d' can be taken as part of a triplet. The properties of the neutral member of this triplet can be deduced by recalling the commutation relations for SU(2). The raising and lowering operators $J_\pm$ of angular momentum, for example, are related to the third component J_3 by $[J_+, J_-] = 2J_3$. The normalization of the currents then is specified by the property $[J_3, J_\pm] = \pm J_\pm$. But a neutral current defined in this way contains strangeness-changing pieces. How could these be avoided?

Each charged lepton (electron and muon) couples to its own variety of neutrino by the charge-changing current (the analogue of $J_\pm$). The corresponding neutral current is then *diagonal* in neutrino species. Moreover, even if one were to define

linear combinations of neutrinos coupled to electrons and muons, neutral currents are avoided as long as these linear combinations are orthogonal to one another.

A quark-lepton analogy, drawn in 1964 by Gell-Mann[175], Bjorken and Glashow[274], Y. Hara[275], and Z. Maki and Y. Ohnuki[276], proposed that as long as each charged lepton had its own neutrino, the d quark and s quark should not have to share the u quark in weak transitions. Instead, one combination $d' = d\cos\theta_C + s\sin\theta_C$ would couple to u quarks, while the orthogonal combination $s' = -d\sin\theta_C + s\cos\theta_C$ would couple to a new quark, which Bjorken and Glashow called *charmed*. This charmed quark c was to be heavier than the u quark, but, like it, would have charge 2/3. The neutral currents as defined by the commutator of two charged currents then are automatically diagonal in flavor.

Several years later, Glashow, J. Iliopoulos, and L. Maiani realized that not only did the Bjorken-Glashow hypothesis guarantee that neutral currents preserve strangeness in lowest order, but strangeness-changing neutral-current effects in higher-order weak processes were also drastically suppressed[277]. The mixing between a neutral kaon and its antiparticle is one such process. Since this mixing appears to be no stronger than the product of two first-order weak transitions (as one would have, for example, in the two-step process $K^0 \leftrightarrow \pi\pi \leftrightarrow \bar{K}^0$), it was possible to deduce an upper limit to the mass of the charmed quark. Glashow, Iliopoulos, and Maiani (GIM) predicted that the charmed quark lay below about 2 GeV/c^2 and proposed ways to search for it.

The GIM mechanism was applied by Gaillard and Lee[278] to a systematic study of rare decays of kaons, setting the stage for experimental investigations that continue to this day. Many suggestions for finding charmed particles began to be made[279], particularly after evidence for the predicted neutral currents began to appear. The role of a charmed quark in the cancellation of *triangle anomalies* (appearing in higher-order electroweak calculations) was stressed[280].

7.4. Experimental confirmation of charm

7.4.1 Early hints. Charmed particles were taken seriously very early in Japan. Some of the initial proposals of quartet models of hadrons had been made by Japanese authors[275,276]. An event seen in emulsion by K. Niu and his colleagues at Nagoya University was interpreted in 1971 as a possible candidate for a charmed particle[281]. It appeared to decay to $\pi^+\pi^0$ with a mass of about 2 GeV/c^2 and a lifetime of about 10^{-14} s. Niu's event (and others like it) suggested that quarks always occured in pairs: u with d and c with s. Kobayashi and Maskawa[282] recognized that with a third pair, one could describe CP violation. Both of the quarks they proposed have now been seen (Sec. 9).

7.4.2 Discovery of the J/ψ and the charmonium spectrum. An early study of the Drell-Yan process (Sec. 6.2.4) by Leon Lederman and collaborators observed a shoulder in the effective mass spectrum of muon pairs[283], which could have been interpreted as a new particle viewed with poor mass resolution. Stimulated by experience in the study of lower-mass dilepton pairs and by this result, Samuel

C. C. Ting and collaborators mounted an experiment to measure the dilepton mass spectrum with mass resolution far better than ever achieved before. The experiment consisted in colliding an intense beam of protons from the Brookhaven Alternating-Gradient Synchrotron (AGS) with a beryllium target, and observing electron-positron pairs with a two-arm spectrometer with approximately 30° between the two arms. Čerenkov counters filled with hydrogen served to identify electrons, with bending magnets and eleven planes of proportional chambers providing precise momentum measurements.

By September of 1974, it was clear to Ting's group that they had indeed come upon something either very wrong or very exciting. A peak in the e^+e^- effective mass was showing up at 3.1 GeV/c^2 with almost no background on either side. While a number of cross-checks were performed, Ting spoke of his result discreetly to colleagues, who generally urged him to publish it[227]. Meanwhile, on the West Coast, studies of electron-positron annihilations with the SPEAR detector (Sec. 6) had been continuing. Cross sections had been measured in steps of 0.2 GeV in center-of-mass energy. The values obtained at 3.2 and 4.2 GeV seemed a bit high in comparison with those at other energies. The cross section was remeasured in those regions in June of 1974, but no structure was noticed.

The SLAC-LBL Collaboration resumed its scrutiny of the energy-dependence data in October of 1974. The cross section at 3.1 GeV, upon closer examination, seemed not to be reproducible. Two out of ten runs at that energy gave much larger values than the others. Measurements were resumed over the weekend of November 9 and 10 in order to check the anomaly.

Ting arrived at SLAC on November 11 for a program committee meeting with the news of his discovery[284]. The peak he and his colleagues were seeing, dubbed the "J" (Fig. 22), was almost free of background. He was greeted with news of an electron-positron annihilation cross section peak seen in the Mark I detector (Fig. 23) by the SLAC-LBL Group, who called their effect[285] the ψ. The dual name J/ψ has persisted for the particle with mass 3.1 GeV/c^2. Within ten days, the SLAC-LBL group had raised the beam energy of SPEAR, finding another bump – the ψ' – at 3.7 GeV[286]. Electron-positron rings at Frascati in Italy and Hamburg in Germany were able to confirm the existence of the ψ in a matter of days[287].

The J/ψ and ψ' could be viewed as the ground state and first radially excited state of a charmed quark and a charmed antiquark with zero relative orbital angular momentum and parallel spins. In analogy with the name *positronium*, for the bound state of an electron and a positron, this system was called *charmonium*. Several sets of authors published interpretations of the new particles based on the charm hypothesis[288]. However, some questions had to be settled before that interpretation could be regarded as established and alternative schemes (see, e.g., Refs. 289) laid to rest.

7.4.3 Early confusion in the search for charm. The charm hypothesis predicted

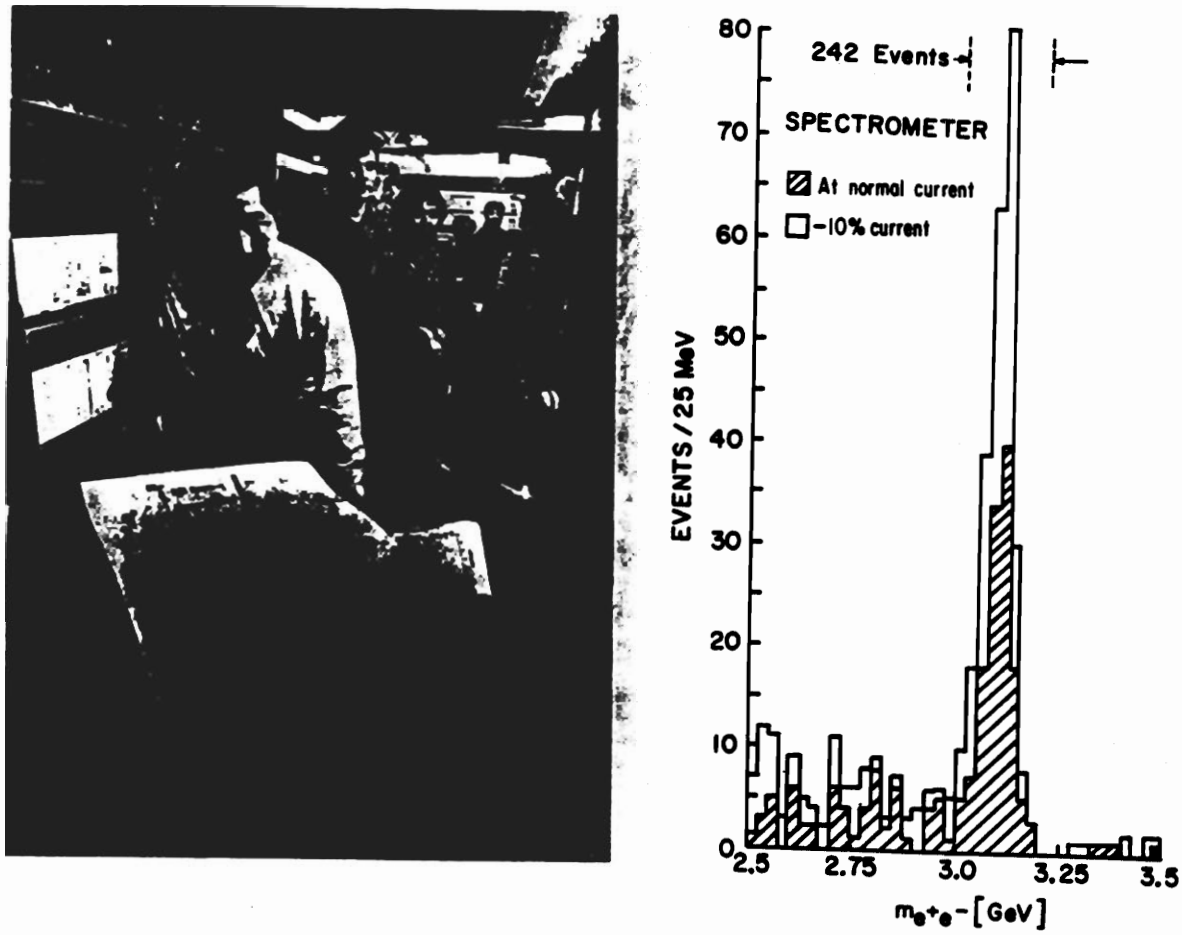
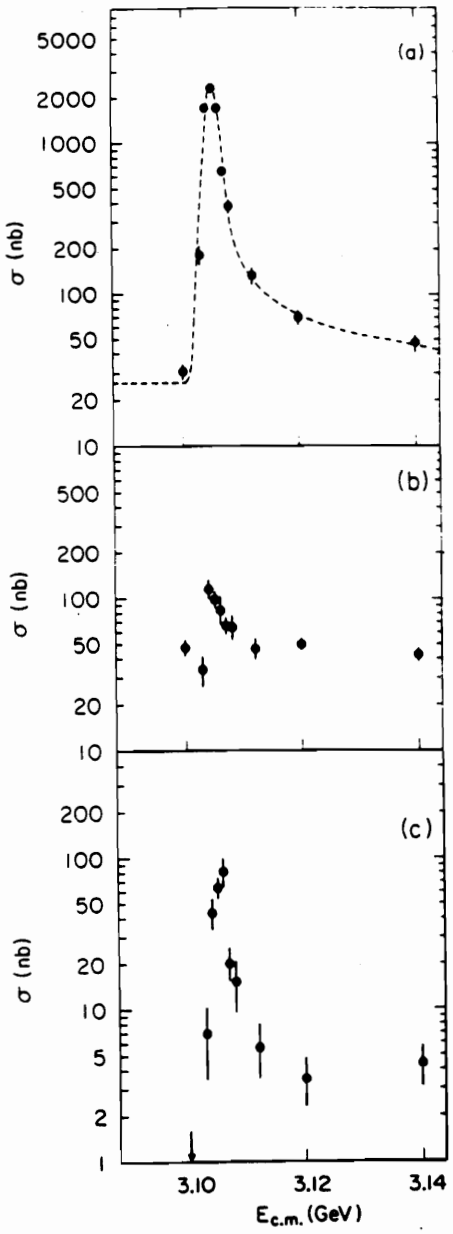


Figure 22: (a) S. C. C. Ting and his group, with a plot of the J resonance. From Ref. 227, p. 291. (b) The mass spectrum of e^+e^- pairs, showing the J peak[284].



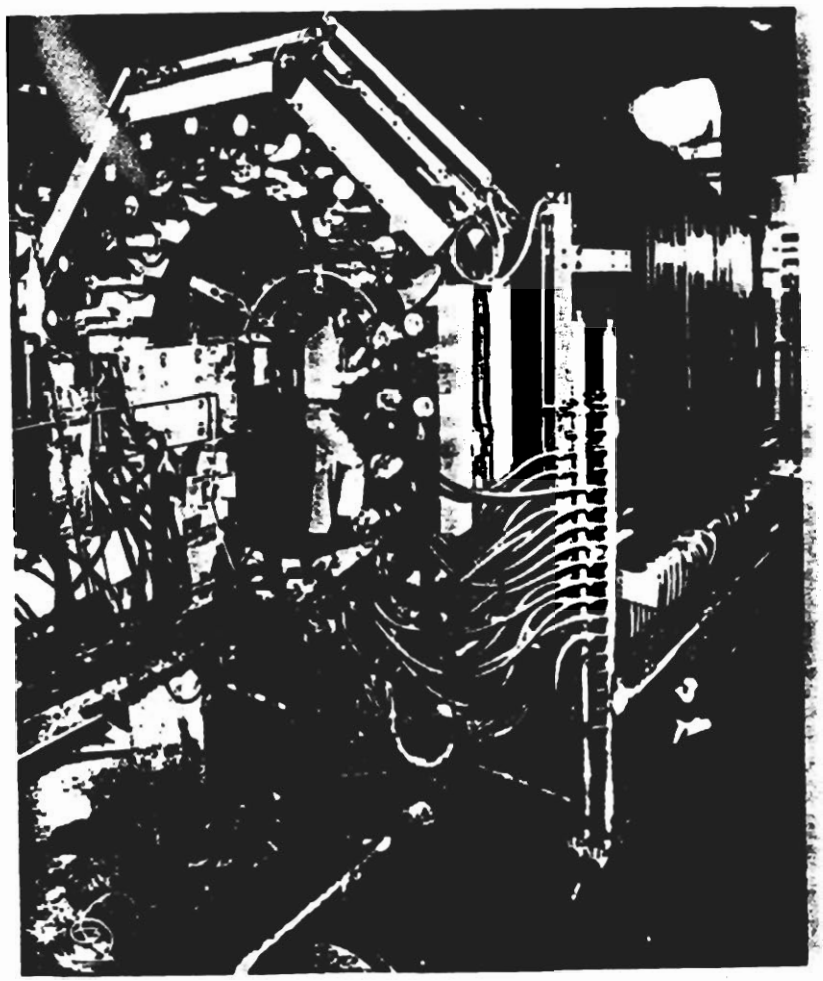


Figure 23: The cross section for e^+e^- annihilations to various final states as measured by the Mark I detector[285]: (a) multihadrons, (b) e^+e^-, (c) $\mu^+\mu^-$. (d) The Mark I Detector with Roy Schwitters. From Ref. 227, p. 256.

P-wave $c\bar{c}$-states lying between the J/ψ and the ψ'. The ψ' should be able to decay to them electromagnetically. A detector at SPEAR (located at the other side of the ring from the SLAC-LBL setup) initially did not see these transitions. They were first found at the DORIS storage ring, and confirmed at SLAC[290].

Mesons were expected containing one charmed quark and one light (u or d) antiquark, decaying to such final states as $\bar{K}\pi$. Early searches were not turning up such decays[291].

The cross section for $e^+e^- \rightarrow$ hadrons was indeed increasing above a center-of mass energy of 4 GeV in a manner indicating new particle production. However, the increase was actually *too large* for what was expected on the basis of charm. Moreover, an increase in the number of kaons, expected since the charmed quark's dominant decay should be to strange quarks, was not materializing.

The resolution of this confusion is traced in Refs. 240. Not only were charmed particles being produced in pairs, but a new lepton, the τ, was also being formed in pairs at roughly the same energy. Many of the signals for charm were counter-balanced by signals of the new lepton! It was not until the identification of the new lepton[292] that the "inclusive" signals for charm could be sorted out.

7.4.4 Observation of charmed particles. By the spring of 1976, the absence of a signal for charmed mesons in the SPEAR experiment was becoming a source of concern. Calculations by De Rújula, Georgi, and Glashow[293] indicated that the lightest charmed mesons should lie between 1.8 and 1.86 GeV/c^2, and the lightest charmed baryons should have a mass of about 2.2 GeV/c^2. The predictions for baryons were borne out by the discovery of two candidates for charmed baryons, a $\Sigma_c^{++}(= uuc)$ decaying to a $\Lambda_c^+(= udc)$ and a pion, in a single neutrino interaction[294]. Observation of additional leptons in neutrino experiments[295] and direct leptons in hadronic reactions[295a] also hinted strongly at the existence of charmed particles. Gerson Goldhaber and F. M. Pierre combed through the Mark I data to see if a charmed-meson signal was lurking there. Indeed it was; the lightest charmed meson, called the D (for doublet[274]) was found[296] in both predicted charge states, $D^0 = c\bar{u}$ and $D^+ = c\bar{d}$, with branching ratios close to those originally estimated in Ref. 277.

Glashow had exhorted a conference of meson spectroscopists in 1974 to go out and find charm[297]. If they didn't do so by the next conference, he would eat his hat. If "outlanders" (non-meson-spectroscopists) found charm, the spectroscopists were to eat their hats. The organizers of the next (1977) conference graciously distributed candy hats to all participants[298].

THE DISCOVERY OF CHARMED PARTICLES

Glashow, Iliopoulos, and Maiani[277] described how the puzzling absence of strangeness-changing neutral currents could be neatly explained if there existed a new fourth quark, the charmed quark. Immediately experimentalists started to ask: "How can we find it? What would be the experimental signature of such an object?" These questions were not answered for some time. Gradually, the details began to be fleshed out[279,297]. By the summer of 1974, the masses of charmed mesons and baryons were predicted, as well as their decay modes and their branching ratios. Even so, when the J/ψ was discovered in November of '74 it was a surprise. However, in fact, the J/ψ fit neatly into the scheme as the $c\bar{c}$ analogue of the ϕ_s, the vector meson. As soon as the J/ψ discovery was announced, the search for charmed mesons and baryons began at laboratories around the world.

At hadron accelerators, searches were started for associated production of charmed mesons and baryons in analogy with the production of strange particles more than 20 years earlier, mainly using the predicted decay of the pseudoscalar charmed meson, $D^0 \rightarrow K^-\pi^+$, as an identifying signature. Of course, the SLAC group, working with the e^+e^- collider detector, started a search for charmed particles, called naked charm to distinguish from the $c\bar{c}$ vector mesons.

The first clear-cut example of a charmed baryon came from a somewhat surprising source: a bubble chamber event at BNL, produced by a high energy neutrino[294]. The search for charm at SPEAR was complicated by the confusion produced by the appearance of the tau lepton. Not until this was unravelled was the D meson clearly identified[296] in 1976, a year and a half after the discovery of the J/ψ. The charmed D meson was found in sufficient numbers to allow the beginning of a systematic study of production channels and decay modes.

In the meantime, the searches for charmed particles at the hadron machines had been singularly unsuccessful, with only faint signals above background leading to upper limits for the production cross-sections. The charmed particles, even though produced in great numbers, were swamped by the high attendant backgrounds in hadronic interactions. It was not until the development of silicon strip detectors with their excellent spatial resolution and a tolerance for high counting rates that charmed particles were detected at hadron machines[298a]. This approach was highly successful, and almost immediately samples of data which previously had been counted in tens at the electron-positron colliders were counted in thousands. This is still another example of how the pace of discovery is determined by the development of instrumentation.

At the present time, near the end of the century, experiments are being conducted at hadron machines in which millions of events carrying charm are being recorded. The study of charmonium itself, long an exclusive province of electron-positron machines, has been extended via proton-antiproton annihilation to states unavailable in e^+e^- collisions.

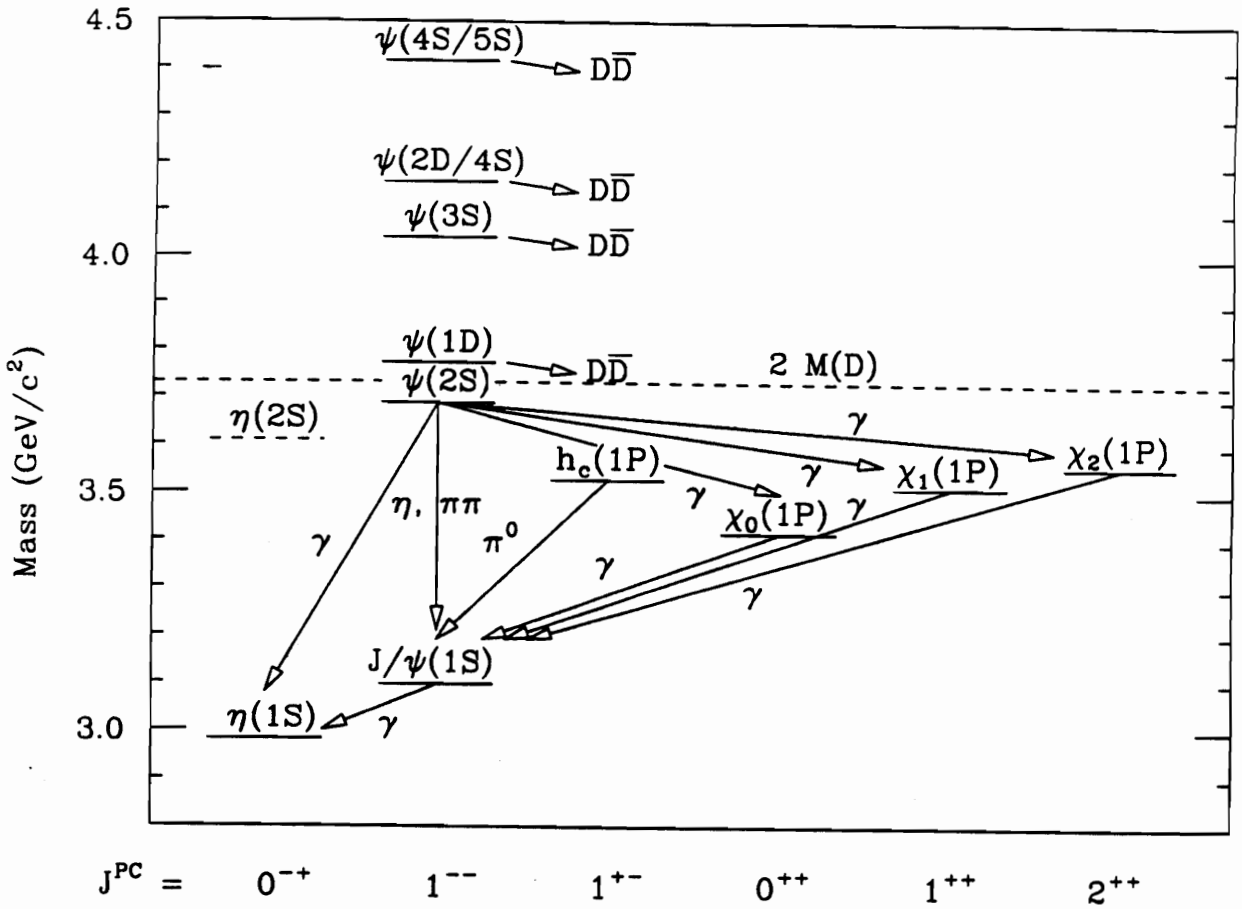


Figure 24: The charmonium spectrum. Observed and predicted levels, as quoted in Ref. 298b, are denoted by solid and dashed horizontal lines, respectively. Arrows are labelled by particles emitted in transitions.

7.4.5 Spectroscopy of charmonium and charmed particles. The study of charmonium and charmed particles has come a long way since the mid-1970s. The charmonium spectrum (see Fig. 24) is already richer than that of positronium, while numerous non-strange and strange charmed mesons and baryons have been discovered. These systems, the lightest for which ideas of perturbative quantum chromodynamics (Sec. 8) begin to hold, thus form one of the testing grounds for the new understanding of the strong interactions that arose in the 1970s.

7.4.6 Charmed particle decays. Since charmed quarks couple to strange quarks with a strength proportional to the cosine of the Cabibbo angle (Sec. 7.2), the lifetimes of charmed particles are very short, ranging between about 10^{-14} and 10^{-13} s. The *differences* among these lifetimes arising from the strong interactions are a topic of much current interest.

7.5. The W and Z

7.5.1 Discovery. In a theory with an intermediate vector boson W, the Fermi coupling constant $G_F = (1.16639 \pm 0.00002) \times 10^{-5}$ GeV^{-2} can be re-expressed as a constant of order 1 times the square of a coupling constant divided by the square of the W mass. The mass thus follows from the value of the coupling constant.

Early searches for W bosons, whose coupling constant was unknown, explored mass ranges of a few GeV[151], as mentioned in Sec. 5.1.6. Part of the motivation for studies of deep inelastic neutrino scattering at Fermilab was to search for indirect effects of W exchange (see, e.g., Refs. 230 and 231). Sensitivity could thus be achieved to masses up to several tens of GeV.

The Glashow-Weinberg-Salam electroweak theory relates the Fermi coupling constant, the SU(2) coupling strength g, and the W mass M_W by $G_F/\sqrt{2} = g^2/8M_W^2$. Moreover, the relation between g and the electric charge e depends on the angle θ: $e = g \sin\theta$. The combined results predict $M_W = 37.2$ GeV$/\sin\theta$ (with $\alpha = e^2/(4\pi\hbar c) = 1/137$ for the electromagnetic fine-structure constant).

The study of deep inelastic neutrino scattering and parity-violating interactions of polarized electrons in the late 1970s gradually yielded a value of $\sin\theta$ slightly lower than 1/2, implying a W mass above 75 GeV$/c^2$. The electroweak theory also predicted the Z mass to be slightly higher than that of the W: $M_Z = M_W/\cos\theta$. With these estimates of W and Z masses, one could anticipate the cross sections for their production in quark-antiquark annihilations. Proton-proton or proton-antiproton collisions with center-of-mass energies of several hundred GeV would provide quarks with energies sufficient to produce the desired particles. Schemes to collide protons with antiprotons at Fermilab and in the CERN Super Proton Synchrotron (SPS), to be described in greater detail in Sec. 10.10.2, began taking shape in the late 1970s. A major step in each project was the collection of sufficient antiprotons in a narrow range of space and momentum. Important steps in this "cooling" procedure were taken by Simon van der Meer, working at CERN[299]. The effort required to turn the CERN SPS into a proton-antiproton collider was coordinated by Carlo Rubbia[300]. First collisions were seen in 1982. The Fermilab project, requiring the construction of a ring of superconducting magnets, came into operation several years later.

Two detectors were constructed at CERN to study the debris of collisions. The UA1 Collaboration (UA stands for Underground Area) was led by Rubbia, while the spokesman for UA2 was Pierre Darriulat. In January of 1983 the first signals of W production[301] were seen by both groups: an electron of high transverse momentum, with apparent imbalance of transverse momentum in the opposite direction, as expected for a W decaying to an electron and a neutrino. Within six months, both groups also reported the observation of the Z (Fig. 25), decaying to pairs of charged leptons[302].

The W and Z masses are slightly higher than anticipated on the basis of the lowest-order theory (with $\alpha = 1/137$). At the short distances characteristic of

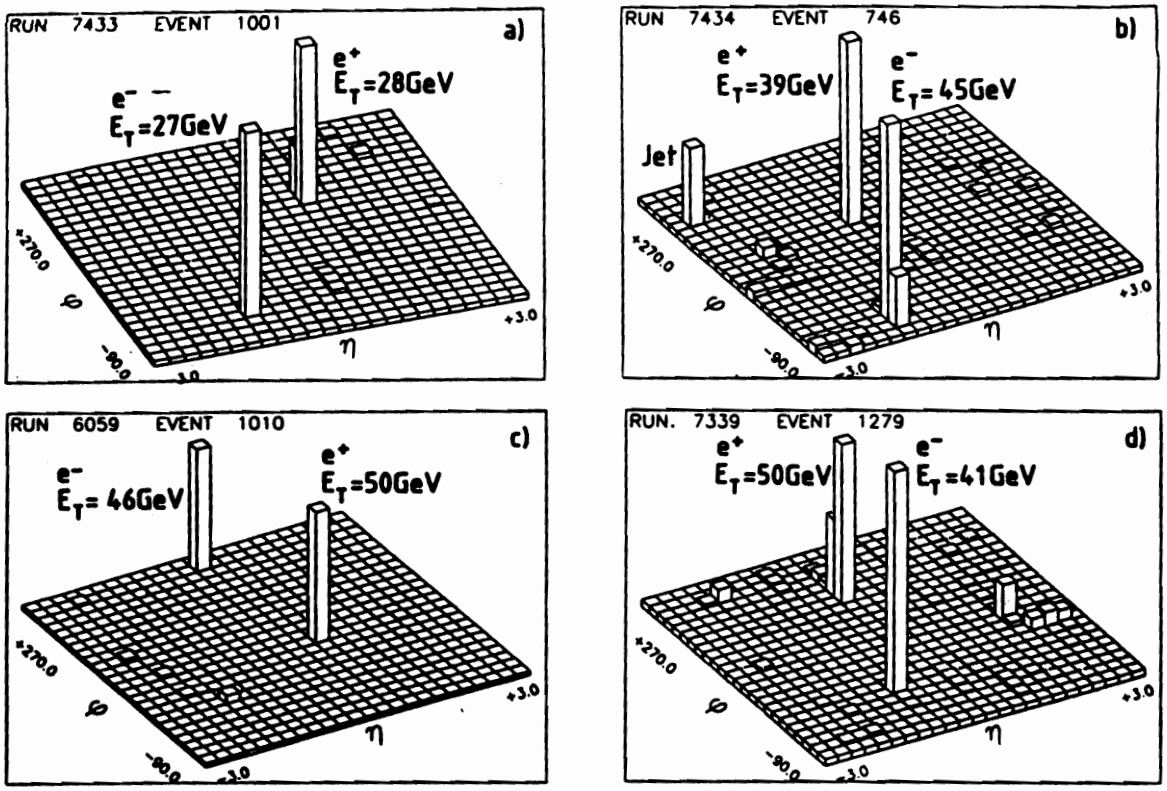


Figure 25: Early evidence for Z production from the first of Refs. 302. Heights of bar graphs denote energy transverse to the beam deposited in various regions of the UA1 detector.

the W and Z Compton wavelengths, the vacuum polarization effects mentioned in Sec. 3 predict $\alpha \approx 1/128$. With this simple correction, the W and Z masses are in remarkable accord with theory.

7.5.2 W and Z properties in hadron colliders. The CERN discoveries of the W and Z were followed by studies of their production and decays with ever increasing accuracy, by the UA1 and UA2 Collaborations and by the Collider Detector Facility (CDF) at Fermilab (Fig. 26). A precise determination of the Z mass was made[303], shortly before electron-positron colliders began to refine that quantity further. Production cross sections were measured; comparison of lepton yields in W and Z decays yielded indirect measurements of the ratio of W and Z widths[304], helping to specify the open W decay channels and thereby place an indirect lower bound on the top quark's mass. We shall return to the top quark in Sec. 9.

Recently the D0 Detector (Fig. 26) has begun operation at Fermilab. (The name refers to its location around the accelerator ring.) Its fine-grained calorimetry and large angular coverage aim at a precise measurement of the W mass.

7.5.3 Results from SLAC and LEP on the Z. The Z mass was predicted by the electroweak theory to be about 90 GeV/c^2. At SLAC and CERN, plans began

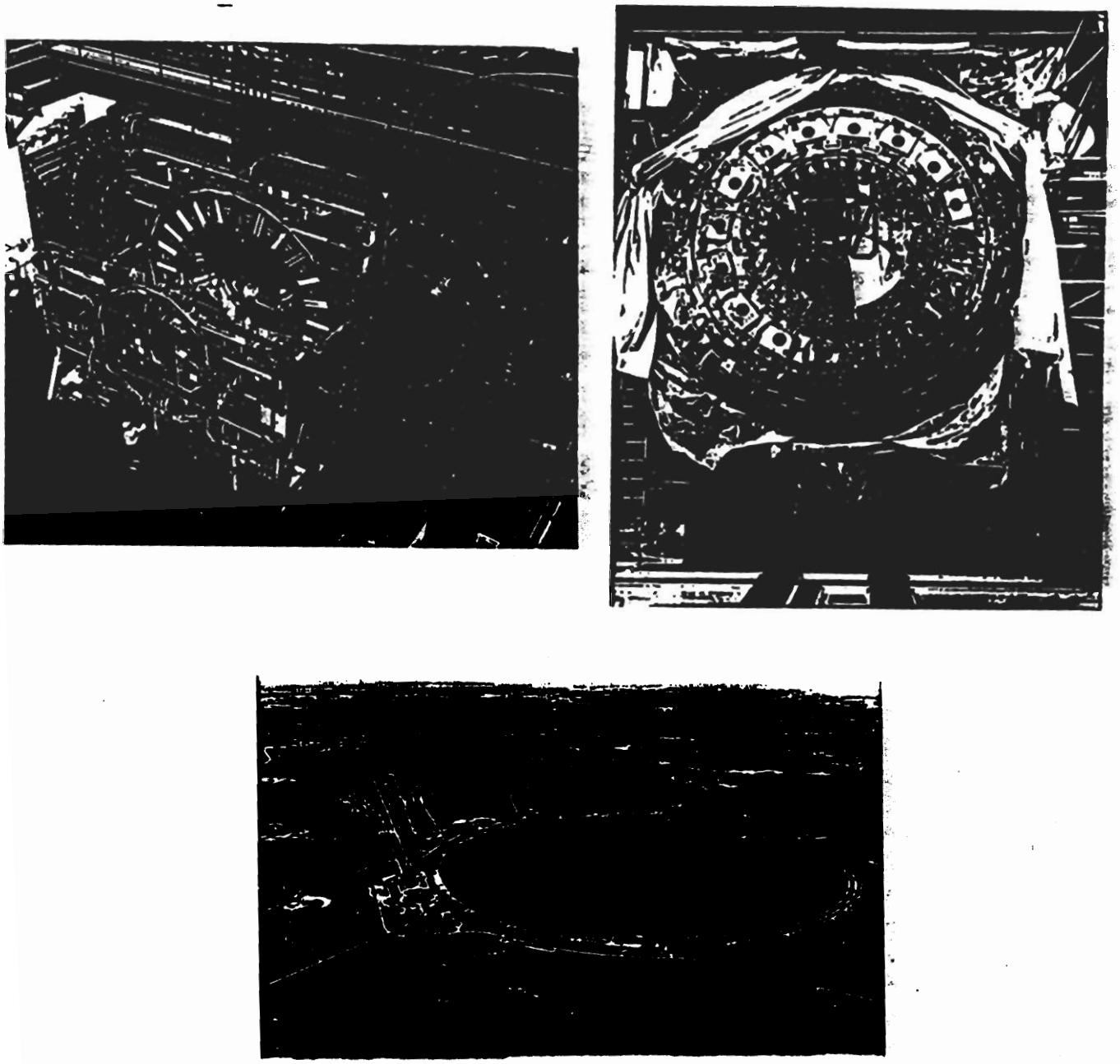


Figure 26: Clockwise from upper left: The CDF detector; the central calorimeter modules of the D0 detector; a recent aerial view of the Fermilab site (courtesy of Fermilab).

to develop in the late 1970s and early 1980s to build electron-positron colliders ("Z factories") with at least that energy in the center of mass.

The Stanford Linear Collider (SLC) involved upgrading the SLAC linear accelerator to a beam energy of 50 GeV, adding a positron source, installing positron and electron cooling, and building two arcs to bring the electrons and positrons into collision [see Fig. 27(a)]. The first results[305], obtained in 1989, included precise measurements of the Z mass and width. More recently, collisions of longitudinally polarized electrons with positrons have provided a precise measurement of $\sin^2\theta$ through the difference between cross sections for left-handed and right-handed electrons[306].

In the LEP (Large Electron-Positron) Collider, lying on the French-Swiss border at the base of the Jura Mountains [see Fig. 27(b)], positrons and electrons injected from the CERN site are detected at four symmetrically placed locations around the ring. The acronyms for the detectors are ALEPH (Apparatus for LEP Physics), DELPHI (Detector with Lepton, Photon, and Hadron Identification), L3 (internal CERN numbering of experiment), and OPAL (Omni-Purpose Apparatus for LEP).

LEP measured the Z width to an accuracy establishing its invisible decay modes to be the three known pairs of neutrinos $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, and $\nu_\tau\bar{\nu}_\tau$. Precise measurements of the Z mass, of its total width, of branching ratios to various final states, and of asymmetries of various sorts, test not only the electroweak theory, but higher-order corrections stemming from the top quark and Higgs boson[307]. The top quark was thereby anticipated to have a mass below 200 GeV/c^2, as indeed transpired[307a] (Sec. 9).

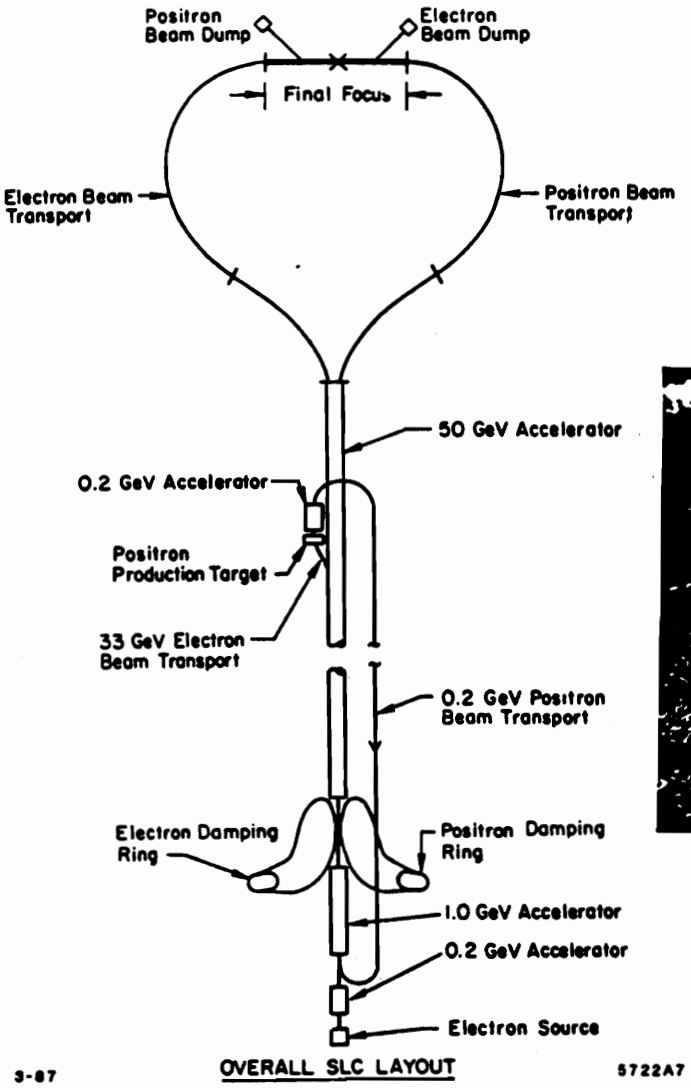


Figure 27: Left: sketch of the Stanford Linear Collider, from Ref. 306a. Right: photograph of the LEP site. The small and large solid circles indicate the position of the SPS and LEP rings, while the dotted line denotes the French-Swiss border. (Courtesy of CERN.)

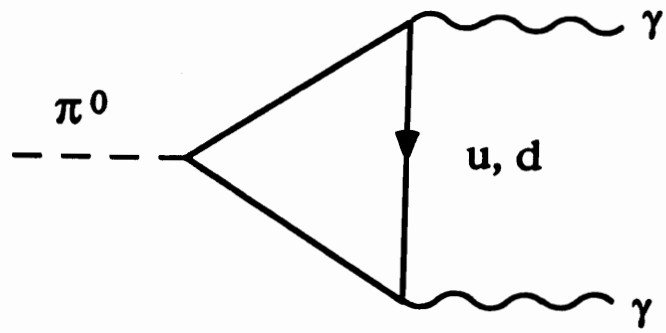


Figure 28: Graph responsible for the decay $\pi^0 \to \gamma\gamma$. The original calculation by Steinberger (Ref. 64) involved protons instead of u and d quarks traveling around the loop.

8. QUANTUM CHROMODYNAMICS

8.1 Early suggestions of color-triplicity

In Section 6 we mentioned briefly that quarks appear classified by three "colors," as evidenced by several circumstances.

8.1.1 Quark statistics. In baryons, the product of the quarks' spin, space, and "flavor" (u, d, s, etc.) wave functions appears to be symmetric under interchange of any two quarks. Since quarks have spin 1/2 and thus should obey Fermi statistics, one would expect their total wave function to be antisymmetric under interchange of any two quarks. This goal is achieved by adding a new degree of freedom in which all the quarks in a baryon are antisymmetric.

According to Greenberg[224] and Han and Nambu[225], the three-quark structure of baryons suggested a new SU(3) symmetry, under which quarks would transform as triplets (**3**), while all known hadrons would be singlets. Since

$$\mathbf{3} \times \bar{\mathbf{3}} = \mathbf{1} + \mathbf{8} \quad , \quad \mathbf{3} \times \mathbf{3} \times \mathbf{3} = \mathbf{1} + \mathbf{8} + \mathbf{8} + \mathbf{10} \quad ,$$

the known mesons would be the singlets of $\mathbf{3} \times \bar{\mathbf{3}}$ (i.e., of quark-antiquark pairs), while the baryons would be the singlets of $\mathbf{3} \times \mathbf{3} \times \mathbf{3}$ (three-quark states). Nambu[308] showed it plausible that the only states manifest in Nature are singlets, and discussed the possibility that this new SU(3) corresponded to a gauge theory.

8.1.2 Decay of the neutral pion. The decay $\pi^0 \to \gamma\gamma$ was attributed by Steinberger in 1949[64] to a diagram involving a virtual proton (see Fig. 28). Nearly twenty years later, a similar calculation (involving quark loops instead) was set on a firmer footing by Adler, Bell, and Jackiw. The amplitude for this process was found proportional to the number of quarks traveling around the loop, indicated to be three by the experimental $\pi^0 \to \gamma\gamma$ rate[309].

8.1.3 Cross section for electron-positron annihilations. The study of electron-positron collisions (see Sec. 6.3) provided a further confirmation of three quark

"colors." The cross section $\sigma(e^+ + e^- \to \text{hadrons})$ is proportional to the number N_c of quark colors. Once the charges of quarks produced at any given energy were understood, the data indicated that $N_c = 3$.

8.2 Requirements of a gauge theory of strong interactions

Murray Gell-Mann and Harald Fritzsch[310] stressed the color-triplet nature of quarks in 1972, summarizing the evidence for a three-fold degree of freedom and emphasizing the need for a gauge theory of the strong interactions which would not destroy the successes of current algebra.

A vector-like interaction, similar to that of electromagnetism, was favored, strong enough at large distances to bind quarks into hadrons yet weak enough at short distances to let the quarks appear quasi-free in deep inelastic scattering. Theories like electromagnetism behave differently. Their vacuum polarization effects (see Sec. 3) augment the strength of electromagnetic interactions at short distances. The stage was thus set for a systematic examination of quantum field theories suitable to describe the strong interactions.

8.3 Asymptotic freedom and infrared slavery

Vacuum polarization effects in Yang-Mills theories were first calculated correctly, using non-covariant methods, by Khriplovich in 1969 [311]. The self-interaction of the Yang-Mills field led to an important contrast with quantum electrodynamics, the force in a Yang-Mills theory becoming *weaker* at short distances as required for a theory of the strong interactions.

Khriplovich's result seems to have escaped general attention until after its rediscovery in the early 1970s. At that time, several people began examining Yang-Mills theories as candidates for the strong interactions[312]. Two manifestly covariant calculations of the coupling strength's dependence on distance[313] appeared in 1973. A student of Sidney Coleman at Harvard, H. David Politzer, and David Gross and his student Frank Wilczek at Princeton both found a result for SU(N) gauge theories which relates a *running coupling constant* α_N measured at a momentum scale μ_1 to its value at another scale μ_2:

$$[\alpha_N(\mu_1)]^{-1} = [\alpha_N(\mu_2)]^{-1} + \frac{1}{4\pi}\left[\frac{11}{3}N - \frac{2}{3}n_f\right]\log\frac{\mu_1^2}{\mu_2^2} \quad .$$

Here n_f is the number of fermion species contributing to the vacuum polarization for a gauge boson. This result made use of the *renormalization group* concept, which specifies the dependence of quantum field theory parameters on changes of scale[314].

The coefficient of the logarithm depending on N stems from gauge boson loops. Its positive sign means that the interaction in a Yang-Mills theory weakens at large momentum scales (equivalently, at short distances), a property dubbed *asymptotic freedom.* In order for it to hold, the number of fermions n_f in the loop must be small enough for the term proportional to N to dominate.

For an abelian gauge theory such as electromagnetism, the term proportional to N is absent; fermion loops contribute a negative coefficient to the logarithm, and the interaction becomes *stronger* at large momentum scales or short distances.

The *long-distance* behavior of the coupling constant also differs markedly in abelian and non-abelian theories. In an abelian theory, since the coupling strength ceases to "run" at scales μ much lower than the mass of the lightest fermion contributing to vacuum polarization, one can measure a well-defined charge at long distances. In non-abelian theories, the logarithmic dependence on μ associated with gauge boson loops eventually leads the coupling constant to diverge at some small value of μ. The interaction then becomes strong, and perturbation theory ceases to be valid.

It was proposed quite early that the Yang-Mills theory of strong interactions would lead to interaction energies proportional to the interquark separation; such a force between quarks and antiquarks at long distances would keep them from ever being torn apart from one another. This suggestion leads[315] to families with angular momentum J linear in M^2, and is supported by the spectrum of particles lying along the highest Regge trajectories (cf. Sec. 5.4.4 and Fig. 15). As a counterpart to asymptotic freedom, the confinement of quarks by an ever-increasing potential has sometimes been called *infrared slavery.*

The theory of the strong interactions based on a Yang-Mills quantum field acting on the color degree of freedom has come to be known as *quantum chromodynamics*, or QCD. The quanta of QCD are called *gluons*, since they provide the "glue" holding hadrons together.

8.4 Scaling violation in deep inelastic scattering

Although deep inelastic lepton scattering experiments (Sec. 6) reveal pointlike constitutents in the proton, the details of nucleon structure depend slightly on the momentum transferred to the target by the leptons. Fig. 29 shows modern data[48a] illustrating this behavior, predicted by QCD. Quarks can emit or absorb gluons, thereby shifting their momenta. A proton probed with very high momentum transfers thus appears to have "softer" and more numerous constituents. The scaling predicted by Bjorken is violated slightly, to a degree that sheds light on the strong coupling constant $\alpha_s(\mu)$ (the subscript denotes "strong") at any chosen momentum scale μ. Several quantitative treatments of this feature appeared in the mid-1970s, starting with the initial discoveries of asymptotic freedom and expressed transparently in the work of Altarelli and Parisi[316]. Since many measurements of α_s are performed at the mass of the Z boson, a convenient reference point is $\mu = M_Z$, even though the deep inelastic scattering experiments probe lower momentum scales. A recent analysis of deep inelastic scattering[317] finds $\alpha_s(M_Z) \approx 0.12$, consistent with other determinations.

8.5 Jets and other high-$p^\perp$ phenomena

An early application of the parton picture, mentioned in Sec. 6.2.5, predicted[237a]

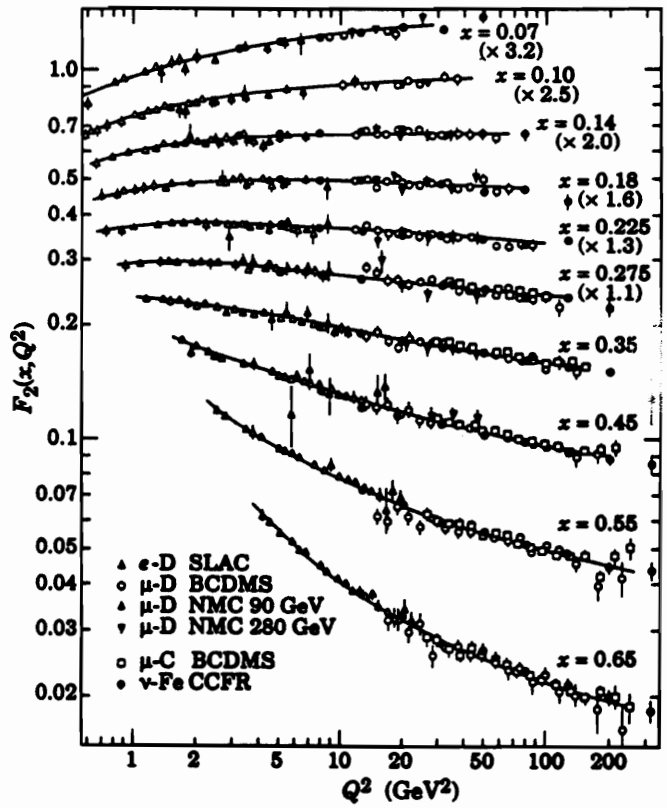


Figure 29: Nonscaling behavior of structure functions. From Ref. 48a, p. 1327.

hadron production at high transverse momenta, confirmed by experiments at the CERN ISR (Intersecting Storage Rings) and Fermilab[237b]. The behavior of cross sections at high transverse momenta indicated that the constituents of colliding protons were interacting with one another at a fundamental level.

Direct evidence for gluons emerged from the study of three-jet events in electron-positron annihilations[318], as detailed in Ref. 227. In quantum chromodynamics, the process $e^+ + e^- \rightarrow$ hadrons evolves in two stages. First (essentially instantaneously), a quark-antiquark ($q\bar{q}$) pair is produced by the electromagnetic current. Then, over a longer time scale, these quarks materialize into hadrons through production of additional quark-antiquark pairs, with transverse momenta small with respect to the original quarks. The original quark and antiquark thereby define a direction for two *jets* of particles, which become more and more clearly defined with increasing energy. Because QCD interactions grow stronger at momentum scales below 1 GeV/c, it took several GeV in the center-of-mass to begin seeing two-jet events. Such jets were identified in e^+e^- annihilations[319] and hadronic collisions[319a] in the mid-1970s.

At the 1978 International Conference on High Energy Physics in Tokyo, a much-discussed particle was the Υ (Sec. 9), a composite of the fifth (b) quark and

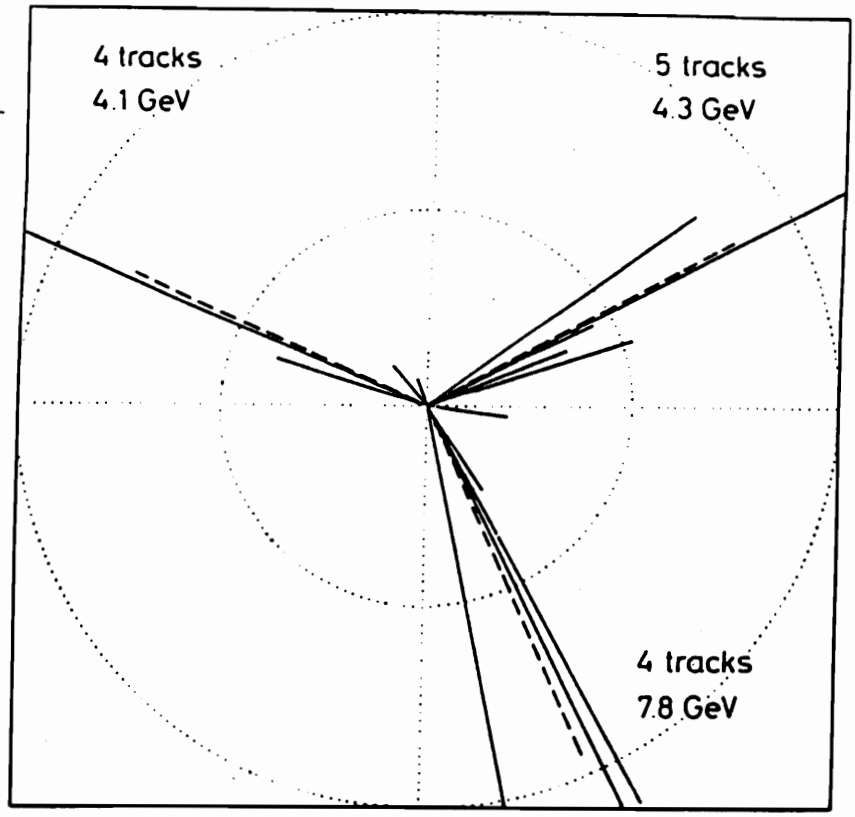


Figure 30: Sketch of particle tracks in an early three-jet event in electron-positron annihilation. From Ref. 321.

its antiquark in the same way that the J/ψ is a charm-anticharm bound state. Had the three-gluon decay of the Υ been seen? It was not clear whether the data were really showing three distinct gluon jets, or just effects of data selection. The higher energies of two new electron-positron colliders, PETRA in Hamburg and PEP at Stanford, allowed a much crisper search for gluon jets. QCD predicted a *third* jet, corresponding to the emission of a gluon by one of the final-state quarks, in a fraction of e^+e^- annihilations into hadrons. This gluon jet should be identifiable if emitted at a sufficient angle with respect to one of the quarks.

A technique for identifying gluon jets[320] was proposed by Wu and Zobernig, members of the TASSO Collaboration at PETRA. A pretty picture of a three-jet event (see Fig. 30) was presented at international conferences during the early summer of 1979[321]. At the Lepton-Photon Symposium at Fermilab in August of 1979, all four groups working at PETRA presented evidence for three-jet events.

As available center-of-mass energies increased, spectacular particle jets at large angles with respect to the initial beams were observed at the CERN SPS Collider[322] and the Fermilab Tevatron[323]. The decays of Z bosons to hadrons seen at LEP have yielded vast samples of events with three, four, and even more jets. The rate for $n+1$ jets is related to that for n jets by one power of α_s, permitting

an estimate $\alpha_s(M_Z) \approx 0.12 \pm 0.01$ from multi-jet production rates compatible with that from deep inelastic scattering.

8.6 Other applications

8.6.1 Quarkonium decays. Bound states of charmed quarks such as the J/ψ, mentioned in Sec. 7, provided the first laboratory for application of perturbative QCD to decays[324]. These studies were helped greatly by the discovery of the fifth quark b and of the corresponding $b\bar{b}$ bound states such as the Υ (Sec. 9). One can measure $\alpha_s(m_b)$, for instance, by comparing decays such as $\Upsilon \to 3g$ (g = gluon) and $\Upsilon \to 2g + \gamma$. With higher-order QCD corrections, the result[317] is $\alpha_s(m_b) \approx 0.19$, corresponding to $\alpha_s(M_Z) \approx 0.11$.

8.6.2 Hadron production in electron-positron annihilations. The lowest-order QCD correction to the ratio R characterizing hadron production in electron-positron annihilations (Sec. 6.3) amounts to a factor $1 + (\alpha_s/\pi)$. Data taken over a wide range of center-of-mass energies, ranging from several GeV to M_Z, are indeed consistent with this correction.

8.6.3 Counting rules. Differential cross sections at high energies and fixed angles[325] behave in ways which may be derived from QCD by tracing the flow of high momentum transfers through diagrams for scattering at the quark level.

8.6.4 Nonperturbative effects. Not all phenomena in high-energy collisions are understood quantitatively within the framework of QCD. Scattering at small momentum transfers is still most economically described within the framework of Regge poles (Sec. 5.4). The Pomeranchuk trajectory may reflect exchanges of a pair (or more) of gluons[326]. The rise of total cross sections at high energies[327] is a topic of interest, with recent data summarized in Fig. 31.

Multiple particle production[327b] in hadronic interactions displays simple regularities understood mainly on a phenomenological basis. The *rapidity* of a particle may be defined as $y \equiv (1/2)\log[(E+p_z)/(E-p_z)]$, where E is its energy and p_z its momentum along the beam axis. A hadronic collision leads to a number of particles per unit rapidity growing only slightly with increasing energy. A qualitative understanding of this behavior exists on the basis of quark fragmentation[328].

QCD has thus proved able to describe a wide variety of strong interaction phenomena. Although QCD only permits perturbative calculations at energies and momenta above one or several GeV, this aspect should not be held against its validity. Methods for dealing with the nonperturbative regime, including include lattice gauge theories[329] and QCD sum rules[330], are being actively pursued.

9. THREE FAMILIES OF QUARKS AND LEPTONS

9.1 The tau lepton

9.1.1 Discovery. The repetitive structure of the leptons (electron and its neutrino, muon and its neutrino) stimulated searches for additional "sequential" doublets, consisting of a heavy charged lepton and its neutrino, with negative results

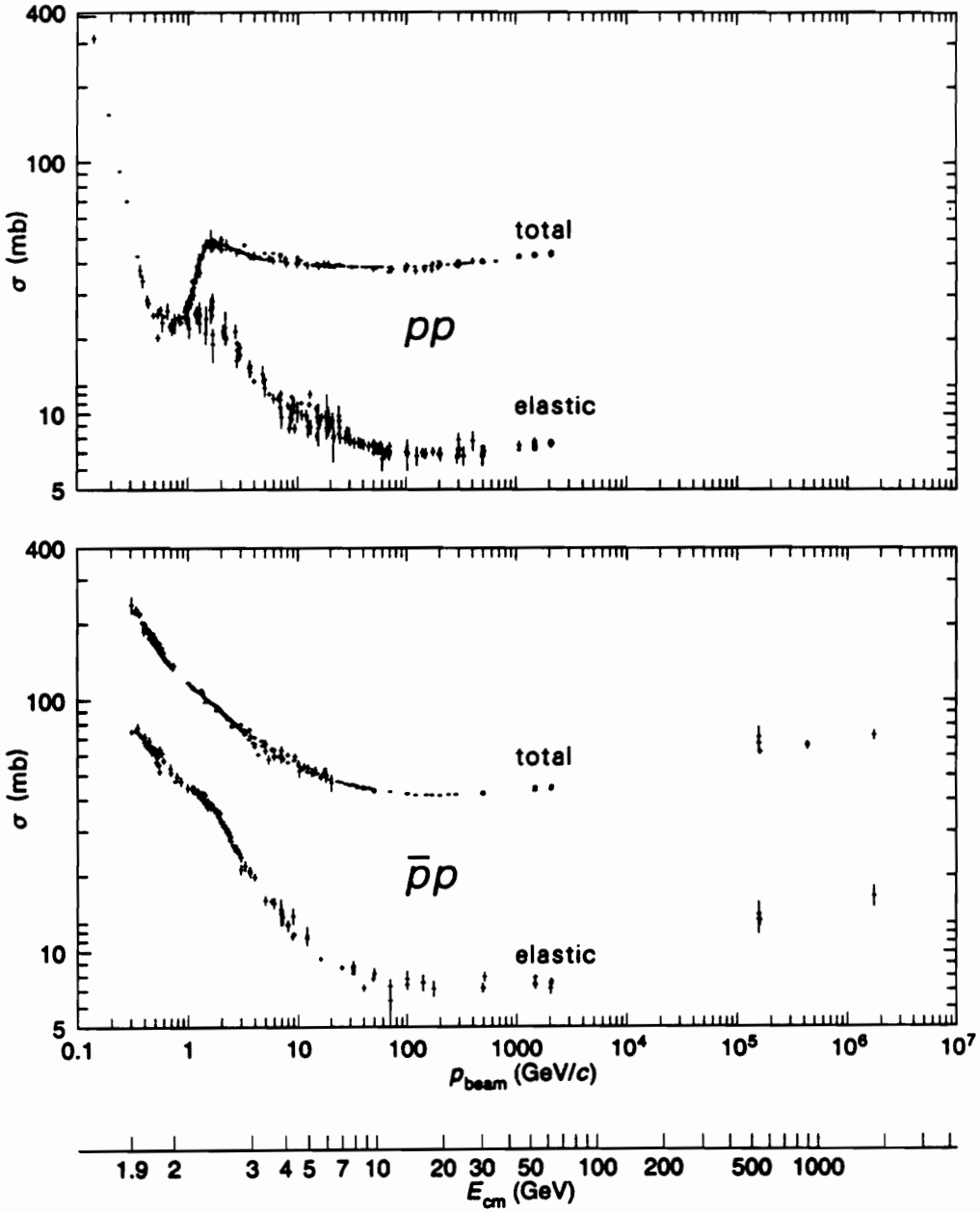


Figure 31: Total and elastic pp and $\bar{p}p$ cross sections as functions of energy. From Ref. 327a, p. III.84.

up to the early 1970s[331]. Around that time, several theorists[332] worked out the consequences of heavy charged leptons. The process $e^+ + e^- \to \ell^+ + \ell^-$, under scrutiny at new electron-positron colliders, was one way to produce these leptons.

The Cambridge Electron Accelerator (see Sec. 6.3) reported in the summer of 1973 that the ratio $R = \sigma(e^+ + e^- \to \text{hadrons})/\sigma(e^+ + e^- \to \mu^+\mu^-)$ at center-of-mass energies of 4 and 5 GeV exceeded the value of 2 expected for u, d, and s quarks[239]. These results were confirmed by the SPEAR Collider later that year[333]. The charmed quark, discovered in 1974 (Sec. 7), accounted for part of the rise in R. It contributed 4/3 to R, leading to a total of $3\frac{1}{3}$. However, the SPEAR results above 4 GeV indicated values of R well in excess of 4.

Other curious features of the SPEAR data at and above 4 GeV appeared not to be attributable to charmed-particle production. Events with an electron, a muon of opposite charge, no other charged particles, and missing energy suggested production of a pair of new leptons: $e^+ + e^- \to \tau^+ + \tau^-$, with one of them decaying to $e\nu\bar{\nu}$ and the other to $\mu\nu\bar{\nu}$. This signature had been sought earlier at the ADONE electron-positron collider at Frascati[331], but below threshold for τ pair production.

Confidence in the existence of the new lepton grew over the next few years[292]. Initial failure to detect a crucial decay mode, $\tau \to \pi\nu$, at the DORIS storage rings at DESY in Hamburg led to some skepticism as late as 1977, but confirmation of this and other modes by the DESY experiments followed soon thereafter[334].

The τ was a truly new discovery in not having been anticipated by any direct theoretical prediction. It was the first member of a third family of quarks and leptons.

9.1.2 Properties. The τ decays to a ν_τ (whose existence remains inferred, having not been detected directly) and a virtual W boson, materializing into $u\bar{d}$, $u\bar{s}$ (with reduced rate), $e\bar{\nu}_e$, or $\mu\bar{\nu}_\mu$. Decay rates for these final states are consistent with the standard weak interaction theory, leading to an overall lifetime of about 0.3 ps. The ratio of the $u\bar{d}$ rate to the $e\bar{\nu}_e$ or $\mu\bar{\nu}_\mu$ rate, a factor of three times a small correction, provides further evidence for three colors of quarks. Ref. 335 provides a sample of the physics that may be learned from the increasing precision in the measurement of τ properties.

9.2 The fifth quark

9.2.1 Kobayashi and Maskawa's suggestion and its implications. Spurred by hints of charmed particles in nuclear emulsions[281] (Sec. 7.4.1), M. Kobayashi and T. Maskawa[282] asked: As long as there seemed to be two families of quarks and leptons, why not three? A third family of quarks would permit the parametrization of CP violation by introduction of a non-trivial phase in the charge-changing weak couplings of quarks.

The search for the charmed quark had been partly motivated by the existence of two families of leptons, a family structure being particularly appropriate for cancelling triangle anomalies[280] (Sec. 7.3). Thus, a third doublet of quarks would imply a third doublet of leptons, and vice versa. Following the τ's discovery, it

was then natural to expect a third quark of charge $-1/3$ (in addition to d and s) named b for "bottom," and a third quark of charge $2/3$ (in addition to u and c) named t for "top" (in analogy to "down" and "up"). The quantum number carried by the b quark has been referred to as "beauty."

Some false alarms and harbingers of the true signal marked the search for the third family of quarks. An apparent anomaly in deep inelastic antineutrino scattering[336] suggested that a threshold for production of the b quark had been crossed. (This effect, not confirmed in other experiments, was later understood in terms of instrumental bias.) A search at Fermilab for particles heavier than the J/ψ decaying to lepton pairs yielded an apparent peak ("Υ") at 6 GeV in the e^+e^- channel, not confirmed in the $\mu^+\mu^-$ channel. However, a peak at 9.5 GeV/c^2 in that channel tempted John Yoh, then a postdoctoral fellow working on the experiment, to put a bottle of Mumm's champagne labelled "9.5" (to be opened presently) in the group's refrigerator[337]. Another group, also studying muon pairs at Fermilab, had a single event at 9.5 GeV/c^2, labelled affectionately "Big Mac." The $\mu^+\mu^-$ spectrum in the 1976 experiment of Ref. 337a showed a small anomaly around 10 GeV/c^2.

9.2.2 Discovery of the Upsilon family. The study of hadronically produced leptons at Fermilab evolved through several stages, culminating in Experiment E-288, dedicated to the study of high-mass lepton pairs, under the leadership of Leon Lederman. After the false alarm of the Υ at 6 GeV in 1976 and a fire in the spring of 1977 whose damage was quickly repaired, the group began running with high intensity and improved resolution in the late spring of 1977. The data soon proved that John Yoh's bottle of champagne had been correctly labelled. Not only was there a peak at 9.5 GeV/c^2, but another smaller one seemed to be riding on its tail, about 0.6 GeV/c^2 higher[338] [see Fig. 32(a)], in a manner reminiscent of charmonium, for which the ψ' lies about 0.6 GeV/c^2 above the J/ψ. In contrast to charmonium, however, there appeared to be *three* narrow peaks[339]. Called $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, they correspond to the first, second, and third S-wave systems of a heavy quark bound to the corresponding antiquark. [Fig. 32(b) shows a recent spectrum.]

The partial width of the Υ for decay into pairs of leptons, measured at the DORIS storage rings[340], suggested that this particle consisted of quarks with charge $-1/3$, a conclusion strengthened upon observation of the second peak[341], the Υ', whose hadronic parameters were predicted with greater confidence. Once the threshold for production of mesons containing a single heavy quark was passed, the ratio R in e^+e^- rose by 1/3, confirming the new quark's charge of $-1/3$ and identifying it with the b. The Υ and its excited levels were $b\bar{b}$ states.

9.2.3 Beauty mesons. The 12 GeV Cornell Electron Synchrotron, first operated in 1967, was converted in the late 1970s to the Cornell Electron Storage Ring (CESR), with beam energies of up to 8 GeV for electrons and positrons. This machine could not have come at a more opportune time, detecting the $\Upsilon(1S)$,

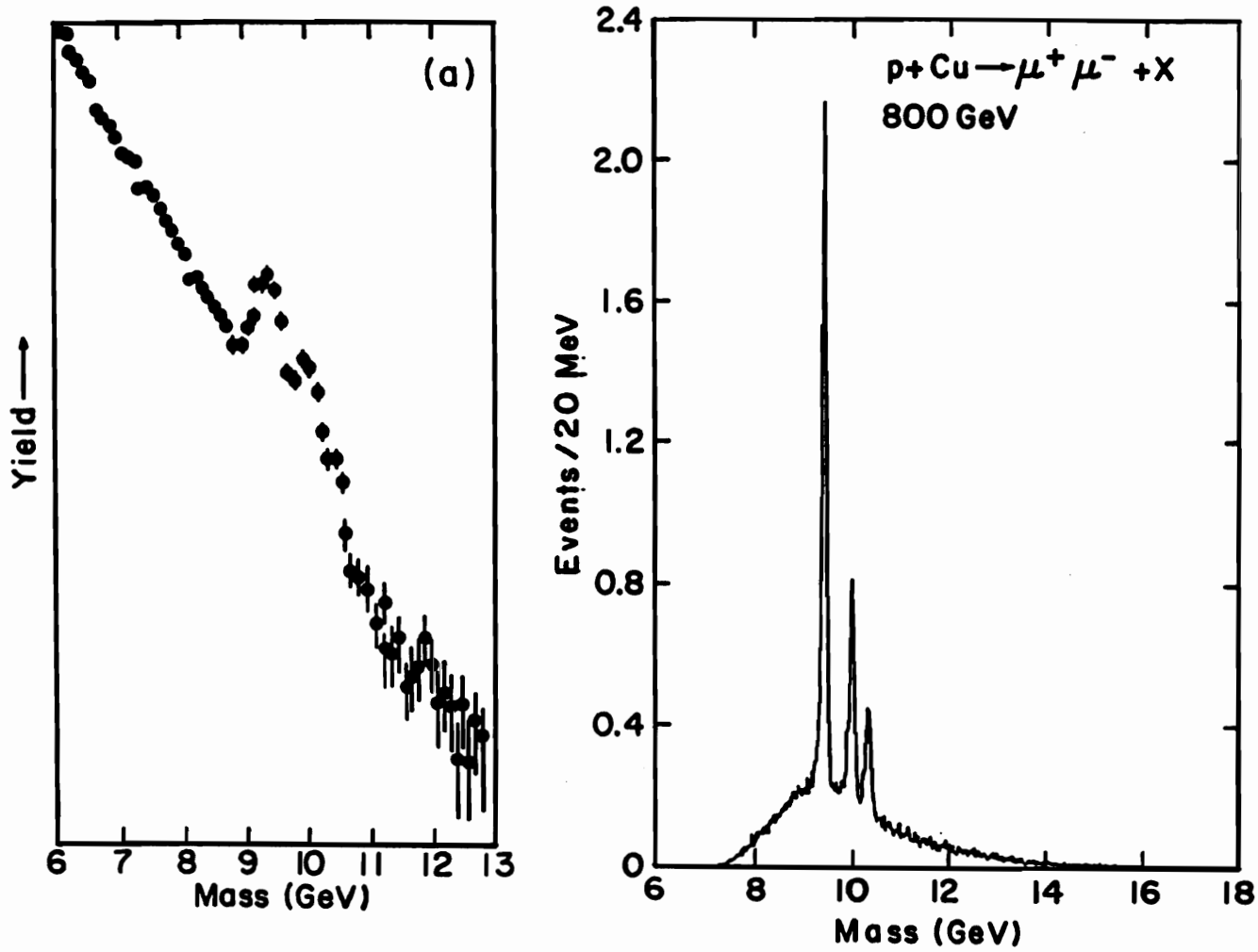


Figure 32: Evidence for the Υ resonances in hadronic interactions. (a) From Ref. 338; (b) a recent spectrum from the second of Refs. 339.

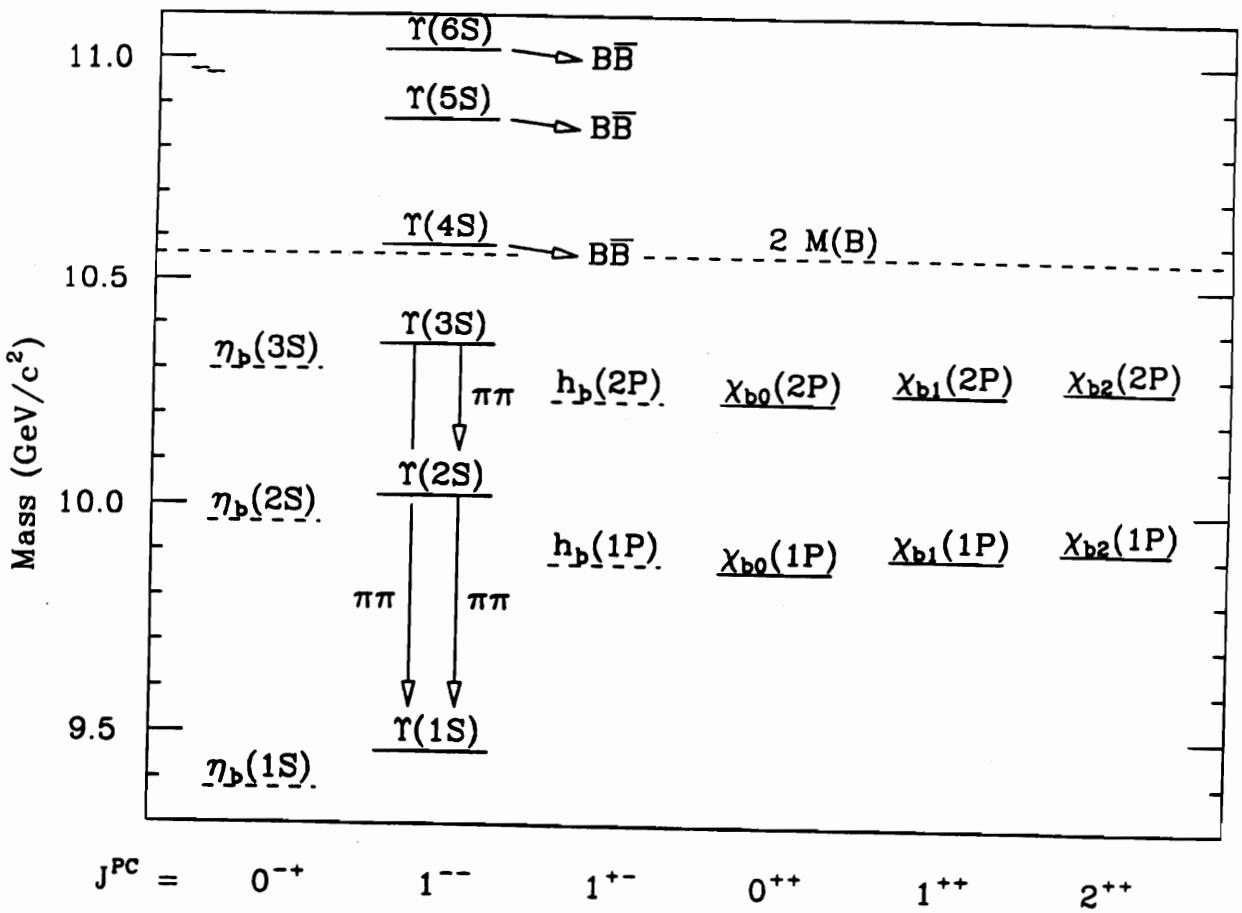


Figure 33: The spectrum of $b\bar{b}$ states. Observed and predicted levels, as quoted in Ref. 298b, are denoted by solid and dashed horizontal lines, respectively. In addition to the transitions denoted by arrows, numerous electric dipole transitions have been seen between the Υ and χ_b states, e.g. 3S $\rightarrow$ 2P $\rightarrow$ 2S $\rightarrow$ 1P $\rightarrow$ 1S, 3S $\rightarrow$ 1P (very weak), and 2P $\rightarrow$ 1S.

$\Upsilon(2S)$, and $\Upsilon(3S)$ in short order. At higher energy a fourth Υ level was seen, with a natural width[342] indicating its decay into pairs of b-flavored mesons, now called B mesons. These new mesons were first identified by the presence of a lepton and additional kaons (corresponding to the weak decay of a b quark) in their decay products[343]. Reconstruction of specific decay channels[344] yielded a B meson mass around 5.28 GeV/c^2. Since the threshold for production of a pair of B mesons is twice this value, the $\Upsilon(4S)$, at a mass of 10.575 GeV/c^2, is thus ideal for producing pairs of B mesons nearly at rest.

9.2.4 Spectroscopy of the b quark. The present state of our knowledge about $b\bar{b}$ levels is summarized in Fig. 33. At least six sets of S-wave levels and two groups of P-wave levels have been identified, all spin-triplets thus far. Their electromagnetic

transitions to spin-singlet levels require a b quark spin to flip, and are expected to occur with rates below present levels of sensitivity.

The $b\bar{b}$ system exhibits the interplay of short-range and long-range effects in QCD[345,346]. The interquark potential combines the short-range Coulomb-like behavior expected from single gluon exchange with the long-range linear behavior proposed by Nambu[315].

9.2.5 Decays of particles with b quarks. Once the b quark was identified, its charge-changing weak decays were seen to favor the c quark and not the lighter u quark[347], a conclusion reached on the basis of the emitted leptons' momentum spectrum. The decay $b \to u\ell\bar{\nu}_l$, initially not detected at all, was eventually identified at the level of about 1–2% of the $b \to c\ell\bar{\nu}_l$ process[348]. Considering the different phase space available for the two decays $b \to c\ell\bar{\nu}_l$ and $b \to u\ell\bar{\nu}_l$, the result implies a ratio of $b \to u$ and $b \to c$ couplings of betweewn 0.05 and 0.1.

Another peculiar feature of b quark decays lies in the relative weakness of the $b \to c$ weak coupling. Charmed mesons, with masses below 2 GeV/c^2, live for about 0.4 to 1 ps, depending on the light quark they contain. By contrast, mesons with a b quark live for about 1.5 ps on the average[349], in spite of their much larger masses. This curiously long life of the b quark was first observed by the MAC Collaboration at SLAC under the leadership of David Ritson[349a].

9.3 The Cabibbo-Kobayashi-Maskawa (CKM) matrix

9.3.1 Role in CP violation. The charge-changing couplings of quarks in the three-family model of Kobayashi and Maskawa[282] can be expressed in terms of a 3×3 matrix with rows pertaining to the charge $-1/3$ quarks d, s, b and columns to the charge $2/3$ quarks u, c, t. The unitarity of this matrix, required by its role in the diagonalization of quark mass matrices, implies the absence of flavor-changing neutral currents, just as for the two-family model.

For n quark families, a unitary $n \times n$ matrix has n^2 real parameters. For $n = 2$, a single angle (the Cabibbo angle) suffices to specify the matrix, the remaining three parameters setting relative quark phases. Three families require four real parameters in addition to five arbitrary relative quark phases.

A convenient parametrization of the CKM matrix[350] is

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} ,$$

with A, ρ, and η of order unity. Only the leading orders of the matrix elements are displayed here. The matrix is unitary as written up to order λ^4. The violation of CP invariance is represented by the nonzero value of η, at least three families of quarks being needed for this purpose.

9.3.2 Experimental information on matrix elements. The parameter $\lambda \approx 0.22$ is the sine of the Cabibbo angle, well-known from the analysis of strange parti-

cle decays. Information on the b quark lifetime places A around 0.8, while the measurement $|V_{ub}/V_{cb}| = 0.05 - 0.1$ implies $(\rho^2 + \eta^2)^{1/2}$ between 1/4 and 1/2.

Individual values of η and ρ are less well known. Values of ρ between -0.4 and 0.4 and of η between 0.2 and 0.6 are compatible with present data. Indirect information is provided by CP violation in the kaon system and by mixing of the neutral B meson $\bar{B}^0 \equiv b\bar{d}$ with its antiparticle $B^0 \equiv \bar{b}d$, first discovered in 1987[351]. Uncertainties plaguing the estimates of η and ρ from these diagrams include errors in the top quark mass ($m_t = 174 \pm 17$ GeV/c^2; see below), and in various hadronic matrix elements, for which estimates from lattice gauge theories[329] and QCD sum rules[330] are beginning to be useful.

A "superweak" theory[161] (independent of η in the CKM matrix) can still account for all the CP-violating phenomena observed in the kaon system. Two main checks of the CKM theory of CP violation hinge on rare decays of kaons and on the search for CP-violating B decays[352].

Detection of a difference between the ratios of the amplitudes for decay of K_L and K_S into pairs of charged and neutral pions would provide evidence against the superweak model, as mentioned in Sec. 5.2.3. Searches for this difference have achieved a level of several tenths of a percent. Two experiments[162,163] give different answers on this detection; improved versions of both experiments are planned.

The study of B meson decays has been pioneered by detectors in e^+e^- colliders (see Fig. 34) such as ARGUS at DESY and CLEO at CESR. More luminous e^+e^- sources of B mesons, with an energy asymmetry useful in studying time-dependent decay effects, are now being planned at several laboratories. It is also becoming possible to isolate B hadron signals from intense backgrounds in hadron colliders.

9.4 On the trail of the top quark; observation

Although the family structure of quarks and leptons is simple and repetitive, the b quark could have broken away from this pattern, just as the transition metals are associated with variation in the periodic table of the elements. However, several pieces of data indicated that the b quark had to be a member of a doublet of weak SU(2).

If the b quark were a singlet, flavor-changing neutral decays such as $b \to s\mu^+\mu^-$ would occur with a rate much higher than anticipated in standard electroweak theory[353]. No such enhanced rate has been observed. Furthermore, the cross section and forward-backward asymmetry in the reaction $e^+ + e^- \to b + \bar{b}$, over a range of energies, imply that the b is a doublet member, just like the d and s. The self-consistency of calculations based on box diagrams for mixing of neutral B mesons with their antiparticles also supports the existence of a heavy top quark.

Ever since the discovery of the b, searches for the top continued at electron-positron colliders such as PEP (Stanford), PETRA (Hamburg), TRISTAN (Japan), and LEP (CERN), and hadron colliders at CERN. With the higher hadronic collision energies available at Fermilab, in a *tour de force* of analysis involving several different decay modes, the CDF Collaboration now has presented evidence for a

Figure 34: The ARGUS (top) and CLEO (bottom) detectors. (Courtesy of *CERN Courier.*)

top quark[307a] with a mass of $m_t = 174 \pm 10^{+13}_{-12}$ GeV/c^2. The D0 Collaboration has a few similar events[354] but cannot distinguish them from background.

The effect of a large top quark mass on electroweak parameters was first pointed out by Veltman[355]. Virtual top quark contributions to W and Z self-energies alter the lowest-order predictions of the ratio $M_W^2/M_Z^2 = \cos^2\theta$ and the Z mass itself. Since independent (very accurate) determinations of the electroweak angle θ and the Z mass exist, for instance from LEP experiments, the top quark had been anticipated to lie below about 200 GeV/c^2. The measurement of its mass within these bounds was a striking confirmation of the electroweak theory, and indirectly places bounds on other effects such as Higgs bosons.

10. ACCELERATORS

Our knowledge of the nucleus and, subsequently, of elementary particles has closely paralleled the development of particle accelerators at higher and higher energies. An excellent and detailed review of accelerator development up to the time of colliding beams (ca. 1960) has been given by two of the principal participants in this effort, Livingston and Blewett[356]. For each type of machine, we give here only a few examples of those actually constructed around the world.

10.1 Electrostatic generators

The first nuclear reactions produced by protons accelerated to high voltages bombarding a target at rest in the laboratory were observed by Cockcroft and Walton[357]. Their work was directly stimulated by the theoretical work of Gurney and Condon and of Gamow on barrier penetration. To produce the required voltage, they developed a scheme to multiply a transformer's output voltage through an ingenious arrangment of rectifying diodes and capacitors. Whereas nearly any multiplying factor can be achieved, the technical advantage lay in the fact that if the transformer's secondary produced a voltage V, no capacitor or rectifier was required to withstand a voltage greater than $2V$.

The more difficult technical problem at the time was posed by the need to provide an ion source at the high voltage and a tube evacuated of air through which the ions could be accelerated. The tube had to be insulated to withstand the high potential between the ion source and the target, with suitable arrangements for a uniform potential gradient along the tube to minimize spurious electrical discharges.

Cockcroft and Walton's incredible technical feat was recognized with a Nobel Prize in 1951. Until the advent of radio frequency quadrupoles, their accelerator served as the low voltage stage of every proton accelerator. While theirs was not the first scheme for voltage multiplication, it was superior, their device becoming unversally known as the Cockcroft-Walton generator.

The other static voltage souce widely used for the acceleration of nuclear particles was the electrostatic generator of Van de Graaff[358]. While a Rhodes scholar

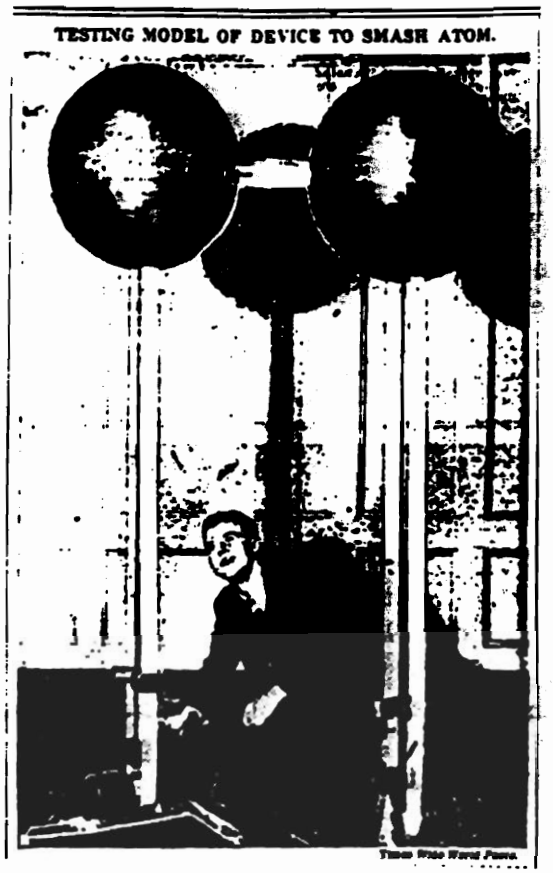


Figure 35: Robert Van De Graaff and one of the earliest versions of his generator (courtesy of Times Wide World Photo and Niels Bohr Library, AIP).

at Oxford in 1927-28 Van de Graaff had become interested in the possibility of producing high voltages by belt-charging. On his return to the United States as a National Research Council Fellow at Princeton University, he constructed his first models (Fig. 35), one for positive and one for negative potentials. Each consisted of a motor at the base turning a pulley which drove an insulating belt. The belt passed vertically about 7 feet into a copper sphere about 24 inches in diameter which contained the return pulley. The sphere and return pulley arrangement was supported on a glass tube about 2 inches in diameter. Charge was "sprayed" on the belt at the bottom and removed in the sphere at the top with brushes.

Van de Graaff's first two generators were used for many years at Princeton in freshman physics demonstration lectures. Eventually one of them was given to the Smithsonian Institution for exhibit on the condition that they supply a duplicate to allow the demonstrations to continue. Subsequently, the duplicate model (made with modern materials) has not performed as well as the original, a wonderful testimony to the inventor's skill.

The Van de Graaff generators were immediately successful at producing high

voltages with relative ease. However, as with the Cockcroft-Walton generator, combining the source of high voltage with an ion source and accelerating column presented a daunting technical problem. With Van de Graaff's success, a number of groups became interested in adapting the generator to particle acceleration. Among these were Ray Herb and his group at Wisconsin, Merle Tuve and his group at the Carnegie Institution in Washington, and Compton and Van Atta at MIT, who, joined by Van de Graaff[359], produced a machine which developed a potential of 5.1 MV. At more modest voltages the groups at Wisconsin[359a] and the Carnegie Institution[360] produced the first practical Van de Graaff generators for accelerating particles. With their machine the Carnegie group made the first excitation measurements showing sharp nuclear resonances.

Electrostatic generators have been adapted to accelerate electrons and to produce high energy X-rays. In this capacity they have extensive industrial and medical usage. In nuclear physics, they have long had the advantage of excellent voltage stability, permitting good control of beam energy in precision measurements of nucleon-nucleon scattering. More recently, the development of negative hydrogen ion sources has permitted the construction of so-called tandem generators. These machines accelerate negative hydrogen ions from ground to a high positive potential where a thin foil strips them of their two electrons; the positive ions are then accelerated back to ground, thereby doubling their energy. Despite these developments, machines relying on high static voltages have been limited to around 50 MeV, restricting them to nuclear physics studies.

10.2 The cyclotron

Concurrently with the development of the static high voltage machines, work began on resonant cyclic accelerators. The first of these, a linear machine designed and constructed by Wideröe[361], consisted of three cylindrical tubes positioned end to end and electrically insulated from each other. A radio-frequency voltage was applied to the central tube, properly phased to accelerate an ion traveling from the first to the second tube. By adjusting the radio frequency to reverse the voltage during the ion's transit down the middle tube, the ion was again accelerated when passing from the second to the third tube. Reading about this device in the library at Berkeley, E. O. Lawrence realized that the ions might be recycled through the radio-frequency voltages again and again by bending the particles back on their original path with a magnetic field. He quickly saw that the angular frequency of revolution of an ion in a circular path in a magnetic field, $\omega = eB/mc$, remains constant, independent of radius and momentum! In such a way the cyclotron and a whole class of magnetic resonant machines were born[362].

The first cyclotron applied to physics research had magnetic pole pieces 10 inches in diameter, producing protons over 1 MeV in energy. It came into operation in 1932 a few months after the disintegration of lithium by protons was announced by Cockcroft and Walton, confirming their results immediately[363].

A number of features important to successful cyclotron operation were not

recognized at the beginning. Happily, the device worked anyway. The cyclotron angular frequency, $\omega = eB/mc$, remains constant only as long as B and m do not change. Countering the requirement of constant B is the need for some vertical focusing to prevent ions with some initial vertical velocity from striking the pole tips of the magnet before undergoing a significant number of rotations. Vertical focusing requires the field to fall off with increasing radius. Fortunately for the cyclotron inventors, any magnet with circular pole tips will, barring heroic attempts at field shaping, naturally show a small decrease of field with radius, thus providing some vertical focusing. At the same time, the change of field with radius should not be so great as to violate the cyclotron equation grossly. This too was the case in the first cyclotron. In addition, relativistic effects cause the mass to increase with energy. Again providence smiled on the inventor, since this effect does not beome limiting until a proton's energy reaches about 25 MeV.

After the cyclotron's success at Berkeley, many similar machines were constructed throughout the world. In the 1930s every research university in the country arranged to have a cyclotron for nuclear physics studies. Berkeley, of course, showed the way, with larger and larger cyclotrons. This activity culminated with the construction of a 184 inch giant, completed only after World War II.

10.3 Phase stability and the synchrocyclotron

Shortly after the war, McMillan at Berkeley and Veksler in the Soviet Union independently showed that the conflict between requiring the field to decrease with radius for vertical focusing and increase with radius to compensate for the relativistic mass increase could be resolved by changing the frequency during ion acceleration[364]. To quote from McMillan's paper:

> "The device proposed here makes use of a 'phase stability' possessed by certain orbits in a cyclotron. Consider, for example, a particle whose energy is such that its angular velocity is just right to match the frequency of the electric field. This will be called the equilibrium energy. Suppose further that the particle crosses the accelerating gaps just as the electric field passes through zero, changing in such a sense that an earlier arrival of the particle would result in an acceleration. This orbit is obviously stationary. To show that it is stable, suppose that a displacement in phase is made such that the particle arrives at the gap too early. It is then accelerated; the increase in energy causes a decrease in angular velocity, which makes the time of arrival tend to become later. A similar argument shows that a change of energy from the equilibrium value tends to correct itself. These displaced orbits will continue to oscillate, with both phase and energy varying about their equilibrium values.
>
> "In order to accelerate the particles it is now necessary to change the

value of the equilibrium energy, which can be done by varying either the magnetic field or the frequency. While the equilibrium energy is changing, the phase of the motion will shift ahead just enough to provide the necessary accelerating force; the similarity of this behavior to that of a synchronous motor suggested the name of the device...."

The advantages of phase stability far exceeded its single disadvantage of requiring the frequency to change during the time the particles are acquiring energy. The ions are injected at the high frequency end of the cycle, and the frequency is reduced during the acceleration. The ions are finally brought to an internal target or ejected from the machine at the highest energy (lowest frequency). The frequency cycle is then repeated. Since ions can only be accepted for acceleration during a small part of the whole frequency cycle, the beam intensity will accordingly be much lower, about 1% of that in conventional cyclotrons.

It did not take long for the fundamental soundness of the idea to be lastingly recognized. The ideas expressed by McMillan have been invoked in every subsequent accelerator. Immediately after World War II the 184 inch cyclotron, after some modelling studies, was converted to a "synchrocyclotron." It first came into operation in November, 1946, accelerating deuterons to 190 MeV and, later, protons to 350 MeV. It was thus an enormous success from the beginning, followed between 1948 and 1952 by five additional synchrocyclotrons with energies ranging from 150 to 450 MeV constructed at various universities in the U.S. and a further six elsewhere in the world. The physics pouring from these accelerators was immense, primarily because their energy exceeded in most cases the 290 MeV threshold for creating pions. With these machines the properties of the pion and the muon were elucidated in detail. Pionic and muonic atoms were discovered and quantitative measurements on these new kinds of atoms were made. Parity violation was observed and thoroughly explored in the pion-muon-electron decay chain. It was a fantastically productive period in the history of particle physics.

10.4 Electron synchrotrons

The concept of phase stability was also exploited in electron accelerators, leading to the first electron synchrotrons. Synchrotrons accelerate particles in orbits of constant radius. After an electron's energy has reached 4 – 5 MeV its speed is essentially that of light so that the transit time around an orbit of fixed radius is nearly constant, requiring minimal change in the frequency of the accelerating voltage. Therefore, use of a separate system such as a Van de Graaff generator for preacceleration to a few MeV simplifies the subsequent synchrotron design enormously.

The acceleration of electrons in circular guide fields is accompanied by significant loss of energy to radiation. This loss implies a smaller orbit and a smaller transit time around the ring. If the particles are accelerated on the falling side of the radio-frequency voltage those particles arriving earlier will be accelerated by

higher voltages thereby compensating for the radiation loss. Under the guidance of McMillan the the first electron synchrotron was started in Berkeley in 1946 and completed in 1949, producing electrons of 335 MeV. Experiments using the photons from the electrons impinging on Pb were immediately started and the first photoproduced charged pions were quickly detected[365]. A major result from this machine was the discovery of the neutral pion[63] in 1950 [cf. Sec. 4.2]. As with the synchrocyclotrons, electron synchrotrons were constructed at many universities, most of them in the range of 300 MeV. They were responsible for tracing out the full peak of the famous (3,3) resonance, mentioned in Sec. 4.5.2.

10.5 The betatron

Independently of all the activity devoted to electron synchrotrons, in fact back in 1940, the first successful betatron was developed by D. W. Kerst[366] with an energy of 2.3 MeV. The electric field associated with a changing magnetic field served to accelerate electrons, while the same magnetic field guided the particles, a combination which would seem fairly obvious. However, the attendant technical problems turned out to be severe, thwarting many attempts before Kerst's. His machine followed the detailed magnet design based on elaborate orbit calculations by Kerst and Serber[367]. An interesting technical point about the betatron has become a favorite examination question in courses in electricity and magnetism: It is easily shown that, for a constant orbit radius, the magnetic field at the orbit must be just one-half the average magnetic field linked by the orbit. One problem associated with extrapolating the betatron principle to high energies lies in maintaining this factor of 2 in the face of iron saturation, etc. The development of the betatron culminated with the construction at the University of Illinois of a 300 MeV device, completed in 1950[368]. We have already noted the desirability of pre-acceleration of electrons in a synchrotron by, for example, Van de Graaff generators. Another even more popular method was pre-acceleration of the electrons in the synchrotron itself using the betatron principle.

10.6 Proton synchrotrons

By 1948 it had become clear that achieving still higher energy protons than accessible by synchrocyclotrons would hinge on the synchrotron principle. Cyclotrons require the quantity of magnetic iron to increase roughly as the cube of the maximum proton momentum, whereas synchrotron requirements scale only linearily with the momentum. The cross-over had already been reached with cyclotrons under construction. The U.S. Atomic Energy Commission planned to construct two machines; one on Long Island at the newly created Brookhaven National Laboratory in the energy range of 2 – 3 GeV and the other with 5 to 6 GeV at Berkeley.

The previous considerations of electron synchrotrons make it clear why physicists were more timid in proceeding with proton machines, whose required frequency change was larger. Furthermore, it was necessary to synchronize the fre-

quency closely with the instantaneous magnetic field. At the Brookhaven machine (ultimately named, somewhat grandiosely, the Cosmotron) the protons were injected from a Van de Graaff generator with 4 MeV energy. The initial machine design involved a magnetic field of 311 gauss and a frequency of rotation around the magnet ring of 0.4 megahertz at injection. At the full energy, 3 GeV, the average field reached 13 kilogauss with a frequency of 4.2 megahertz. In contrast to the early electron machines, whose acceleration time was typically 5 milliseconds, the period of acceleration was 1 second, allowing the final energy of 3 GeV to be reached with only about 2 kilovolts of accelerating voltage per turn.

The Cosmotron started operating in 1952 at 2.3 GeV. Almost immediately it began producing noteworthy physics, such as the first observation of associated strange particle production (cf. Sec. 4.4). Early in 1954 it started operating at its full design energy of 3 GeV.

The Berkeley synchrotron, called the Bevatron (a name based on the earlier abbreviation for GeV), reached its design energy of 5.4 GeV in October 1954. It could be pushed to 6.4 GeV at a lower cycling rate. Ostensibly the design energy of the Bevatron was chosen to exceed the antiproton production threshold, which is 5.6 GeV for protons striking protons at rest. Appropriately, antiprotons produced in the Bevatron were found by the Chamberlain-Segré group[68] in 1955 (cf. Sec. 4.3).

10.7 Strong focusing

At the 1952 January meeting of the American Physical Society, held on the campus of Columbia University in New York City, a highlight was an invited talk by Enrico Fermi[369], describing research in progress at the University of Chicago's 450 MeV synchrocyclotron which had started operation the preceding year. It was the highest energy accerator then in operation. Near the end of his talk Fermi described, in jest, the ultimate accelerator of the future, a machine circling the earth.

Another talk at this same meeting contained the seeds of an idea that made ultra-high energy accelerators possible. Quoting from the abstract[370] of a paper describing the original pair of quadrupoles devised to focus the external beam of the Princeton cyclotron:

> "Under these conditions, because of the curvature of the fringing field, their focal lengths in the plane of the field are very nearly equal, but opposite in sign, to their focal lengths in the plane of the pole faces. However, if two of these astigmats are spaced a distance comparable with their focal lengths with their field directions orthogonal, a point image of a point source may be obtained. If the source distance, the separation of the astigmats, and the desired image distance are specified, the focal lengths required for double focusing can be reliably calculated from the thin lens equation."

This is the first published reference to a principle eventually called strong--focusing. This idea was quickly exploited by the early summer of 1952 to focus external pion beams at Columbia's Nevis cyclotron[371].

Strong magnetic focusing was in the air. In a highly influential paper, Courant, Livingston and Snyder showed how that principle could be used with great advantage in the design of synchrotrons[372], demonstrating in particular that strong focusing, implemented by alternating the gradient of the magnetic field guiding the particles, could be maintained in the closed orbits required in accelerators, that phase stability would persist, and that the large "momentum compaction" would result in relatively small beam displacements in spite of rather large momentum spreads. This paper also created a magnetic quadrupole design which would not produce a net bending of the beam, a disadvantage of the original design by the Princeton group.

It developed that Nicholas Christofilos, an electrical engineer working in Greece, had applied in 1950 for a U.S. patent on a conceptual design for an accelerator using alternating gradient focusing. His seminal contribution went unrecognized because his work was never published, but his patent (awarded February 28, 1956) is contained in Ref. 373.

Following the prescriptions supplied in the Courant, Livingston and Snyder paper, designs of two alternating gradient synchrotrons to operate at about 30 GeV, one at Brookhaven and one at CERN, were immediately started. However, the first accelerator to employ the alternating gradient strong-focusing principle, producing 1.1 GeV electrons in 1954, was constructed under the direction of R. R. Wilson at Cornell University. The 28 GeV machine at CERN (called the Proton Synchrotron or PS) started operations in 1959, while at Brookhaven experiments were begun in 1960 with the machine (the AGS) operating at 33 GeV and still in current service.

For many years, proton synchrotrons became the machines of choice in the push toward ever-increasing energies. An accelerator at Serpukov in Russia began operation at 76 GeV in 1971. The Fermilab accelerator, planned for 200 GeV, was constructed by Robert R. Wilson (see Fig. 36 and box) ahead of schedule and under budget to operate at 400 GeV. It revealed the Υ (Sec. 9.2) and produced a wide variety of other physics results. It has now been outfitted with a ring of superconducting magnets which permit beam energies of 0.9 – 1 TeV and can collide protons with antiprotons, yielding center-of-mass energies of up to 2 TeV (see Sec. 10.10.2 below). A machine similar in scope to the original Fermilab accelerator, the SPS, was constructed at CERN, with a beam energy of 400 GeV. It achieved proton-antiproton collisions a few years ahead of Fermilab, discovering the W and Z (Sec. 7.5).

ROBERT R. WILSON

Robert Rathbun Wilson, testifying as director of the Fermi National Laboratory before the US Congress in support of the budget for the construction of the new accelerator, was pressed to explain what the new accelerator had to do with defending the United States against its enemies. Wilson responded to his questioner, Senator Pastore, "It has nothing to do directly with defending our country except to make it worth defending." Wilson has always been an outspoken champion of the value of basic research and the beauty of science and its value to our culture.

When Wilson was chosen to lead the construction of a 200 GeV accelerator in 1967 he was given 10 square miles of farmland about 50 miles west of Chicago and a budget of 240 million dollars. By taking high technical risks and eschewing conventional engineering practices, Wilson finished, under budget, a machine yielding twice the energy originally specified. Along with the machine was a great laboratory which attracted particle physicists from around the world. Wilson, an amateur sculptor, had a passionate interest in architecture as well as accelerator design. Every construction on the site bore his stamp of originality. Who is this charismatic, controversial, buccaneerish physicist, machine builder, and architect responsible for this great accomplishment?

Wilson was born in 1914 in Frontier, Wyoming, where his family had a cattle ranch. Educated through high school in local schools, he went to the University of California at Berkeley where he obtained an undergraduate degree followed by a Ph. D. working under E. O. Lawrence. In 1940 he went to Princeton as an instructor in the physics department (where Richard Feynman was still a graduate student). Almost immediately, because of World War II, he headed a project intended to separate the isotopes of uranium, based on a device of his own invention, the isotron. Moving on to Los Alamos in 1943 at the insistence of Robert Oppenheimer who had known him in Berkeley, Wilson became head of the experimental nuclear physics division. After the war and following a brief period at Harvard, he moved to Cornell University where he was director of the Laboratory of Nuclear Studies. In this capacity he supervised the design and construction of a series of electron accelerators of ever increasing energy, one of which was the very first machine to use alternating gradient strong focusing. During this early period he was the first in particle physics to use Monte Carlo methods: in his case, to study the development of electromagnetic showers. (In this pre-computer era he used, in effect, a roulette wheel to simulate random behavior.) With his considerable experience in experimental physics and accelerator construction it was natural for him to be selected in 1967 to create, out of the farmlands of Illinois, the Fermi National Accelerator Laboratory.

Figure 36: Robert R. Wilson, the builder and first director of Fermilab. (Courtesy of Fermilab).

10.8 Linear Accelerators

As we have seen, special problems arise with injection and extraction in accelerators such as cyclotrons employing magnetic confinement. These problems are not nearly as challenging for linear machines such as Van de Graaff generators. However, large fixed potentials are impossible to deal with beyond about 25 MV. Linear accelerators or linacs, were developed to maintain the ease of beam injection and extraction of fixed potential machines without the limiting high potentials, avoided by using cyclic resonant voltages.

The first proposal for a linear accelerator powered by radio frequency voltages was by G. Ising in Sweden in 1925. However, no attempt was made to implement its general idea until Wideröe succeeded in accelerating potassium and sodium ions in 1928. As noted above, Wideröe's device provided inspiration for the cyclotron of E. O. Lawrence.

Lawrence was clearly driven to make accelerators to do physics. Concurrently

with his development of the cyclotron with his student, M. S. Livingston, he had another student, D. H. Sloan, working on a linear device more in keeping with Wideröe's scheme. This early machine consisted of a number of cylindrical tubes arranged in a line with a spacing between tubes sufficient to prevent breakdown of the radio-frequency voltage applied between adjacent sections. Acceleration of the particles occurred only between the tubes. The ions drifted down the axis of each tube for a time sufficient for the alternating voltage to change sign. Progressing down the accelerator, the tubes were made progressively longer to compensate for the ions' acceleration. By 1931 Lawrence and Sloan had, with ten tubes, accelerated mercury ions to 1.25 MeV. Unfortunately, RF generators then available did not permit operation at high frequencies. These early machines were restricted to accelerating slow-moving heavy ions, too slow and highly charged to overcome the Coulomb barrier and initiate nuclear reactions in target materials.

The modern linac stems from the work of William W. Hansen at Stanford University starting in the middle 1930s. The initial work centered on developing a single cavity for accelerating electrons, requiring large amounts of RF power at high frequency. Correspondingly, Hansen, with the Varian brothers, set about to invent an appropriate RF generator. This activity yielded the klystron, which played an important role for radar in World War II. In the meantime, Kerst's successful development of the betatron raised doubts whether a linear device could ever compete.

The radar developments during the war, especially with respect to powerful RF sources, raised hopes. After the war, Hansen, with E. L. Gintzon and J. J. Woodward, concluded that the magnetrons then available would be suitable for linear accelerators of a few MeV, but that higher energies would require the further development of RF power sources. Hansen pursued the idea of accelerating the electrons with an electromagnetic field traveling in a cylindrical wave guide held in phase with the electrons by "loading" the wave guide, leading to the first (Mark I) Stanford linac with an energy of 6 MeV.

Concurrently, work initiated by Chodorow and Gintzon was proceeding on a high power pulsed klystron. After a successful test in 1949, plans went forward for a GeV electron linac, completed in 1952 (the Stanford Mark III)[374]. Unfortunately, W. W. Hansen, who had been the inspirational leader of the whole project, died prematurely in 1949 after living to see the successful test of the high-powered pulsed klystron.

The Mark III linac was the progenitor of the two-mile Stanford Linear Accelerator, constructed on the Stanford campus in the early 1960s under the direction of W. K. H. Panofsky (Fig. 37). Initially operated at 20 GeV with an average current of 50 microamperes, this machine now regularly operates at 50 GeV, corresponding to an average accelerating field of about 150,000 volts/cm.

The post-war development of electron linacs was paralleled by work on proton machines, principally at Berkeley under the direction of L. Alvarez and W. K. H.

Figure 37: Wolfgang K. H. Panofsky, the builder and first director of the Stanford Linear Accelerator Center. (Courtesy of Fermilab.)

Panofsky[375]. Since protons of equal energy travel much more slowly than electrons, far lower RF frequencies (of the order of 200 MHz) are required, making the accelerators considerably more cumbersome. In fact, the technique of accelerating electrons with a traveling wave in the wave guide cannot be successfully applied to protons, necessitating methods more akin to the old drift tube idea. In particular, what emerged was a resonant cavity 40 ft long and 39 in in diameter, operated in the TM_{010} mode at 202.5 MHz and filled with 42 drift tubes. This pioneering work at Berkeley yielded a machine which accepted protons from a 4 MeV Van de Graaff generator and accelerated them to 31.5 MeV.

The advantage of a high beam current with low angular divergence has retained for proton linacs a unique place in the accelerator hierarchy. They are used as injectors to the large proton synchrotrons, typically following a Cockcroft-Walton machine or radio-frequency quadrupole. An elaboration of the original standing

wave design of the Berkeley group has been highly successful at the Los Alamos Meson Factory, LAMPF, where protons are accelerated to 800 MeV with an average beam current of 1 ma.

10.9 Colliding beams

As noted above, the trail-blazing paper of Courant, Livingston, and Snyder showed the feasibility of accelerators using the strong-focusing principle. It also introduced a new era in the sophistication of machine design. In particular, designs could be contemplated providing a new level of precision in beam handling and transport, whether around the closed orbits of an accelerator, or in beam lines external to the machine.

In 1956 it was first recognized that high intensity beams, positioned and focused with high precision and directed against beams of equal and opposite momenta, could achieve reaction rates sufficient for interesting physics results. Just to contemplate this possibility is somewhat astonishing since the density of target particles in a beam is vastly smaller than in more usual targets such as liquid hydrogen or solid materials. It was Kerst[376] who first recognized that beams stored in fixed orbits could be made to collide with each other repetitively, thereby compensating for their diaphanous nature. All previous accelerators had directed their beams against targets at rest in the laboratory, either within the machine itself, or in an external beam extracted after the completion of the acceleration cycle.

Two beams of equal and opposite energy deposit all of their energy in the center-of-mass (cm) system, in contrast to the collision of a particle with another at rest, for which the requirement of momentum conservation decreases rather spectacularly the energy available in the cm system at high energies. For example, two protons directed against one another, each with energy E, have an energy $2E$ in the cm system, whereas the cm energy of a proton of energy E striking another at rest is $\sqrt{2m(m+E)}$, where m is the proton mass. Energy is not wasted, of course, in fixed target machines; it yields high energy beams of secondary particles, such as mesons and neutrinos. However, achieving the maximum energy for the production of new particles hinges on the colliding-beam technique. In 1956, when the notion of colliding beams was being advanced, the 30 GeV proton accelerators at Brookhaven and CERN were under construction. With 30 GeV on a fixed target, the available cm energy is 7.6 GeV; arranging these machines to collide beams with one another would yield almost 8 times as high a cm energy.

The proposal by Kerst, et al., *Attainment of Very High Energies by means of Intersecting Beams of Particles*[377], recognized that two fixed-field alternating-gradient accelerators[377a] could be arranged to circulate their high-energy beams in opposite directions over a common path in a straight section common to the two accelerators. G. K. O'Neill, at about the same time, published a paper entitled *Storage-Ring Synchrotron: Device for High-Energy Physics Research*[378]. (A non-technical review of the origin of the ideas and the development of the first practical storage rings has been provided in Ref. 378a.) Since beams had already been

extracted, highly successfully, from the Cosmotron, he proposed that such an extracted beam be stored in two magnet rings with the stored beams rotating in opposite directions. If the two rings were tangent at one point, the beams could be made to collide. Some details of the O'Neill proposal relating to injection were unworkable, but the general scheme has been followed in every one of the many colliding beam machines constructed subsequently.

Making proposals and suggesting ideas is easy and fun. A rare person is sufficiently convinced of their ultimate value to make a very major commitment of time and effort over a number of years. O'Neill, then an instructor in the Princeton University Physics department, was such a person. He quickly realized that storage rings might be easier to implement with electrons than with protons. With electrons, radiation quickly damps out transverse oscillations, reducing the cross sectional area of the beams, a major advantage since the beam particles' interaction probability depends inversely on the area. (In those days no mechanism was known for damping the transverse oscillations in proton machines.) Furthermore, radiation automatically provides the energy loss mechanism necessary at injection for the particles to end up in stable orbits.

With a tentative design for an electron-electron collider in hand, O'Neill went to Stanford where the linear electron accelerator already provided an ideal injector. He convinced the director of that facility, W. K. H. Panofsky, as well as Burton Richter and Carl Barber, of the proposal's worth. Somewhat later, O'Neill recruited B. Gittelman, also a Princeton faculty member, to work on the project. After a year of detailed design and after funding had been secured from the office of Naval Research, construction was begun in 1959 on a pair of 0.5 GeV electron storage rings at Stanford. The team of Barber, Gittelman, O'Neill, and Richter did the pioneering work.

And pioneering work it was. As soon as the first electrons were stored, totally new and unanticipated difficulties arose. To quote O'Neill, "We were crudely reminded that nature is an ingenious troublemaker." For example, the large peak currents induced in the vacuum chamber electromagnetic fields that reacted back on the beam destructively. One by one these problems were solved, with many people contributing to their solution. Finally, in 1965, the first electron-electron scattering results were obtained. The quantum electrodynamics of Feynman, Schwinger, and Tomonaga survived an especially clean test. As Feynman has said, "The test of all knowledge is experiment. Experiment is the sole judge of scientific truth."

Electron-electron colliders were limited to studies and tests of electrodynamics. It was clear from the beginning that electron-positron collisions offered a much richer opportunity for interesting physics. Electron-positron annihilations proceed through a virtual photon and thus are ideal for creating vector particles as well as particle-antiparticle pairs. This option had been considered by the Princeton-Stanford group but rejected because of the worry that the positron intensity could

never reach the level needed to get physics results.

A most important contributor to the development of storage rings was a group working under the direction of B. Touschek at the Frascati laboratory in Italy near Rome. Early in 1960 they decided to make an electron-positron storage ring of 0.25 GeV. An immediate simplification is associated with electrons and positrons which, traveling in opposite directions, can be guided by the same magnetic field and vacuum chamber. However, it was the spirit of the Italian group that guaranteed this electron-positron collider (called ADA, for *aniello d'accumulazione*, or accumulation ring) would be a useful test facility.

Originally constructed and tested at Frascati only for electrons, ADA was loaded on a truck and transported to Orsay near Paris in 1962 with its ultra-high vacuum chamber intact. The development of storage rings was characterized by the appearance of unexpected instabilities whenever the operation was pushed into a new realm of intensity or energy. Here, true to the pattern, more intense beams could be injected by a 1 GeV linear electron accelerator, and new instabilities (the Touschek effect) associated with the new intensities were found. The source of the new difficulties was eventually identified and the problems brought under control. The first electron-positron annihilations were recorded in ADA in 1963. While their intensity was too low for significant physics to emerge, it was apparent that the problem of low positron intensity could be overcome. Indeed, this was the case and every collider constructed since has been of this type.

ADA had a glorious career as a testing ground for $e^+ - e^-$ colliders and was suitably retired in 1965. Early in 1965 the Italian group started the construction of a much larger machine, ADONE, which was to have an energy of 1.5 GeV per beam. The first beam-beam interactions from this machine were observed early in 1967. The maximum energy of ADONE turned out to be a most unfortunate choice. The J/ψ, produced in 1974 at an energy of 3.1 GeV at SLAC, could have been uncovered much earlier at ADONE had that machine been designed to reach, say, 1.6 GeV per beam.

In the early 1960s a French group at Orsay started constructing an electron--positron machine with an energy of 0.385 GeV per beam. Activity in storage ring design and construction was also initiated in Russia at Novosibirsk under the direction of G. Budker. At the Electron-Photon Conference at Stanford University in 1967, experimental results were reported from three storage rings[379]: Orsay (385 MeV), Novosibirsk (510 MeV), and Stanford (550 MeV). The Orsay and Novosibirsk machines were both electron-positron colliders.

Electron-positron colliders were also on the drawing boards in the U.S. Competitive proposals were received by government agencies from groups at the Cambridge Electron Accelerator (CEA) and the Stanford Linear Accelerator Center (SLAC). The SLAC proposal won out but no funding was forthcoming. Finally, the Stanford Positron-Electron Collider, SPEAR, was constructed as an experiment, albeit a somewhat expensive one, with a maximum energy of 3.5 GeV per

beam, starting operation in 1972. In the meantime, the group at CEA, still wanting to build a collider, started by inventing a "low-β interaction region," a scheme which increases the interaction rates by factors of 10 to 100. This idea, combined with an ingenious and difficult beam handling arrangement, converted the CEA's electron synchrotron into a colliding beam machine, yielding collisions at energies much higher than could be achieved elsewhere and indicating the high value of R already mentioned in Secs. 6.3 and 9.1.

The CEA results were largely discounted at the time. A popular impression viewed the collider operation of the CEA as exceedingly difficult and thus unlikely to yield good physics. In the end the CEA group was vindicated; their results were shown to be correct by the more extensive measurements at the SPEAR collider.

We have already shown the behavior of R as a function of energy in Fig. 19. Below the mass of the top quark the value of R from simple quark and color counting should approach $3\frac{2}{3}$. This it does, rising at the highest energies as the low energy tail of the Z^0 is approached.

After SPEAR many electron-positron colliders have been constructed throughout the world, each with a name derived from some appropriate acronym. A listing of those existing near the end of the 20th Century is given in Table 3.

Machine	Beam Energy (GeV)	Location
DORIS	4–5.3	DESY (Germany)
VEPP-4	5	Novosibirsk (Russia)
CESR	8	Cornell
PEP	17	Stanford
PETRA	23	DESY (Germany)
TRISTAN	35	KEK (Japan)
LEP	50–100	CERN

Table 3. Electron-positron colliders with c.m. energies above 10 GeV.

This activity has culminated in the construction of LEP, the Large Electron Positron collider at CERN, with a circumference of 27 km operating, in its first phase, at single beam energies up to about 50 GeV. The energy of this machine, completed in 1989, was designed to produce the Z^0, with a mass of 91 GeV. In the second phase of operation, the beam energy will be raised to about 90 GeV, to produce $W^+ - W^-$ pairs. This energy represents the practical limit for electron-positron storage rings, because energy loss to synchrotron radiation is proportional to the fourth power of the beam energy divided by the radius of curvature of the bending magnets. When operating at 50 GeV per beam it amounts to 1.6 MW at the design luminosity, rising to 14 MW at the higher energy. This energy loss must be made up by the considerable radio-frequency power delivered to the beam.

To avoid the limitation of synchrotron radiation, a daring proposal was made at SLAC in 1979[380], to accelerate alternate pulses of electrons and positrons down the length of the two-mile long machine to 46 GeV. Each type of particle is then separately steered to arrange for their head-on collision. Clearly, for these collisions to take place with an appreciable chance of interaction, the beams must be incredibly small (of the order of two wavelengths of visible light) and must be steered with even better accuracy. To appreciate this technical *tour de force,* imagine a needle-shaped bunch of electrons with the diameter of the needle, one-fifth that of a human hair and perhaps a centimeter long, colliding with a similar bunch of positrons moving in the opposite direction, each bunch of particles having traveled through a semi-circle half a mile in radius. This project, the SLC (for Stanford Linear Collider), was successfully completed; while its flux of Z^0's is significantly lower than obtained in LEP, its electrons and positrons can be polarized, adding important information to the results. It is generally agreed that still higher energy electron-positron collisions will require the further development of the idea of the linear collider.

10.10 Hadron colliders

10.10.1. Proton-proton colliders. As noted above, machines intended to collide protons are intrinsically much more difficult to design. The absence of radiation damping complicates considerably both injection and storage. As has been noted, every proton remembers its history forever in the absence of damping. The first proton storage-ring-collider complex (the ISR, or Intersecting Storage Rings) was constructed at CERN using the 28 GeV protons provided by the PS synchrotron, first operating in 1971. It was, technically, a very complex device with elegant solutions to many difficult problems concerning beam handling and proton stacking and storage. Its most significant new technical development was the invention by Simon van der Meer[299] of stochastic cooling, which replaces the radiation cooling in electron machines and has made possible all of the subsequent hadron colliders. This invention recognizes that protons' radial positions oscillate about a central orbit at the so-called betatron frequency. The technique samples the departure of the mean beam position from its nominal radius at a particular point on the ring of magnets, feeding back the amplified signal across a chord to make up for delays in amplification and signal transmission. The amplified signal is applied to correcting electrodes appropriately positioned relative to the pickup electrodes in terms of betatron wavelengths so as to deflect the protons toward their central orbit. Since the pickup electrodes only sense the average position of the beam, some of the protons will be "heated," but, on the average, the beam is cooled; hence the name "stochastic cooling."

Concurrently, a different cooling method was developed by G. Budker at Novosibirsk. His method enveloped a beam of protons with an intense beam of electrons moving with the same speed and in the same direction. Any proton with a velocity different from the electrons will scatter from them, losing energy. This

technique is most useful for low energy beams and has been applied successfully to cyclotrons.

10.10.2 Proton-antiproton colliders. The cooling method of van der Meer became the crucial feature in the next round of accelerators, the proton-antiproton colliders mentioned in Sec. 7.5. Early in 1976 a proposal was prepared by C. Rubbia, P. McIntyre, and D. Cline[381] to convert the existing highest energy accelerators to proton-antiproton colliders, with a physics motivation explicit from their proposal's title, ***Producing Massive Neutral Intermediate Bosons with Existing Accelerators.*** This proposal was complete with estimates of the production cross sections of $W^{\pm}$ and W^0's (called Z^0's by the time of their discovery). It required beam handling techniques considerably beyond current methods:

> "The main elements are (1) an extracted proton beam to produce an intense source of antiprotons at 3.5 GeV/c, and (2) a small ring of magnets and quadrupoles that guides and accumulates the $\bar{p}$ beam, (3) a suitable mechanism for damping the transverse and longitudinal phase spaces of the $\bar{p}$ beam (either electron cooling or stochastic cooling), (4) an R. F. system that bunches the protons in the main ring and in the cooling ring, and (5) transport of the 'cooled' R. F. bunched $\bar{p}$ beam back to the main ring for injection and acceleration."

The authors also provided a sketch of the proposal's implementation at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. This proposal implied that the projected production cross sections would permit the construction of a proton-antiproton collider with sufficient luminosity to produce a reasonable rate of detected W's and Z's. When budgetary constraints at Fermilab did not allow the laboratory to proceed with these plans, despite the importance of the possible results, the authors took their proposal to CERN where a machine of similar energy (the SPS) was also in operation. Here their plans were accepted and construction was started on this grand experiment. As mentioned in Sec. 7.5, it resulted in the discovery of the $W^{\pm}$ early in 1983 and of the Z^0 several months later.

In 1984 Simon van der Meer and Carlo Rubbia were awarded the Nobel Prize "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction[299,300]."

In the meantime, plans at Fermilab were evolving in the late 1970s to make a $p\bar{p}$ collider of much higher energy using superconducting rings piggy-backed on the original iron magnet ring. This machine is another technical *tour de force* owing to the additional complications associated with the use of superconducting magnets in a pulsed mode around a 6.3 km ring. It was brought into operation in 1985. Each beam has an energy close to 1 TeV, hence its name, the Tevatron. From its initial operation it has been the lead accelerator in the search for the top quark, culminating in its observation (Sec. 9.4).

11. DETECTORS: FROM RUTHERFORD TO CHARPAK

Newtonian mechanics, Maxwell's equations, and Einstein's relativity are all recognized as monuments to deductive reasoning. Their place in history both in time and in the development of our understanding of Nature are well known and are part of the textual lore of physics. Conclusions drawn from experimental data which have changed the way we view things – Rutherford scattering, the Bohr atom, the Hubble radius – are likewise part of every textbook. Only rarely do major conceptual developments in the history of science go unnoticed. One example is the recognition that the sun itself is a star[382]. This was surely a most profound contribution to understanding the universe, but who first proposed it and how it came to be accepted is totally unknown. Similarly, some developments in instrumentation, in the tools physicists use which have had profound consequences, have had such diffuse origins that it is difficult to identify the individuals who might be credited. Bardeen, Brattain, and Shockley are credited for the transistor. Dating from the late 1940s, this is recognized quite properly as a momentous invention. It had a greater impact on the nature of physics research in the last half of the 20th Century than any other invention. But a further development, which truly brought about a revolution not only in physics research but in nearly every aspect of life, was the large scale integration of transistor circuits on single pieces of silicon. This profound development, occurring in the 1960s, came from incremental advances in many different laboratories, and has a more diffuse history. Near the end of the century commercially available devices are available which have four million transistors on a single piece of silicon!

In a charming essay[383] entitled "The Craft of Experimental Physics", P. M. S. Blackett begins "More has been written of what the experimental physicist has discovered than of how he has discovered it. Because he has changed the technique of living by his intense curiosity to find out about obscure things, many of his discoveries have become common knowledge. But his method of experimental discovery, how he works and thinks, is much less known."

Also, many of the tools which the experimental physicist has invented and developed for the purpose of doing experiments have not been accorded the attention they deserve. Since these investigations are not an end in themselves, there is nothing which is forgotten faster than an outdated technique no matter how clever or original its conception. From 1920 to 1960 an important device for the physicist was the vacuum tube. Today's students are hard pressed to recognize one, and the inventors are forgotten. In the present section we review the development of some of the tools and techniques which have most contributed to our present knowledge of particle physics.

At the last "turn of the century", in 1900, the electron had just been discovered. So too with radioactivity. The immediate problem was to unravel the nature of the alpha, beta, and gamma rays that had just been discovered. The principal tools consisted of electroscopes and electrometers for measuring ionization.

In 1903 Crookes and also Elster and Geitel discovered the phosphorescence of zinc sulfide on exposure to alpha particles. It had also been discovered rather early that pure zinc sulfide did not fluoresce; some impurity, e.g., copper, was necessary to make it work. A thin layer of finely powdered zinc sulfide spread on a glass plate and exposed to an alpha source such as radium or polonium could be seen to scintillate, with dark-adapted eyes, through a low powered microscope. The scintillation technique served not only to count particles but also to locate their positions in space. This method became famous later when used to study the scattering of alpha particles, leading to Rutherford's discovery of the atomic nucleus. Earlier Rutherford and Geiger had become involved in studying the nature of the α-particle itself. The question of its charge was crucial. By measuring the total charge deposited on an electrometer from a particular source within a set period of time and knowing the flux of particles from the number of scintillations with the same source in the same period of time, the charge on each particle could be obtained. Of course, this method assumes an efficiency of 100% for α-particles producing scintillations, an assumption that had never been tested. In a classic experiment published in 1908 Rutherford and Geiger made an invention to resolve the question[384].

11.1 Ionization Detectors

The ionization produced by individual α-particles did not provide a sufficient signal in an electrometer. To quote Rutherford and Geiger, "Some preliminary experiments to detect a single α-particle by its direct ionisation were made by us, using specially constructed sensitive electroscopes. As far as our experience has gone, the development of a certain and satisfactory method of counting the α-particles by their small direct electrical effect is beset with numerous difficulties.

"We then had recourse to a method of automatically magnifying the electrical effect due to a single α-particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend[385] has worked out the conditions under which ions can be produced by collisions with the neutral gas molecules in a strong electric field."

As implemented by Rutherford and Geiger, the high electric field was produced by applying voltage on a fine wire running down the center of a conducting cylindrical tube, 25 cm long and 1.7 cm in diameter. They operated the device with a gain of only a few hundred but it was enough to give distinguishable kicks ("throws") to their electrometer.

The paper ends with six conclusions.

"(1) By employing the principle of magnification of ionisation by collision, the electrical effect due to a single α-particle may be increased sufficiently to be readily observed by an ordinary electrometer.

"(2) The magnitude of the electrical effect due to an α-particle depends upon the voltage employed, and can be varied within wide limits.

"(3) This electric method can be employed to count the α-particles expelled from all types of active matter which emit α-rays.

"(4) Using radium C as a source of α-rays, the total number of α-particles expelled per second from 1 gram of radium have been accurately counted. For radium in equilibrium, this number is 3.4×10^{10} for radium itself and for each of its three α-ray products.

"(5) The number of scintillations observed on a properly-prepared screen of zinc sulfide is, within the limit of experimental error, equal to the number of α--particles falling upon it, as counted by the electric method. It follows from this that each α-particle produces a scintillation.

"(6) The distribution of the α-particles in time is governed by the laws of probability."

After these conclusions the authors go on to observe, "Calculation shows that under good conditions it should be possible by this method to detect a single β-particle, and consequently to count directly the number of β-particles expelled from radio-active substances."

In connection with this paper two comments are of interest. The first is that Rutherford and Geiger took the charge of the electron to be $e = 3.6 \times 10^{-10}$ esu, vastly different from the currently accepted value of 4.8×10^{-10} esu. This was obtained by averaging the results of J. J. Thompson, 3.4, H. A. Wilson, 3.1, and R. A. Millikan, 4.06 (times 10^{-10} esu), all of which were obtained by observing the effect of an electric field on charged water droplets. In a subsequent paper[386] Rutherford and Geiger report the charge of the α-particle to be 9.3×10^{-10} esu. Independently, they conclude that the charge of the α-particle must be $2e$ and hence $e = 4.65 \times 10^{-10}$ esu, close to the currently accepted value. They then go on to identify the source of the error in the previous determinations of e, i.e., the evaporation of the water droplets during the measurements. Millikan eventually avoided this problem by using oil drops.

The second comment relates to conclusion 6, which is correct but not supported by their data. Discussing the interval distribution between successive α-particles the authors show, very qualitatively, a curve which starts from zero, rises, and then comes down. They appear to have neglected to allow for the dead-time of the apparatus. We now know that the interval distribution must be, from the Poisson distribution, purely exponential.

And so was born the proportional counter, in general form not dissimilar to that used today. This device continued to be one of the most important detectors of charged particles through the rest of the century. The counter was invented to answer a particular physics question. Necessity is indeed the mother of invention.

It is perhaps surprising that it took 20 more years before the so-called Geiger--Müller counter emerged[387]. Of course, World War I removed 4 years from this period since, unlike in World War II, counting nuclear particles was hardly at the top of the wartime priority list. Nonetheless, it is still surprising that it took

so long. In retrospect it is difficult to imagine the circumstances under which experimental physicists labored and the relatively primitive materials available. It was literally the era of string and sealing wax. It is a sobering experience to read, e.g., the chapter on Geiger counters in Ref. 388. Making G-M tubes was apparently still something of a black art ten years after their invention.

The Geiger-Müller (or "Zählrohr") counters were an immediate success, with many applications. They were sensitive over the area projected by the outer cylinder, a large area at the time, producing signals sufficiently large to require a minimum amount of vacuum tube amplification to drive mechanical registers for tabulating counts. The G-M counters were indiscriminate, responding to any and all types of ionizing radiation, a serious disadvantage in many applications. However, when arranged in time coincidence the counters could be used to define beams of particles. In this mode, initially in the hands of Bothe[389] and Rossi, these devices became a principal tool in the study of cosmic rays. In 1954, W. Bothe was awarded the Nobel Prize in physics "for the coincidence method and his discoveries made therewith." (Rossi's circuit was a very significant improvement: a triple coincidence device, totally symmetric in all the inputs, whereas the original Bothe circuit was two-fold and asymmetric. Coincidence circuits, now called logical "AND" circuits, have continued to be incrementally improved in timing resolution ever since, first in the vacuum tube form and now in transistor versions.)

Somewhat earlier, physicists had started using vacuum tube amplifiers in conjunction with ionization chambers. In 1926 Greinacher[390] showed it possible to amplify the current due to an α-particle sufficiently to register as a click in a headphone. Subsequently, he also detected single protons by the same method. High-voltage power supplies utilizing transformers and vacuum tube diodes became the norm, largely replacing the banks of batteries used previously.

The mechanical counting registers used in conjunction with G-M tubes were limited to a maximum rate of about ten per second. Correspondingly, a counting loss of the order of 10% occurred for rates as low as one per second, stimulating the invention of electronic "prescaling" of the counts by divide-by-two circuits before registering on mechanical counters. The first of these binary counting circuits, devised by Wynn-Williams in 1932 [391], consisted of two vacuum tubes coupled so that only one could be conducting at a time. The driving pulse would turn off the conducting tube, but at the end of the driving pulse, in the absence of special provisions, either tube could become conducting whereas it was desired that the tubes conduct alternately on successive driving pulses. Memory of the previous conducting state, a necessary intrinsic feature, was provided by an RC circuit with a time constant long enough to more than cover the duration of the driving pulse. The divide-by-two circuits could be cascaded to any power of two. Binary division with six stages (by 64) before recording on mechanical registers was common.

A very significant improvement in the reliability of binary dividers was made in

the early 1940s by W. A. Higinbotham using diode coupling between stages. While Higinbotham neither published nor patented his contribution, it is included in Ref. 392. The early vacuum tube circuits could respond in the microsecond range, thus avoiding the counting-loss problem of mechanical counters. The essential ingredients of these circuits, bi-stable elements with intrinsic memory, persist in the highly refined binary transistor circuitry of today.

In the 1960s large-scale integration of transistors was accompanied by a striking decrease in the cost of complex circuits. Their reliability, as measured by the mean time between failures, made it possible to contemplate experiments with massive quantities of electronics. It was in this technological environment that G. Charpak, working at CERN, started a revolution in particle detectors by constructing large-area multi-wire proportional chambers. (See also Thompson in first of Refs. 3, p 274.)

Ever since the advent of scintillation counters, proportional counters had almost become extinct, but now they were resurrected on a grand scale. Multi-wire chambers had been used earlier, but never approaching the magnitude pursued by Charpak. Each wire had its own solid-state amplifier and discriminator to produce the signals necessary to log on magnetic tapes for later computing processing. Charpak further refined the idea of the drift chamber: The time between the passage of a particle through a chamber and the appearance of the signal on the "sense" wire indicated the distance of the particle's trajectory from the wire. In certain gases the electron drift velocity was remarkably independent of the electric field, making the device very linear. Layers of chambers with the wires at fixed angles to each other provided $x-y$ position information, critically dependent on the position of the sense wires themselves. While the scheme required unprecedented electronic circuitry, that was inexpensive, and perhaps more importantly, reliable. These devices were fast, acquiring great quantities of data in a short time and providing in ideal form the sort of data required in a modern particle physics experiment. The drift chamber is now a standard part of the particle physicist's tool kit. For this work Charpak was awarded the 1992 Nobel Prize in physics.

11.2 Scintillation and Čerenkov Counters

By 1903 zinc sulfide was known to emit visible flashes of light when bombarded by alpha particles, but was relatively insensitive to the gamma and beta radiations most often accompanying the α-particles. The arduous business of counting visible scintillations in dark rooms with dark-adapted eyes was the technique of choice for many years, yielding much information about α radiating sources, the nature of the α-particles and Coulomb scattering. It was only the invention of photomultipliers able to detect the scintillations and convert them to electrical signals that afforded full exploitation of the scintillation phenomenon.

In the early 1900s certain materials when bombarded with electrons of rather low energy (about 100 volts) showed a propensity to emit more electrons than struck the surface. These surfaces were thus acting as electron multipliers! The

first patent on using these materials to amplify small currents, granted in 1919 to Joseph Slepian[393], did not result in practical applications. Only later[394], in 1936, were multiple-stage devices, using both magnetic and electrostatic focusing, invented and applied to the amplification of photoelectric currents. Even though the early photomultipliers were scarcely practical, they were recognized to present a unique noise problem, which Shockley and Pierce addressed[395].

The first device resembling those in current use was described by Zworykin and Rajchman in 1939[396]. With careful attention to electrostatic focusing, these inventors managed to avoid the severe space charge limitations of the early models. In the nomenclature of the RCA company, the new device became the 931A photomultiplier. This tube had commercial applications in sensing the sound track on movie film, and was also used in World War II, far from its original purpose, as a generator of white noise for masking radio and radar signals. Tubes selected for exceptional sensitivity were labelled as 1P21.

In the meantime a new effect associated with the energy loss of charged particles passing through material had been discovered. In 1934 Čerenkov[397] had observed "feeble visible radiation" from β-rays passing through a clear liquid. In 1937 Frank and Tamm[398] developed an energy loss formula which included radiation at a particular angle relative to the track of the particle. That this radiation was emitted at a characteristic angle was very shortly afterward confirmed by Čerenkov[399]. Photomultipliers had still another application: detecting Čerenkov radiation.

While zinc sulfide was almost ideal for detecting slow-moving α-particles, it appeared difficult, if not impossible, to produce the large crystals needed for electron and γ-ray detection. For this reason, the discovery in 1947 by Kallman[400] of scintillation by various organic crystals proved enormously important, immediately stimulating investigations of various materials. P. R. Bell[401] found that anthracene and later stilbene were good scintillators and could be grown in large sizes. These materials, with very short recovery times, were quickly exploited by experimentalists. Viewed by the RCA 1P21 phototubes, they made sensitive counters with exceedingly fast response that could cover relatively large areas. These devices played a pivotal role in the discovery of the neutral pion, the early lifetime measurements on positronium, and the measurement of the relative polarization of the two γ-rays from positronium annihilation.

Certain fluorescing chemicals were also found which, when added to organic liquids, would result in a solution that would scintillate with good efficiency[402]. Such liquid scintillators proved extremely useful for large volume detectors. Later, in the middle 1950s, it was found that a plastic such as polystyrene could serve as the source. Now, towards the end of the Century, plastic is the scintillation material of choice in every application except γ-ray spectroscopy, being available commercially in all shapes and sizes.

Paralleling the developments in organic scintillators in the late 1940s, Hofstadter[403]

found that that sodium iodide activated by thallium impurities proved a very efficient scintillator. Unlike zinc sulfide, it could be grown into very large transparent crystals, and despite its highly deliquescent nature could be packaged into quite stable forms. The high atomic number of the iodine gave the crystal a high sensitivity to γ-rays. Indeed, it became possible, depending on the γ energy and the size of the crystal, to capture the full γ-ray energy. When coupled to a photomultiplier and a device for measuring the resulting spectrum of pulse heights, this crystal led to an enormously valuable spectrometer for γ-rays and mesic X-rays.

Again necessity stimulated invention. The RCA 1P21 phototube had a high sensitivity to photons, but it was difficult to channel the light from a crystal efficiently to photocathodes in the tube's interior. To correct this disadvantage, the RCA company, as well as EMI, developed the first end-window phototubes, the 5819 (RCA) and the 5060 (EMI). (See Ref. 404.) These new phototubes proved critical for the new spectrometers, essentially making them feasible.

The electronic developments associated with pulse-height analyzers (kick-sorters in England) had started at Los Alamos during World War II for use with ionization chambers and proportional counters. In general, they were rather cumbersome and complicated devices, notoriously difficult to maintain. The threshold for each channel would drift relative to its neighbor, which in turn would distort pulse amplitude spectra. It was Wilkinson[405] who first hit on the solution to this problem, by "laying the pulse on its side," i.e., by converting a pulse height to a pulse time. He charged a capacitor with the input pulse, then discharged it linearly in time, measuring the time between input and the end of the discharge by simply using an oscillator. The resulting time interval was then proportional to the original pulse amplitude. Electronically, it was much easier to keep time intervals constant than to keep voltage amplitude thresholds constant. Today, these circuits, called ADC's ("analog-to-digital converters"), are ubiquitous throughout the electronic industry. The old technique of setting channel intervals with voltage comparators is still alive because of its speed advantage. When applied to transistor electronics, the device is called a "flash ADC."

11.3 The Visual Techniques

We have already mentioned (Sec. 4.1) the key role played by photographic emulsions in detecting tracks of elementary particles. Cloud chambers, bubble chambers, and spark chambers were also of importance.

11.3.1 Cloud chambers. Even before the new century began, C. T. R. Wilson had been studying the process of droplet formation in supersaturated water vapor. It is not a simple process. Even in a supersaturated vapor, tiny droplets will inevitably evaporate in the absence of a formation nucleus, such as a dust particle, which in effect provides a flat surface for condensation. Alternatively, Wilson learned that charged molecular ions also provide centers for droplet formation since the repulsion of the charges causes the droplet to become larger, overcoming the tendency to evaporate away.

Experimentalists were quick to seize on the effects uncovered by Wilson. As we have noted, in the early 1900s the study of the behavior of charged water droplets in an electric field provided the first measurements of the electron charge. It was not until 1911, however, that Wilson first observed and photographed[406] the formation of tracks of droplets along the paths of single charged particles in a gas of water vapor supersaturated by a sudden expansion of its volume. Therein was born one of the most important tools in particle physics, the expansion cloud chamber. In 1927 Wilson was awarded the Nobel Prize "for his method of making the paths of electrically charged particles visible by condensation of vapor."

The application of this technique to the study of cosmic rays was considerably enhanced when the tracks of ions were found to persist for a time sufficiently long to permit the chamber's expansion and the growth of droplets along the tracks. The expansion could be triggered by signals from counters[47] (cf. Sec. 4.1). The discoveries of the positron, the muon, and strange particles were all made using the expansion cloud chamber.

It occurred to a number of people in the 1930s to arrange for a cloud chamber to be continuously sensitive. A first crude device was constructed by Hoxton[407], but its general principle was elaborated by Langsdorf into a device called a "diffusion cloud chamber" that became the model for all subsequent chambers[408]. (See also Ref. 409.) A vertical temperature gradient was arranged in a gas such that the vapor was unsaturated at the top but highly saturated at the bottom. In between, droplets would form in a narrow horizontal layer. The sensitive region tended to be rather thin, making the device unsuitable for vertically moving particles such as cosmic rays but presenting clear advantages for the horizontally moving particles from accelerators.

Ralph Shutt's group at Brookhaven exploited the diffusion chamber, initially at the Nevis cyclotron[410] and later at Brookhaven. The chamber could be made of a size ideal for studying the production and decay of the recently discovered strange particles. Traditionally the practice had been to place sheets of material, copper or lead, in the chamber to serve as sources of the new particles when struck by other particles incident from outside the chamber. The ideal target material was hydrogen. To this end, the diffusion chamber of Shutt *et al.* contained 21 atmospheres of hydrogen with methanol vapor. When the chamber was exposed to 1.5 GeV negative pions at the Cosmotron at BNL, the associated production of strange particles was discovered.

11.3.2 Bubble chambers. Using the diffusion chamber both as a target and as a detector was a clear advantage. However, even when operating at a pressure of 21 atmospheres, the probability of a pion interacting in the chamber was only about one in a thousand. Even with as many as ten incident particles in each photograph, it was still necessary to take 100 pictures per observed interaction. Therefore, when Glaser's invention of the bubble chamber[94] (see Sec. 4.5.3) proved that liquid hydrogen (with a density fifty times that of gaseous hydrogen at 21

atmospheres) would work[411], the diffusion chamber was doomed as a tool for doing physics.

The explosive development of the Glaser bubble chamber in its liquid hydrogen version culminated in the 1950s with the Berkeley 72 inch chamber. A development of the Alvarez group, it was to be the source of discovery of many unstable particles, as discussed in Sec. 4.

Appropriately, the Nobel Prize was awarded in 1960 to Donald Glaser "for the invention of the bubble chamber," and in 1968 to Luis Alvarez[95] "for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonant states, made possible through his development of the technique of using the hydrogen bubble chamber and data analysis."

11.3.3 Spark chambers. An effort was made in the late 1940s to find a counting device that would improve on the rather poor timing resolution characteristic of Geiger counters. Keuffel[412] and Pidd and Madansky[413] constructed "spark counters" consisting of parallel conducting plates between which high voltages were applied. An electrical discharge would occur whenever a charged particle traversed the gap between the plates. While Keuffel observed that the discharge occurred along the path of the particle, the emphasis at the time was on electronic timing, so the feature of track delineation was ignored. Shortly after, scintillation counters with superb timing characteristics were invented, removing the principal motivation for further spark counter development. In addition, spark counters with steady voltages were plagued with spurious discharges not associated with the passage of particles. When pulsed voltages were used[414] it was found that spurious discharges could be avoided, but only single tracks could be recorded.

The spark chamber was first proved viable for recording particle tracks by Fukui and Miyamoto[415]. Using pulsed voltages, initiated by scintillation counters, with a neon-argon mixture as the gas between the plates, they showed that tracks of more than one particle could be recorded. The receipt of the preprint of their paper in the U. S. initiated a flurry of activity devoted to further development. Foremost among the leaders in this development were Cronin at Princeton[416] and Cork and Wenzel at Berkeley[417]. By 1960 these groups were doing highly interesting physics using spark chambers. Guided by their work, a Columbia-Brookhaven group built a large, massive spark chamber to detect neutrino interactions at the AGS at Brookhaven (Sec. 5.1.6).

Spark chambers had a clear advantage over bubble chambers in that the interaction and tracking of particles could be separated, and the multiple Coulomb scattering, which limited the momentum resolution in bubble chambers, could be reduced significantly. Furthermore, spark chambers could be triggered on interesting events, as determined by accessory information from counters. These advantages were quickly exploited and at least two major discoveries (the existence of two neutrinos[147] and CP violation[154]) were shortly made with this technique.

Initially, information from spark chambers was obtained photographically. The

spark positions were digitized from film records and processed on large mainframe computers. Subsequently, in some experiments, the thunder, not the lightning, was recorded using acoustical detectors. Later, the chamber electrodes were made of wire crossing magnetostrictive lines. The discharge current would generate an acoustical signal in the line, to be sensed at its end. The arrival time provided a measure of the spark's position. Such acoustical schemes lent themselves to full automation in a computer environment. Variations developed in the 1960s included the wide gap chamber and the streamer chamber. The spark chamber, operated in a nonvisual mode, became the detector of choice in many experiments until replaced by the multiwire proportional chambers and by Charpak's drift chambers[418], able to acquire data at far higher rates.

12. OVERLAPS WITH OTHER SUBJECTS

As emphasized earlier, particle physics was very different in the periods before about 1960 and after about 1973. Before the 1960s, properties of individual particles were studied without the unifying themes of quarks and leptons. Similarly, the understanding of strong and weak interactions underwent a significant change with the employment of non-abelian gauge theories after the early 1970s.

During these developments, particle physics drew on a number of other areas for insight and experimental results. We mention a few of these.

12.1 Nuclear physics

12.1.1 Neutron lifetime and decay properties. Nuclear reactors provided copious sources of neutrons, whose mean lifetime and ratio of axial-vector to vector couplings were important ingredients in the evolution of weak-interaction theory. In view of the difficulty of confining a neutron for its mean lifetime (about 15 minutes), an accurate measurement of this quantity remained elusive for many years. "Magnetic bottle" techniques to contain neutrons led to significant progress. The present value[48a] of 887 $\pm$ 2 s provides not only useful information on the axial-vector coupling constant[419] (see Secs. 5.1 and 5.3), but also constrains the rate at which hydrogen was incorporated into helium in the early Universe (Sec. 12.4.4).

12.1.2 Neutrinoless double beta decay. All processes observed so far conserve *lepton number*, an additive quantum number equal to 1 for the negatively charged leptons and their neutrinos, and -1 for the corresponding antiparticles. However, since neutrinos can, in principle, mix with their antiparticles[420], an interaction changing lepton number by two units is conceivable. Such a *Majorana mass* can lead to neutrinoless double-beta decay through the graph illustrated in Fig. 38.

Present searches for neutrinoless double-beta decay have observed no signal for this process, leading to an effective upper limit of a few eV on the relevant neutrino Majorana masses[421].

12.1.3 Beta-decay limits on neutrino masses. Details of the electron spectrum in nuclear beta decay can reveal distortions stemming from neutrino masses. No

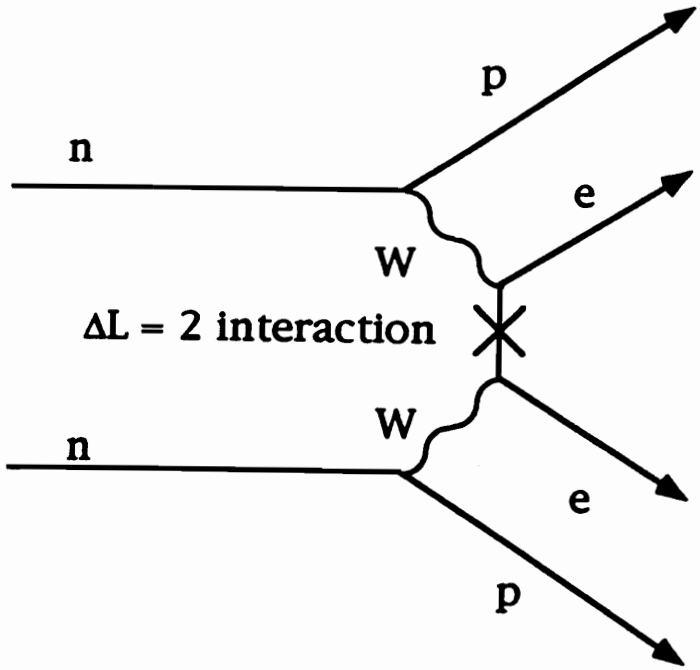


Figure 38: Diagram contributing to neutrinoless double beta decay. The line labeled by a cross is a Majorana neutrino, containing components with lepton number $L = 1$ and $L = -1$.

such effects have been observed, leading to upper limits of several electron volts on the electron neutrino mass[422].

12.2 Atomic physics

We referred in Sec. 7.3.3 to experiments searching for parity violation in atomic physics due to the neutral-current interaction. Many of these results rely on detailed atom-trapping methods developed since the earliest post-World War II days. The trapping methods have also been of great help in measuring anomalous magnetic moments of leptons (Sec. 3), in studying neutron decays (see Sec. 12.1.1), and in searching for the neutron's electric dipole moment (so far, without success).

12.3 Condensed matter

12.3.1 Nambu-Jona-Lasinio model. The bound state model of the pion proposed by Nambu and Jona-Lasinio[170] was inspired by analogy with superconductivity[423]. In both cases, a pair of fermions can form a bound state, leading to an energy gap and a zero-mass excitation.

12.3.2 Renormalization group. The behavior of physical quantities under changes in scale was studied not only in elementary particle physics[314], but also in condensed-matter problems, where "real-space" aspects of scale changes emerged particularly explicitly[424].

12.3.3–Lattice gauge theory. Non-relativistic field theories have been formulated on discrete lattices, such as occur in actual solids, yielding many properties of elementary and collective excitations. For example, one can determine the presence or absence of phase transitions, the masses and spatial extent of bound states, and bulk properties such as critical temperatures and specific heats. The methods for describing these phenomena are readily adapted to continuum field theories by approximating space-time with a discrete lattice. This program[329] has been particularly vigorously applied in constructing a lattice version of quantum chromodynamics (QCD), aimed at understanding all of low-energy hadron physics. The lattice spacing must then be much less than a hadron's size (10^{-13} cm). One current obstacle to this program is its inability to reproduce the pion well. In the limit of exact (spontaneously broken) chiral symmetry, the pion would be massless, with an infinite Compton wavelength, requiring for its represention a lattice of infinite extent. The actual pion has a Compton wavelength exceeding 10^{-13} cm, demanding many lattice points (and hence larger and faster computers) to correctly reproduce both pions and the rest of hadron physics.

12.3.4 String theory and soluble two-dimensional models. We mentioned dual models in Sec. 5.4.6, and will come to their present incarnation (string theories) in Sec. 13.5. Such theories also have been found relevant to two-dimensional models of critical behavior in condensed-matter systems[425].

12.4 Astronomy, astrophysics, gravitation, and cosmology

The interface between elementary particle physics and astrophysics is a vast subject (see, e.g., the seminal text of Ref. 425a), for which we can only touch on a few selected topics. Particle physics is at the heart of many astrophysical processes (such as supernova evolution), while astrophysical constraints have proved useful in anticipating elementary particle properties (such as the number of types of light neutrino). For many problems in astrophysics, solutions based on fundamental particle physics are among several options.

12.4.1 Solar neutrinos. The detection of neutrinos from the sun was proposed long ago by Pontecorvo[426]. The first search for solar neutrinos was mounted by R. Davis and collaborators[427], employing the reaction $\nu + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$ with chlorine in the form of cleaning fluid contained in a large tank located in the Homestake Gold Mine in South Dakota to shield against cosmic ray backgrounds. The detection of a signal relies on the extraction from the tank of less than one atom of argon per day, whose radioactive decay is the signature of its production.

Expectations for Davis' experiment were worked out in detail by Bahcall and collaborators[428]. The rate observed in the chlorine experiment was lower than expected and has remained so over more than twenty years. The present ratio of experiment to theory is about 0.3.

More recently, several other experiments, sensitive to different neutrino energies, have also indicated a solar-neutrino rate lower than expected. An experiment in the Kamioka mine in Japan, sensitive only to the highest-energy neutrinos

(above 5 MeV), sees a rate about half that expected. Its detector consists of a large tank of very pure water, viewing neutrino-electron interactions via Čerenkov light[429]. Two experiments sensitive to a lower neutrino energy threshold[430] rely on the reaction $\nu + {}^{76}\mathrm{Ga} \rightarrow e^- + {}^{76}\mathrm{Ge}$, with extraction of the radioactive germanium and subsequent detection of its decay. These also show a signal somewhat lower than predicted by the standard solar model.

Do these results, if correct, indicate a shortcoming of solar models (with all their attendant details of nuclear physics), or do they point to new elementary particle physics[431]? For example, do electron neutrinos (the type emitted in the Sun) undergo oscillations[432] to other species undetected in the above experiments? Such oscillations could either take place in vacuum or be induced by interaction with the Sun's matter.

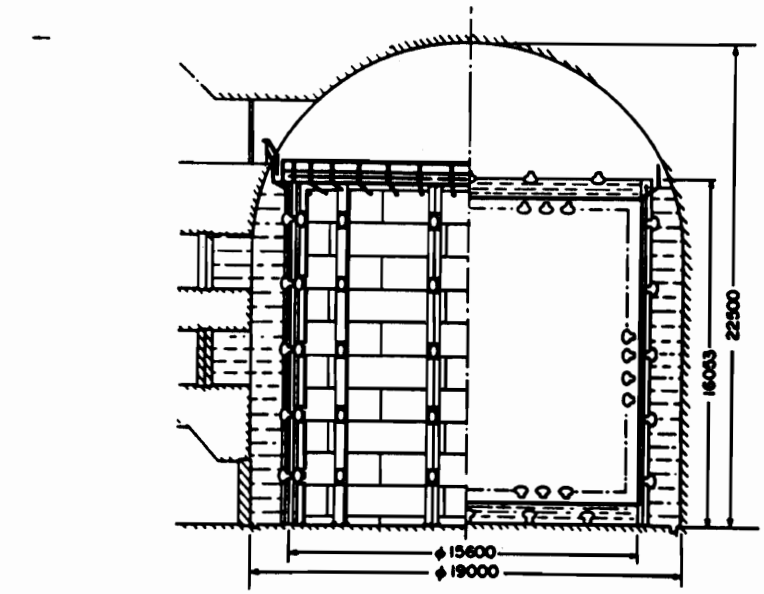
Further experiments are in the construction or planning stage[433]. An ideal detector would be sensitive to (a) a wide range of neutrino energies, ranging from less than a few hundred keV to many MeV, (b) the direction of the neutrinos' source, as in the Kamioka experiment, and (c) interactions of neutrinos other than ν_e through neutral-current effects.

12.4.2 Supernova neutrinos. The Kamioka detector was one of a number set up in the early 1980s for the entirely different goal of searching for proton decay (see Sec. 13.3). Another large water Čerenkov detector had been set up in the Morton Salt Mine northeast of Cleveland, Ohio, with the same purpose. (See Fig. 39.) After several years of operation, neither detector had seen any signal for proton decay. However, on February 23, 1987, both saw bursts of counts induced by neutrinos emerging from the explosion of a supernova in the Large Magellanic Cloud[434]. The observation by Kamioka was particularly fortunate since the detector was just a minute away from a scheduled shutdown. The supernova was the first seen in 1987, and hence was denoted SN1987A.

This observation confirmed basic predictions of the life cycle of a supernova[435], which in turn relied crucially upon the presence of neutral as well as charged currents in the weak interactions. Furthermore, the neutrinos arrived at the Earth within a few seconds of one another despite travelling about 160,000 light years, allowing estimates of upper limits on their masses[436].

If and when a supernova explodes in our own galaxy (whose diameter is about 60,000 light years), the neutrinos emitted will produce a stronger signal than SN1987A. Several other detectors, to be mentioned in Sec. 13.5.5, may be sensitive to this signal.

12.4.3 Cosmic microwave background. In 1948, George Gamow, R. A. Alpher, and R. C. Herman predicted[437] that the black-body radiation remaining from the birth of the Universe should have a temperature of a few degrees K. This expectation was verified by Penzias and Wilson in 1964, whose microwave radiometer revealed a persistent noise signal[438]. A Princeton group that had been looking for the same effect supplied its explanation[439].



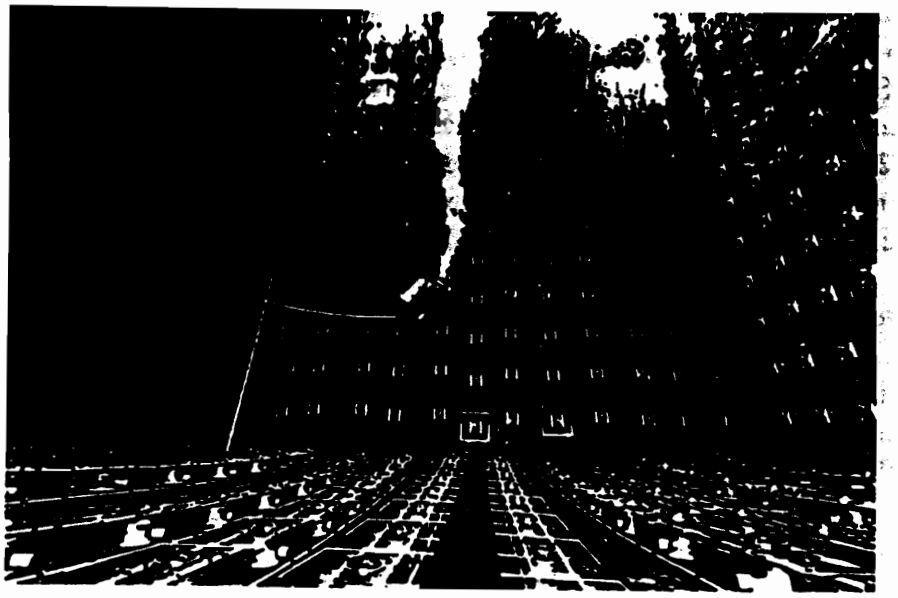


Figure 39: Top: Sketch of the Kamiokande II Detector, from Ref. 433a. Bottom: wide-angle photograph of the IMB-3 detector. The hemispheres partially visible in the square plastic sheets are large photomultiplier tubes. The plastic squares, called waveshifters, catch a portion of the light which does not directly strike the photomultipliers. Also visible is a diver. The photograph is taken through about 20 meters of water, showing the remarkable clarity of the purified water. (Courtesy of Joe Stancampiano and Karl Luttrell, ©National Geographic Magazine.)

The microwave background has proved remarkably homogeneous and isotropic, with a black-body temperature of 2.74 K, but displays a distortion caused by the velocity of our galaxy of some 600 km/s toward a point in Virgo, as well as fluctuations of order 10^{-5} recently identified by the Cosmic Background Explorer (COBE) Satellite and other experiments[440]. These fluctuations are a relic, looking backward in time, of the physics generating the much larger fluctuations now seen as galaxies and clusters.

12.4.4 Nucleosynthesis and number of neutrinos. The neutron lifetime, as mentioned earlier[419], affects the rate at which hydrogen was incorporated into helium in the early Universe. Another crucial variable in that calculation lies in the number of light neutrino species. The microwave background radiation provides a calibration of the mass density of the Universe contributed by each neutrino species at the time of helium nucleosynthesis. This density affects the rate of the Universe's expansion and hence the competition between the decay of neutrons and their incorporation into helium. Too many neutrino species would imply too much helium. An upper limit was thus set[441] of no more than four species; even this number started to look unlikely when limits on the neutron lifetime became tighter. Theorists thus breathed a sigh of relief (and at least one theorist won a case of wine) when the study of Z decays at LEP (Sec. 7.5.3) indicated that indeed three was the correct number.

12.4.5 Baryon asymmetry of the Universe. The observed part of the Universe contains far more baryons than antibaryons. As mentioned in Sec. 5.2.5, the groundwork for understanding this asymmetry was laid by A. Sakharov[166] in 1967. The necessary ingredients, still important in any current theory[167], included:

- CP violation
- Baryon-number violation (to be discussed in Sec. 13.3.2)
- A period in which the Universe was out of thermal equilibrium

The possibilities for realizing these conditions are quite varied, but the form of CP violation incorporated into the phases of the Cabibbo-Kobayashi-Maskawa (CKM) matrix seems insufficient. Rather, the CKM phases may be only one manifestation of a broader role for CP violation.

12.4.6 Cosmic ray physics. Cosmic rays played an important role in elementary particle physics until the advent of accelerators in the mid-1950s, as mentioned in Sec. 4. Even today, however, information on fundamental interactions continues to emerge from cosmic ray studies. As one example, total cross sections for particle interactions appear to rise with increasing energies beyond the limits of terrestrial accelerators[442].

A new field of cosmic ray physics has been spawned by the possibility of observing point sources of gamma rays at TeV energies and beyond. Čerenkov detection of TeV air showers has pinpointed emissions from the Crab Nebula (the remnants of a supernova seen by Chinese astronomers in 1054), and possibly even from extragalactic sources[443]. The search for point sources of gamma rays at

higher energies and for the highest-energy cosmic rays is being undertaken using extensive arrays, some as large as 10^8 m^2 in area[444].

12.4.7 Black holes. A star may form with a mass so great that its own gravitational field prevents everything, even light, from escaping from its surface. To quote Laplace[445] (1798):

> "A luminous star, of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us; it is therefore possible that the largest luminous bodies in the universe may, through this cause, be invisible."

Astronomical evidence has now been accumulating that such objects, now called[445] "black holes," do, indeed, exist.

The relation between black holes and elementary particle physics is one of the fascinating unsolved problems of the present century. Stephen Hawking showed a black hole to be capable of producing pairs of particles in its vicinity, one of which is ejected and one of which falls into the black hole[446]. The ejected particle carries off energy which the black hole must supply by losing mass. Thus, a black hole eventually evaporates. Is this behavior the source of a paradox? A pure quantum-mechanical state is thereby converted to a mixed one, leading to numerous suggestions for modifying the laws of classical gravitation, quantum mechanics, or both. As candidate quantum theories of gravitation, string theories (Sec. 13.4) are being used to model such processes.

12.4.8 Dark matter. There is ample evidence that not all matter in the Universe takes the form of visible stars, gas, or dust. One can measure the mass in our galaxy (or others), for example, by plotting the velocity of rotation of objects around the center as a function of distance from the center[447]. Much more mass is inferred than is seen.

Is the "dark matter" of the Universe in the form of failed stars (Jupiter-size objects) or is it more exotic? Many proposals have been made, including a variety of as yet unseen elementary particles such as very light spinless particles (for example, particles known as "axions"[448]), particles predicted by supersymmetry (see Sec. 13.1.2), and massive neutrinos (see Sec. 13.2). Each species seems to be able to account for some but not all of the desired properties of dark matter. For instance, a neutrino with a mass of about 10 eV, stable on the time scale of the Universe's lifetime, can provide just the right amount of mass for the universe to neither expand indefinitely nor contract back to a point after a finite time. But a 10 eV neutrino does not form the seeds for small-scale structure seen in galaxies, requiring another mechanism for galaxy formation.

12.4.9 Inflation and baryogenesis. The study of the early phases of the Universe led in the early 1980s to a remarkable observation that persisted in essence while undergoing various revisions in detail[449]. It is likely that at one or more

stages, the Universe underwent an exponential increase in scale, wiping out all fluctuations. We infer this behavior from the remarkable isotropy and homogeneity of the Universe today. A consequence of this "inflationary scenario" is that the Universe should be exactly on the boundary between open (expanding forever) and closed (collapsing back to a point). This observational question remains to be settled by the study of the Universe's dark matter mentioned above.

12.4.10 Searches for deviations from Einstein's gravitation theory. The general theory of relativity does not distinguish between the gravitational force felt by any object; all that matters is its mass. Early tests[450] confirming this "equivalence principle" had been refined to considerable precision by the mid-1960s[451]. A reanalysis[452] of the original experiments seemed to show a departure from the equivalence principle in the mid-1980s, leading to a flurry of improved tests and searches for a "fifth force." No evidence for it has survived these improved experiments[453].

13. UNSOLVED PROBLEMS AND HOPES FOR THE FUTURE

13.1 Electroweak theory: symmetry-breaking sector

13.1.1 Hunting for the Higgs boson. The electroweak theory described in Sec. 7, though immensely successful in reproducing current data, is incomplete. We do not know how the masses of the W, Z, quarks, or leptons (all of which break the original symmetry) actually arise.

The Weinberg-Salam mechanism for breaking electroweak SU(2) $\times$ U(1) involves the existence of a ***Higgs boson*** H, corresponding to the fluctuations of a neutral field with respect to its vacuum expectation value v. The non-zero value of v gives rise to the W and Z masses, with $v = 2^{-1/4}G_F^{-1/2} = 246$ GeV fixed by the value of the Fermi coupling constant. Masses of quarks and leptons arise through their Yukawa couplings to the Higgs field.

The *mass* of the Higgs boson, not specified by the electroweak theory, is arbitrary, lying anywhere between the experimentally determined lower limit[454] (about 60 GeV/c^2 at present) and about 1 TeV. The upper limit reflects a requirement that the scattering of two longitudinally polarized gauge bosons preserve S-matrix unitarity[455]. A similar requirement for pion-pion scattering is met by the observed spectrum of $\pi\pi$ resonances.

The search for the Higgs boson is one reason often quoted in support of multi-TeV hadron colliders (see Sec. 13.5). A straightforward Higgs signature would be a resonance in the W^+W^- and ZZ channels; this and many others are discussed, for example, in Refs. 456 and 457.

13.1.2 Alternatives for the Higgs sector: supersymmetry, compositeness. Two main streams of theoretical thought concern the underlying nature of the Higgs boson. One of them views the Higgs boson as an elementary scalar particle whose mass must be "protected" by some mechanism from acquiring large (and uncontrollable) radiative corrections. *Supersymmetry*[458], the most popular of such

schemes, postulates for every particle of spin S the existence of a partner of spin $S \pm 1/2$, whose presence in radiative corrections would exactly cancel the contribution of its "superpartner" if exactly degenerate with it in mass. Supersymmetry, of course, would be verified by observing superpartners, not too different in mass from their ordinary counterparts to facilitate the desired cancellation. Most current versions of supersymmetric theories predict that at least some superpartners should exist below a mass of a TeV.

The other class of theories views the Higgs boson as a composite of more fundamental objects[459]. Such theories of *dynamical electroweak symmetry breaking* require the Higgs boson to reveal its structure by an energy of one or two TeV, implying a rich spectrum of resonances in $W-W$, $Z-Z$, and $W-Z$ scattering starting at such energies.

13.2 Neutrino mass

13.2.1 Direct searches. Searches for electron-neutrino masses in beta-decay experiments have substantially improved over the past few years, as mentioned in Sec. 12.1.3, with hopes for further advances[460]. Accelerator-based experiments are expected to make modest but not spectacular gains over present bounds on muon and tau neutrino masses.

13.2.2 Oscillations. A major hope for future observation of neutrino masses rests upon the phenomenon of neutrino oscillations (Sec. 12.4.1), detectable in several ways.

(a) Further experiments could confirm the proposed role of neutrino oscillations in solar neutrino physics, by measuring the *spectrum* of neutrinos from the Sun and comparing it with predictions of solar models.

(b) Studies of the fluxes of different neutrino types generated by cosmic rays in the atmosphere can test for oscillations. At present the observed ratio of muon neutrinos to electron neutrinos seems somewhat smaller than anticipated theoretically[461], but further data are needed.

(c) Direct searches for oscillations at accelerators[462] are probing new ranges of masses and mixing parameters. Experiments also have been proposed in which an accelerator neutrino beam is directed at an underground target several hundred or more km away[463].

13.3 Grand unified theories

13.3.1 Particle content. The description of electroweak and strong interactions through two separate Yang-Mills theories in the early 1970s suggested that a *single* such theory might describe particle physics. The "grand unified" group would have to include $SU(3)_{QCD} \times SU(2)_{weak} \times U(1)_{weak}$ as a subgroup. Whereas the coupling constants of these groups differ at low energies, their different dependences on changes of momentum scale suggest that they approach one another at high energies. At such a "unification energy," quarks and leptons behave very similarly to one another[464].

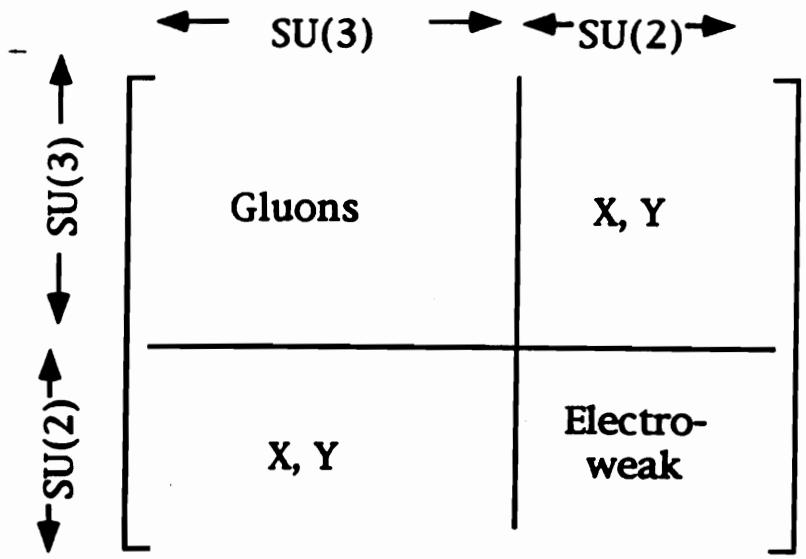


Figure 40: Gauge bosons contained within the SU(5) grand unified group.

Grand unified groups proposed quite early included SU(5) (Ref. 465) and SO(10) (Ref. 466). The structure of SU(5), in particular, is very easy to visualize, involving the 3×3 matrices of SU(3) and 2×2 matrices of SU(2) arranged in block diagonal form, as shown in Fig. 40. The U(1) fits in naturally as a diagonal SU(5) matrix commuting with both SU(3) and SU(2). A minor blemish on the theory lies in its slightly arbitrary choice of quarks and leptons as members of 5- and 10-dimensional representations of SU(5). This aspect is handled more elegantly in the SO(10) scheme, where a single 16-dimensional representation suffices for each family of quarks and leptons. The presence of small but non-zero masses for neutrinos in SO(10) can be arranged, since the theory includes both left-handed and right-handed neutrinos[467].

Coupling constants in SU(5) do not approach a common value at high energy, a feature which can be bypassed by making the theory supersymmetric[468] or by permitting unification at more than one mass scale[469]. These possibilities are compared with the standard SU(5) scheme in Fig. 41.

13.3.2 Proton decay; experiments. Grand unification predicts that the proton can decay, with a pair of quarks turning into an antiquark and a lepton by the exchange of a gauge boson of the extended group (see Fig. 42). This generic feature[464] was anticipated earlier by Sakharov as a way to generate the baryon asymmetry of the Universe[166] in the presence of CP-violating interactions, as mentioned in Secs. 5.2.5 and 12.4.5. Many experiments were mounted beginng in the late 1970s to search for proton decay. The simplest SU(5) grand unified theory predicted a proton lifetime lower than about 10^{30} years[167], accessible to experiments with detectors of several tens of tons.

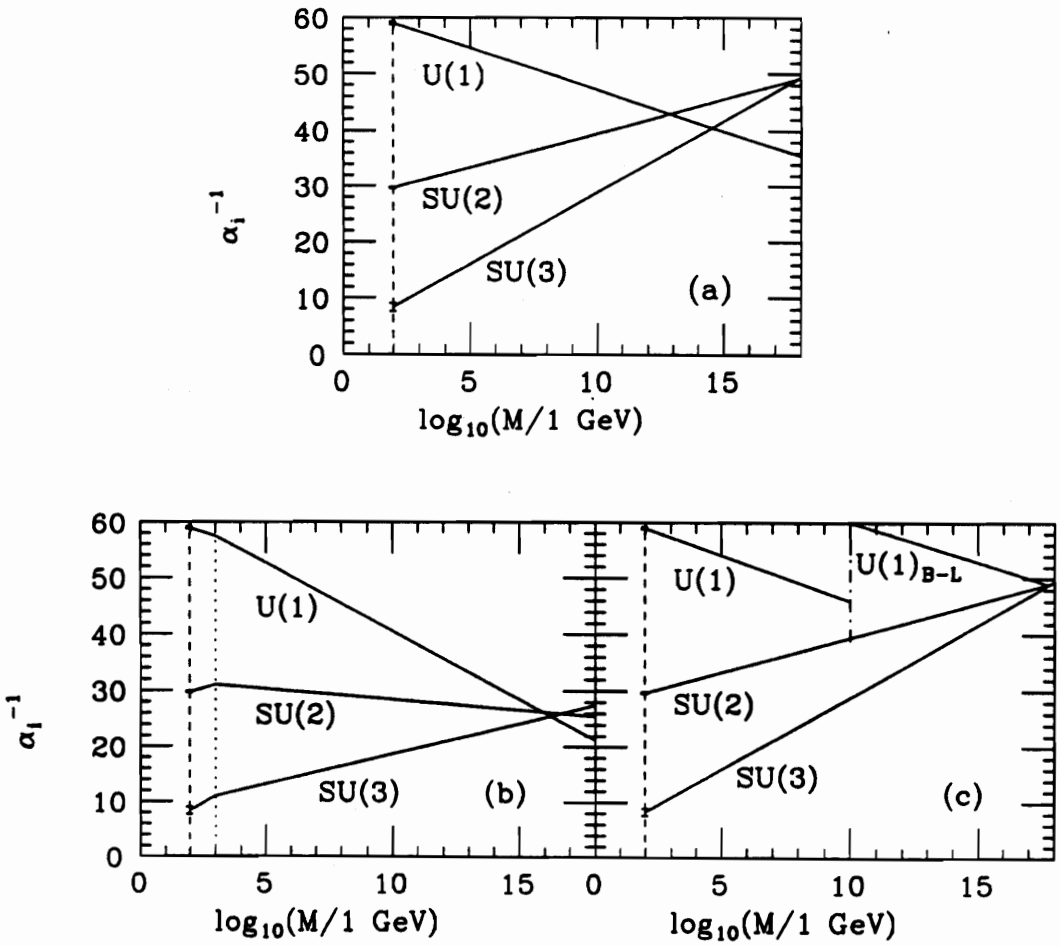


Figure 41: Behavior of coupling constants predicted by the renormalization group in various grand unified theories[469]. Error bars in plotted points denote uncertainties in coupling constants measured at $M = M_Z$ (dashed vertical line). (a) SU(5), showing failure of coupling constants to meet at a point; (b) supersymmetric SU(5) scheme (Ref. 468) with superpartners at 1 TeV (dotted line); (c) example of a two-scale SO(10) model with an intermediate mass scale (dot-dashed vertical line).

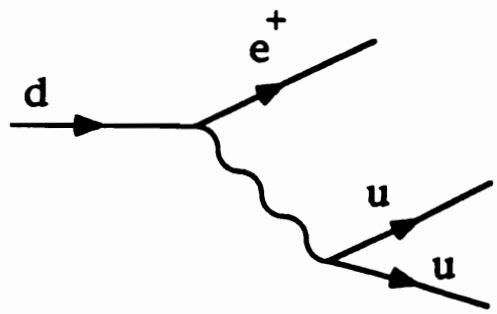


Figure 42: Example of process contributing to proton decay.

As of now, several multi-kiloton detectors have set limits[470] on the proton lifetime near $\tau_p > 10^{32}$ yr. The two largest, the Kamioka and IMB water Čerenkov detectors mentioned in Sec. 12.4.2, did record neutrinos from SN1987A. A 50-kiloton version of the Kamioka detector ("Super-Kamiokande") is now under construction[471], aimed at extending the lifetime limit to about 10^{34} yr.

13.3.3 Magnetic monopoles. The transition in the early Universe from a symmetric phase to one with broken symmetry can generate large numbers of magnetic monopoles[472]. Limits on their existence are very stringent[473], thus requiring means to greatly dilute their abundance or to avoid their generation. The apparent dearth of monopoles contributed to the inflationary universe scenario mentioned in Sec. 12.4.9.

13.4 String theories

Some aspects of dual resonance models and their connection to the physics of strings have already been mentioned in Sec. 5.4.5. The connection of string theories to condensed-matter problems was mentioned in Sec. 12.3.4. A "heterotic" version, with both 26- and 10-dimensional properties, gave the promise of realistic grand unification schemes[474]. It was hoped that the observed quarks and leptons could be explained in terms of singularities on surfaces generated when the extra dimensions curled up into unseen structures[475].

The predictive power of string theories for physics at the 100 GeV scale was soon recognized to be limited, as expected for theories whose fundamental scale is the Planck mass $m_P \equiv (\hbar c/G_N)^{1/2} \approx 10^{19}$ GeV/c^2, where G_N is Newton's gravitational constant. Nonetheless, construction of string theories with implications for grand unification schemes continues. Attention has also recently been devoted in string theories to problems of their internal self-consistency and to the construction of models of quantum gravitation. As mentioned in Sec. 12.4.7, string theories are being used at present to investigate the behavior of quantum-mechanical information loss accompanying black hole evaporation[476].

13.5 Future facilities

As questions in elementary particle physics shift to higher energy domains and different particles, new facilities are under construction or under consideration

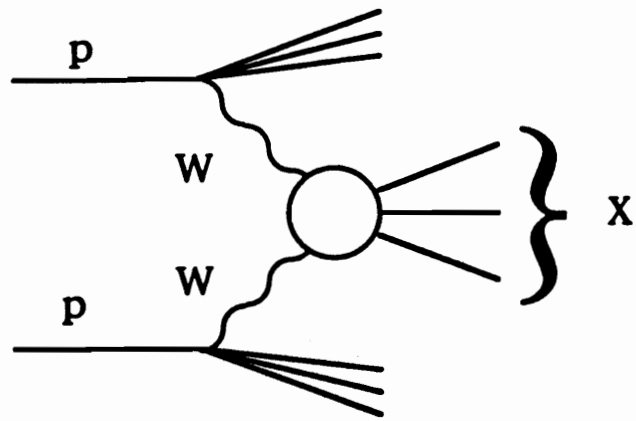


Figure 43: $W - W$ scattering induced by a hadronic collision.

to investigate the new domains. These include the first electron-proton collider (HERA), multi-TeV hadron colliders, facilities for producing B mesons copiously ("B-factories"), and large electron-positron colliders.

13.5.1 HERA. The first electron-proton collider began operating in 1991 at the DESY laboratory in Hamburg, Germany[477], colliding 27 GeV electrons with 820 GeV protons at a total center-of-mass energy of about 300 GeV. So far, HERA has measured the photon-proton total cross section, has produced its first data on proton structure functions, and has observed the expected reaction $e^- + p \to \nu_e +$ (anything). It will be a welcome instrument for measuring the behavior of structure functions (Sec. 6.2) in new kinematic regions and in searching for new particles.

13.5.2 Multi-TeV hadron colliders. In the early 1980s, with the discovery of the W and Z anticipated, plans were laid to explore the mechanism of electroweak symmetry breaking through multi-TeV hadronic collisions. These plans crystallized into a proposal for a Large Hadron Collider (LHC) in the LEP tunnel at CERN and a project to construct the Superconducting Supercollider (SSC) in Texas. A good sampling of the physics accessible to these machines may be found in Ref. 456. The LHC is designed for a center-of-mass energy of 14 TeV and a luminosity of 10^{34} cm^{-2} s^{-1}, affording the study of such processes as $W - W$ scattering (Fig. 43). The SSC was to have 40 TeV in the center of mass and about ten times less luminosity, but support for it was withdrawn after several years of construction[478].

13.5.3 B factories. The standard electroweak theory (described for three families of quarks and leptons in Sec. 9) predicts B meson decays to exhibit CP-violating asymmetries which can be quite large, depending on values of parameters still being determined. However, since B mesons decay to any given final

state with a typical probability of less than 10^{-3}, many B mesons are needed in order to permit such studies: probably at least 10^8 $B\bar{B}$ pairs, out of the reach of present electron-positron colliders.

The purest source of B mesons, lying just above the $B\bar{B}$ threshold, is the $\Upsilon(4S)$ resonance, produced in e^+e^- collisions with a cross section of about 1 nb. An upgraded version of the CESR e^+e^- collider at Cornell, operating at the $\Upsilon(4S)$ for several years with a luminosity of several times 10^{33} cm^{-2} s^{-1}, could produce 10^8 $B\bar{B}$ pairs. The most clear-cut CP-violating signatures at the 4S resonance require one to observe the time-dependence of both B mesons' decays, most easily accomplished using electrons and positrons of different energies. Asymmetric B-factories are planned at KEK in Japan and at SLAC in the U. S.

13.5.4 Large linear electron-positron colliders. The likely existence of a top quark below 200 GeV, the hopes that Higgs bosons and superpartners may exist with masses below several hundred GeV/c^2, and the sheer technical challenge of taking the next step in energy and luminosity have led to planning for a large linear electron-positron collider with a center-of-mass energy of 500 GeV and a luminosity of 10^{33} cm^{-2} s^{-1}. Workshops on this facility have been held now for several years. In contrast to the Stanford Linear Collider, whose beams are bent in arcs to achieve collisions, this machine would be truly linear, with dimensions set by the attainable accelerating gradients; a total length of about 20 km is typical of plans.

13.5.5 Non-accelerator facilities. Several large facilities under construction or under consideration will shed light on particle physics without any need for an accelerator. The "Super-Kamiokande" detector mentioned earlier will take a further step toward observing a proton's decay or setting improved limits on its lifetime. It will also be sensitive to neutrino interactions, as will a number of other facilities located underground (Soudan[479] in Minnesota, MACRO[480] in Italy, the Sudbury Neutrino Observatory [SNO][481] in Canada), underwater (DUMAND[482] off the coast of Hawaii), or even under ice (AMANDA[483] at the South Pole). The MACRO detector will also search for monopoles at unprecedented sensitivities.

Searches for "dark matter" will take on a new dimension with the development of cryogenic techniques, able, in somewhat simplified terms, to detect "things that go bump in the night," otherwise invisible[484].

Large surface arrays are envisioned to detect cosmic ray air showers. It may be possible to synchronize electronically the operation of an array as large as 5000 km^2 in area[485]. More modest surface arrays at higher elevations than currently in use are also planned[486].

14. CONCLUSIONS

Elementary particle physics in the second half of this century has oscillated between complexity and simplicity, between confusion and order.

The number of known "elementary" particles grew enormously in the years after World War II thanks to new production and detection techniques. While some physicists despaired in the 1950s and 1960s of ever comprehending this burgeoning zoo of particles and their interactions, symmetries such as SU(3) began organizing these particles into families; the advent of the quark model introduced further regularity. However, not until a genuine theory of the strong interactions based on quantum chromodynamics (QCD) appeared in the early 1970s could one understand these successes in a fundamental way.

The weak interactions at the midpoint of the century were in a similar muddle. Failure to identify the most fundamental beta-decay processes made it hard to deduce the structure of the basic interaction. The discovery of parity nonconservation in the weak interactions lifted blinders from physicists' eyes, helped identify some experiments as right and some as wrong, and led almost immediately to a satisfactory description based on the so-called $V - A$ theory. Still, the weak interactions remained incompletely understood. The $V - A$ theory could not be used for calculations of higher precision or at higher energies. It took the synthesis of weak interactions with electromagnetism to construct a theory with these features.

Our present understanding of both strong and electroweak interactions relies on quantum field theory. At the midpoint of the century, field theory appeared to apply to a small area of particle physics, namely, quantum electrodynamics (QED), a limitation that vanished entirely in the course of twenty years.

Now that we understand the strongly interacting particles as consisting of quarks, held together with gluons, and understand the basis for both strong and electroweak forces, new questions have arisen. One of the earliest, arising just seven years after the discovery of parity violation, concerns the violation of combined charge-reflection (C) and parity (P) symmetries. A proposal that this violation requires at least three families of quarks has been supported by the discovery of the third family, but we still do not know whether the observed CP violation arises from this source.

Still mystifying, and possibly related to the origin of CP violation, is the pattern of masses and electroweak couplings of quarks and leptons. Quark masses necessarily break the electroweak symmetry. So do the masses of the weak force carriers, the charged W's and the neutral Z. The source of this symmetry breaking has been generically termed the "Higgs mechanism," and vague predictions exist for a "Higgs boson," whose discovery would undoubtedly shed light on the electroweak symmetry breaking mechanism. However, lurking in the background of any scenario involving the Higgs boson are many other new particles or effects, to be probed in the next generation of experiments.

The study of elementary particle physics in the past fifty years has been a noble enterprise, complete with its share of successes and setbacks. Let us hope that the progress in the next century is as rich as that in the present one.

ACKNOWLEDGMENTS

We thank J. Bernstein, J. D. Bjorken, M. M. Block, L. M. Brown, U. Fano, P. Freund, H. Frisch, R. Hildebrand, Y. Nambu, R. Oehme, A. Pais, P. Ramond, R. Sachs, M. M. Shapiro, F. C. Shoemaker, V. Telegdi, and A. Tollestrup for helpful advice, and Gordon Fraser and Adrienne Kolb for help in obtaining illustrations. Ugo Fano provided indispensable editorial advice in the course of a careful reading of the manuscript. This work was performed in part at the Aspen Center for Physics, and was supported in part by the United States Department of Energy under Grant No. DE FG02 90ER 40560. J. L. R. wishes to thank the Theory Group of Fermilab for their hospitality during the completion of this article.

ADDITIONAL SOURCES

In addition to the conference proceedings and historical works mentioned at the beginning of this article[1–5], and in the course of our discussion (see, e.g., Refs. 14, 123, 131, 214, 227, and 257), several other useful references are worth mentioning. They include an eminently readable account by Jeremy Bernstein[487], a brief report by the United States Department of Energy[488], a thoughtful book by Steven Weinberg[489], a memoir spanning seven decades by Victor Weisskopf[490], a concise account of results in The Physical Review by Sam Treiman[491], a new work by Murray Gell-Mann[492], Robert Marshak's last opus[493], and an early history of particle accelerators based on the life and work of Rolf Wideröe[494]. A biennial compilation of relevant data is produced by the Particle Data Group[48a], carrying on a long tradition begun in the 1950s by Arthur H. Rosenfeld and collaborators.

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