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Probing the Structure of the Universe from Quarks to Cosmology

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Abstract

The study of fundamental physical systems in the laboratory has implications for the evolution of our Universe as a whole. The next step toward an ultimate understanding of the Universe requires a powerful new instrument for the study of the physics of elementary particles: the Superconducting Super Collider.

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I. Introduction

Some of the most important discoveries in the history of science have arisen from the identification of simple and general rules that underlie the behavior of complex systems. The idea that the same laws of Nature hold at all times and in all places is the basis for our conception of the Universe as an orderly, rather than capricious, place — a system we may hope to understand.

Every high-school student knows that Newton discovered the Law of Gravity. However, Newton achieved something even more remarkable; he recognized the *universality* of the Law of Gravity. His recognition that the force responsible for objects falling to earth is the same force responsible for the motions of the stars and planets was perhaps more important than the determination of the form of the force law itself. The realization that in terrestrial laboratories we can learn the physical laws that govern the structure of the Universe has had a profound influence on our civilization.

The application of physical law to understand the Universe has continually been rewarded. An outstanding example in the twentieth century is the application of nuclear physics to the study of the structure and evolution of stars [1]. The temperatures in the stellar interiors are typical of the energies studied in nuclear physics, and in earthbound nuclear physics laboratories it is possible to measure the nuclear reactions that account for the production of energy in stars. Any attempt to understand the life cycle of stars without a knowledge of nuclear physics would be as futile as an attempt to comprehend the movements of the planets without a knowledge of Newton's Law of Gravitation. Nuclear astrophysics applies lessons learned on the scale of the nucleus (about 10^{-13} cm) to the structure of the Universe on the scale of stars (about 10^{11} cm).

The energies studied in elementary particle physics are larger than those in nuclear physics, and the corresponding distance scale is smaller than that of the nucleus. We have now probed the structure of matter at energies of more than 100 GeV [2], corresponding to distances of 10^{-16} cm. Such energies exceed the temperatures in even the most extreme stellar environments. Outside of high-energy accelerators, they have existed only in the collisions of rare, high-energy cosmic rays, or in the earliest moments of the Big Bang. In this article we focus on the interplay between particle physics and the study of the early Universe.

In the past decade, as a result of many crucial experimental discoveries and theoretical insights, a radically new and simple picture of the fundamental constituents of matter and their interactions has emerged [3]. This progress has resulted in the development of an extremely successful "standard model" of particle physics. No experimental evidence suggests that the standard model is incomplete, but most physicists believe that it is not the ultimate description of Nature. Theoretical arguments suggest that new clues are to be found at an energy of about 1 TeV (1000 GeV), revealing a new simplicity. A proposed new accelerator known as the Superconducting Super Collider, or *SSC*, will allow particle physicists to explore this regime in detail. In this article we discuss the potential for new discoveries at the *SSC*, and how the knowledge gained may allow us better to understand the earliest moments of the Universe.

II. The Standard Model of Particle Physics

The search for a simple and general characterization of physical law has led to the identification of a set of fundamental constituents of matter, and to the understanding that all known phenomena result from the action of just a few basic forces [4].

An elementary particle, in the time-honored sense of the term, is structureless and indivisible. History cautions that the physicist's list of elementary particles is subject to revision with the passage of time and the improvement of experimental instruments. Natural substances have been found to consist of molecules, molecules of atoms, atoms of protons, neutrons, and electrons, and so on. Indeed, there has been recurring competition since antiquity between the view that elementary particles exist and the belief that matter is infinitely composite. Nevertheless, the hope that interactions among the elementary particles of the moment would be simpler and more fundamental than those among composite systems has repeatedly led to important progress. Experiments over the past two decades have led to the identification of two classes of elementary particles, which exhibit no internal structure at the current limits of resolution, about 10^{-16} cm. One class, the *leptons*, experience gravitational, electromagnetic, and weak interactions, but are indifferent to the strong force. The other class, the *quarks*, are affected by all four of the fundamental forces.

The most familiar of the leptons is the electron. Six distinct species (colloquially called *flavors*) of leptons have been identified. Their properties are summarized in Table 1. Three of them, the electron, the muon, and the tau, are electrically charged. The other three, called the neutrinos, are electrically neutral. All of the leptons are spin-1/2 particles which means, in terms of a classical metaphor, that they can be regarded as microscopic tops which can point either up or down. As Table 1 suggests, the leptons appear to be grouped in three families, each composed of a charged lepton and its neutrino.

To each species in relativistic quantum theory there corresponds an antimatter or antiparticle species with the same mass and spin, but with opposite charge. The existence of the first known antiparticle, the antielectron or positron, was verified in 1932. The antileptons include the electrically neutral antineutrinos, and the positively charged antielectron, antimuon, and antitau.

Where are the leptons observed? The electron is a constituent of the atoms that make up ordinary matter. Electron neutrinos and antineutrinos are emitted in the radioactive beta decay of atomic nuclei. Nuclear reactors provide copious sources of electron antineutrinos. The remaining leptons are chiefly produced in collisions of high-energy subnuclear particles. These collisions occur naturally in the interactions of cosmic rays in the earth's atmosphere, or in controlled experiments using particle accelerators.

Protons, neutrons, and the hundreds of other subnuclear particles that undergo strong interactions make up the second great class of particles studied in the laboratory. They are collectively called *hadrons*. They are a diverse group, differing from one another in mass, spin, and other intrinsic properties. Some, like the proton, are extremely stable; many others exist only ephemerally in the products of high energy collisions. All of the hadrons are composite particles, of finite size (typically $\sim 10^{-13}$ cm), and with internal structure.

In 1964, Murray Gell–Mann and George Zweig independently proposed that the observed spectra of hadrons could be explained by the hypothesis that the hadrons are made up of fundamental entities which we call *quarks*. Studies of violent collisions between high-energy electron beams and protons or neutrons carried out in the late 1960s at the Stanford Linear Accelerator Center in California indicated that small, electrically charged objects were present within the protons and neutrons. These objects were readily identified as quarks. Experiments of great variety at many laboratories have subsequently extended these inferences, and have refined our knowledge of the quarks.

The pattern of hadrons now known is explained by the fancifully-named flavors of quarks shown in Table 1. Like the leptons, all of the quarks are spin-1/2 particles which are structureless at the current limits of resolution. Quarks have a number of unusual properties, one of which is that they bear charges which are fractions of the electron's charge. They also carry a new kind of charge, called *color*, which governs the strength of their strong interactions. Each quark flavor may occur in three distinct colors, designated *red*, *green*, and *blue*. These colors are merely labels, and have nothing to do with visible light. The antiquarks carry opposite electrical charges and color charges. The leptons, which do not have strong interactions, are regarded as color neutrals.

In contrast to the leptons, isolated free quarks have never been observed. Because of this, all the evidence we have for the physical reality of quarks is circumstantial in nature. It is, however, impressive in its consistency, diversity, and strength. The fact that free quarks have never been observed suggests that the interaction between quarks must be extraordinarily strong, and perhaps permanently confining. On the other hand, the quark model description of violent collisions rests on the assumption that quarks within hadrons may be regarded as essentially free.

This paradoxical state of affairs may be visualized as follows. We may think of a hadron as a bubble within which the constituent quarks are imprisoned. The quarks move freely within the bubble, but cannot escape from it. This picturesque description yields an operational understanding of many aspects of hadron structure and interactions.

In everyday experience, the effects of countless forces are familiar: the force of the wind, bouyancy, adhesion, friction, and so on. Physics seeks to simplify the description of Nature by finding the underlying causes of natural occurrences and, where possible, by relating apparently distinct phenomena. The result of this effort has been to show that all natural processes may be understood as manifestations of a small number of fundamental interactions. For half a century, physicists have identified four fundamental forces: gravity, electromagnetism, the weak interaction responsible for radioactivity, and the strong interaction that binds atomic nuclei. Some characteristics of these forces are summarized in Table 2. Electromagnetism is itself the union of electricity and magnetism, which until the work of Michael Faraday, James Clerk Maxwell, and others in the nineteenth century were regarded as distinct and unrelated phenomena.

In the classical physics of Newtonian mechanics, force has a precise meaning as an agent which alters the state of motion of a body by changing its speed or direction. A more comprehensive notion of force, often called *interaction*, is appropriate in the realm of elementary particles. Interactions may cause changes of energy, momentum, or species to occur either among groups of particles, in collision processes, or spontaneously to isolated particles, in decay processes.

Of the four forces of Nature, gravitation is the one most familiar in the world of ordinary experience. It is responsible for the large-scale structure of the Universe, for the regular orbits of planets and satellites, and for keeping our feet planted on the ground. So far as is known, Einstein's general theory of relativity provides a complete description of gravitational phenomena in the macroworld. In contrast with the successes of relativity on a large scale, a complete quantum mechanical theory of gravity, which would be applicable at very high energies and very short distances, has not been achieved. In the realm of elementary particles, the gravitational interaction is so feeble as to be utterly negligible at the energies which have been attained, and can be safely ignored.

Electromagnetism shapes the world around us. The structure of matter, the chemistry of life, and the propagation of light all may be traced to the basic laws of electrodynamics. In relativistic quantum theories, interactions are mediated by *force particles*. The carrier of the electromagnetic interaction, the *photon*, was postulated in 1905 by Einstein. Its existence was confirmed in the 1920s by experiments which showed that light scattered like a massless particle from electrons.

Quantum electrodynamics (*QED*) is the most successful of physical theories. The predictions of *QED* have been verified over an extraordinary range of distances, from less than 10^{-18} m to more than 10^{8} m. Like the other theories of the fundamental interactions, *QED* is a *gauge theory*, derived from a symmetry principle. It may be constructed mathematically by requiring that the complex phase of the quantum mechanical wave function of a charged particle may be defined independently at every point in space and time.

A theory of the strong interactions is modeled on *QED*. Since color is an attribute of quarks but not of leptons, it can be considered a strong-interaction charge. When the color symmetry among red, blue, and green quarks is taken as the basis for a gauge theory called quantum chromodynamics, or *QCD*, the resulting interactions are mediated by force particles called *gluons*. There are eight gluons corresponding to the distinct color-anticolor combinations. [The "white" combination representing an equal mixture of red-antired, blue-antiblue, and green-antigreen is not included.] Because the gluons carry color, they can interact among themselves. The photons of *QED*, being electrically neutral, have no such self-interactions. One of the unexpected results to emerge from *QCD* is the prediction that quarks should behave as suggested by the bubble metaphor introduced earlier: they interact feebly when close together, but cannot be separated macroscopically without the expenditure of infinite energy.

From the earliest investigations of radioactivity in the 1930s, *QED* has also served as a model for the theory of weak interactions. It is appealing to hypothesize that the weak interaction is carried by a so-called *intermediate boson*, denoted W for weak. The weak boson must be electrically charged in order to mediate nuclear radioactive decays such as the disintegration of a neutron into a proton, electron, and antineutrino. It was apparent from early investigations of natural radioactivity that the conjectured intermediate boson must be extremely massive. A second aspect of theoretical work has been the idea of a synthesis, following the example of electricity and magnetism. The idea that the weak and electromagnetic interactions — so different in apparent strength — have a common origin provides an estimate of the W-boson's mass of approximately 100 times the proton's mass.

To advance from these general notions of analogy and synthesis to a viable theory of the weak and electromagnetic interactions has required a half-century of experimental discoveries and precision measurements and of theoretical insights and inventions. Like *QED* itself, the resulting *electroweak theory* is a gauge theory. In this case, the symmetry is a family pattern among quarks or leptons which was suggested by experiments. A self-consistent theory could not be based upon the "known" force particles (the photon and the conjectured W) alone, but required in addition an electrically neutral weak force particle Z^0 and an auxiliary object known as the Higgs particle. The latter plays a key role in hiding the electroweak symmetry, which is required to account for the varied masses of the quarks and leptons, and the great mass of the intermediate boson. The new form of weak interaction mediated by the Z^0 was first observed in 1973.

It remained to observe the intermediate bosons as real particles, rather than merely seeing the interactions attributed to their existence. In the electroweak theory, the properties of the intermediate bosons, such as their masses, depend upon a single parameter which has been determined from experiments. On this basis, we expect the mass of the charged intermediate bosons W^+ and W^- to be about 81 GeV/c^2, and the mass of the neutral intermediate boson Z^0 to be about 93 GeV/c^2. Both particles have recently been observed by international teams in experiments using the proton-antiproton collider at the European Laboratory for Particle Physics in Geneva, Switzerland. This successful search is the culmination of fifty years of speculation on intermediate bosons, and an impressive confirmation of the electroweak theory.

The description of particle physics based on elementary quarks and leptons with interactions described by *QCD* and the electroweak theory has come to be called the *standard model* of particle physics. It provides us with a coherent point of view and a single language appropriate for the description of all subnuclear phenomena. This new maturity of particle physics promises new insights into the origin of our world.

Two final points must be made with respect to the standard model: it has not been verified in every detail, and it represents a point of departure, rather than the final word on physical law. The Higgs particle, required to explain the masses of quarks and leptons and of the intermediate bosons, has not yet been observed. Until it is found, we cannot be confident that the standard model correctly explains the electroweak interactions and the masses of the elementary particles. Even if it should be found, some considerations of mathematical consistency and elegance lead many physicists to suspect that our understanding is incomplete. At the same time, the very success of the standard model impels us to seek a more ambitious theory. One important current in present thought is the idea of a *grand unification* of the strong, weak, and electromagnetic interactions into a single *electronuclear* interaction. This is motivated by the similarities between quarks and leptons, and by the fact that *QCD* and the electroweak theory are both gauge theories, with a similar mathematical structure. We shall return to a discussion of some of the frontiers of particle physics after a brief excursion into the realm of the very large.

III. The Standard Model of Cosmology

Cosmology is the study of the origin and evolution of the large-scale structure in the Universe. Cosmology comes from the Greek word *κόσμος*, which means *order*. In the modern sense, the *order* in cosmology is provided by physical law. To understand the present structure of the Universe, we must study its origin and evolution to its present state.

Just as there is a standard model in particle physics, there is a standard model for the origin of the Universe: *the Big Bang* [5]. The Big Bang model explains many of the observed features of the present Universe: the expansion of the Universe (the Hubble recession of galaxies), the existence of a thermal background of photons (the 2.7 K microwave radiation) [6], the cosmic abundance of the light elements (Hydrogen, Deuterium, ^{3}Helium, ^{4}Helium, and ^{7}Lithium), and the existence of structure in the form of galaxies, galactic clusters, etc. In the Big Bang model, the Universe arose in an initial explosion from a state of infinite temperature and density. The Universe then expanded and cooled, eventually reaching the present (*average*) temperature of 2.7 K ($2.3 \cdot 10^{-4}$ eV), some 15 billion years after the initial cataclysm.

To understand the Universe at early times in the cosmic expansion we must understand the behavior of matter under conditions of high density and temperature. It is useful to illustrate this statement by looking back at a few important moments in the history of the Universe.

The oldest astrophysical objects we see in the Universe are *quasars* [7]. The light we see from the most distant quasars was emitted when the temperature of the Universe was about 10 K. At that time, some 13 billion years ago, the Universe already resembled the one we now inhabit. There was an early generation of galaxies and stars, and to the naked eye the night sky might have resembled the one we observe today.

The photons that cooled to become the 2.7 K microwave background last scattered from electrons when the temperature of the Universe was near 5000 K (close to 1 eV). At this early time, some 300,000 years after the Bang, the Universe did not yet resemble its present structure. Its density was so great that the material that became individual galaxies was merged in one great primordial plasma. Stars had not yet formed, and the Universe was hot enough to dissociate any atoms into nuclei and free electrons. The Universe consisted of a cosmic soup of primordial nuclei, electrons, photons, and neutrinos. Our basic understanding of the properties of matter under these conditions allows us to model the behavior of the Universe during this phase.

At still earlier times, about one second after the Bang, when the temperature of the Universe exceeded 1 MeV, any nuclei present would be dissociated into their constituent neutrons and protons. Our knowledge of nuclear physics can be used to predict the relative abundances of elements synthesized when the primordial neutrons and protons cooled enough to combine into nuclei. Primordial nucleosynthesis — the creation of light elements in the original Bang — depends upon the rate of nuclear fusion, which is determined by microphysics, and upon the expansion rate of the Universe. This combination of the physics of the very small and the very large leads to the prediction that the primordial nucleons emerged as Hydrogen nuclei (75 % by mass), ^{4}Helium (24 %), small amounts of Deuterium and ^{3}Helium ($\sim 10^{-5}$), and a trace amount of ^{7}Lithium ($\sim 10^{-10}$). These yields are in the right proportions to explain the present abundances of the light elements.

As we look back toward the initial singularity, the time t elapsed since the Bang is related to the temperature T by

$$t(\text{seconds}) \propto T(\text{MeV})^{-2}. \qquad (1)$$

The numerical relationship is shown more precisely in Fig. 1. Extrapolating back to times earlier than about one second after the Bang, we enter the realm of high energies, in which a knowledge of particle physics is required to describe the interaction of the particles that populated the early Universe [8].

At about 10^{-6} seconds after the Bang, the temperature of the Universe was about 1 GeV, and the density of the Universe was so large that the distance between nucleons was smaller than the size of a nucleon ($\sim 10^{-13}$ cm). Nucleons merged into a plasma of quarks and gluons. The cosmological quark-nucleon phase transition, in which the cooling matter organized itself into protons, neutrons, and other strongly-interacting particles, can be understood in terms of the physical laws discovered in high-energy collisions at particle accelerators. In fact, it may soon be possible for a brief instant to reproduce in the laboratory the conditions present in the early Universe when the quark-nucleon phase transition took place.

The standard model of particle physics enables us to explore the Universe as early as 10^{-14} seconds after the Bang, when the temperature was 100 GeV. Although in the present Universe the electroweak symmetry is hidden, and the intermediate bosons $W^{\pm}$ and Z^0 have large masses, at sufficiently high temperature the symmetry should be restored, and the intermediate bosons will be massless like photons. This phenomenon is similar to the phase transition between the superconducting state and the normal conducting state in metals. At low temperature in a superconducting material, the gauge symmetry of electromagnetism is hidden, and the photon behaves as a massive particle. As the superconductor is heated above the critical temperature for the transition, the symmetry is restored and the photon becomes massless. The dynamics of the electroweak symmetry breaking transition is determined in the standard model by the parameters of the Higgs boson system — the only remaining unexplored sector of the model. As the prototype of a symmetry breaking transition, the electroweak Higgs system may be the key not only to an improved understanding of particle physics, but also to an understanding of symmetry breaking transitions in the history of the Universe. One such transition may have been crucial in producing the Universe we observe.

One of the most interesting recent developments in cosmology has been the suggestion that the large-scale homogeneity and isotropy of the Universe were established during an early symmetry breaking phase transition [9]. According to these ideas, the Universe began in a highly symmetric phase in which all the fundamental interactions were equivalent, and evolved to the present phase in which different forces have different manifestations. The vacuum state of the Universe is modified when the symmetry is hidden. Below the transition temperature the vacuum is occupied by a Bose condensate of a type of Higgs particles, so the vacuum energy of the Universe changes during the transition. It is possible that during the transition the vacuum energy of the Universe was so large that the Universe expanded exponentially. This exponential expansion, or *inflation*, is capable of explaining in a natural way a great deal about the present structure of the Universe: homogeneity and isotropy in the large-scale distribution of galaxies, the large age of the Universe, the spatial flatness of the Universe, and possibly the existence of small primordial perturbations in the distribution of matter that eventually grew to become galaxies, stars, planets, and people.

We know that the inflationary phase did not occur in the electroweak symmetry breaking transition. However, if Nature is more symmetric at high energies than at low energies, the electroweak transition is but the last in a series of similar transitions. Various scenarios have been proposed for the inflationary phase, including the transition accompanying the breakdown of the "grand unified" electronuclear symmetry. Almost all proposals for inflation are associated with spontaneous symmetry breaking, and have their own types of Higgs systems. We are now faced with the prospect of the most revolutionary and exciting development in cosmology depending upon the least understood element of the standard model of particle physics — the Higgs sector. Exploration of the electroweak Higgs sector should give us not only a more complete understanding of the electroweak interactions, but also a model for the mechanism that drives inflation.

IV. Current Issues in Particle Physics

To this point we have summarized our current understanding of the physics of elementary particles and of the evolution of the Universe. On both fronts, the progress of the past decade has been dramatic, and in many respects the resulting vision of our world is extremely satisfying. The successes of the standard models of particle physics and cosmology encourage us to reconsider unsolved problems in a new light, and prompt us to raise many new questions. These include both specific predictions of the new theory and general issues of principle and consistency. Each new success also results in raised aspirations. Our ultimate goal must be not only to describe the world as we find it, but also to understand why it is as it is.

Attempts to test the standard model of particle physics and to overcome its limitations inevitably shape the ongoing program of experimentation at existing accelerators, our expectations for the devices under construction, and the imperative for major new facilities for the 1990s. In this context, the importance of the standard model is that it raises significant questions which create new experience.

Over the next decade, the experimental program at accelerators now operating or under construction will exhaustively test QCD and the electroweak theory, and non-accelerator experiments such as searches for proton decay will explore some of the dramatic consequences of unified theories. It would be presumptuous to say that these investigations will turn up no surprises. However, the consistency and experimental successes of the standard model strongly suggest that to learn why the theory works, where it will break down, and how to construct more complete descriptions of Nature, we need to take a large step in energy. In order to explain what sort of experimental guidance we seek, it is useful to summarize some of the shortcomings and open problems of the current paradigm.

No particular insight has been gained into the pattern of quark and lepton masses. The electroweak theory shows how the masses of the fundamental constituents may arise, but does not enable us to calculate their values. The idea that quarks and leptons should be grouped together into extended families, or generations, is suggested by the need for internal consistency of the electroweak theory, but we do not know why there are three generations, or whether there should be more.

Twenty or more numerical parameters are required to specify the standard model completely. These include the coupling strengths of the strong, weak, and electromagnetic interactions, the masses of the quarks and leptons, and parameters specifying the interactions of the Higgs boson. This seems at odds with our viewpoint, fostered by a history of repeated simplifications, that Nature should be comprehensible in terms of a few simple laws. Much of the appeal of the gauge theory synthesis is precisely that it provides a guiding principle which reduces the arbitrariness of physical law.

We do not have a satisfactory quantum theory of gravity. Can gravity be made consistent with quantum theory, and can it be unified with the other fundamental forces?

When we count the number of apparently fundamental constituents and force particles, we find the 18 quarks (six flavors times three colors) and 6 leptons indicated in Table 1, plus the photon, three intermediate bosons (W^+, W^-, and Z^0), eight colored gluons, and the needed Higgs particle, for a total of **37**. Compared, at least numerically, to the earth, air, fire, and water of antiquity (interacting by means of love and strife), this does not necessarily represent progress! Indeed, encouraged by historical precedent, many physicists are raising the possibility that the quarks and leptons are themselves composites of some still more fundamental constituents. To inspect the quarks and leptons at finer resolution than the current limit of 10^{-16} cm requires studying interactions at higher energies.

The most serious problem of the standard model is associated with the Higgs particle of the electroweak theory. This particle is responsible for the most obvious feature of the electroweak symmetry (that it is hidden), but its dynamical nature is the least understood aspect of the theory. In the standard model, the interactions of the Higgs particle are not prescribed by the gauge symmetry in the same way that those of the intermediate bosons are. Whereas the masses of the W and Z are specified by the theory, the mass of the Higgs particle is only constrained to lie between about 7 GeV/c^2 and 1000 GeV/c^2 (1 TeV/c^2). If the Higgs particle mass exceeds this bound, weak interactions must become strong on the TeV scale. This is perhaps the most general argument that new physics of some sort must show up at or below the energy scale of 1 TeV. The same scale is suggested by all of the theoretical speculations for improving upon the standard model by deepening our understanding of electroweak symmetry breaking.

One possible solution to the Higgs problem is based on the idea that the Higgs particle is not an elementary particle at all, but is in reality a composite object made out of elementary constituents analogous to the quarks and leptons. Although they would resemble the usual quarks and leptons, these new constituents would be subject to a new kind of strong interactions, often called "technicolor," that would confine them within about 10^{-17} cm. Such new forces could yield new phenomena as rich and diverse as the conventional strong interactions, but on an energy scale a thousand times greater — around 1 TeV. The new phenomena would include a rich spectrum of bound states, akin to the spectrum of known hadrons.

A second approach to the Higgs problem involves the introduction of a complete new set of elementary particles whose spins differ by one-half unit from the know quarks, leptons, and force particles. These postulated particles are the consequences of a new "supersymmetry" which relates particles of integer and half-integer spin. They are likely to have masses less than about 1 TeV/c^2.

Both general arguments and specific conjectures for resolution of the Higgs problem point to the necessity of new phenomena and important clues at energies between a few hundred GeV and a few TeV. Exploration of this regime therefore seems a clear and compelling goal for the 1990s.

V. The Superconducting Super Collider

How can we reach the 1 TeV scale for fundamental particle interactions? The charged particles that are stable, and so can be accelerated with relative ease to high energies, are the electron and proton together with their antiparticles the positron and antiproton. One of the important developments in accelerator technology over the past two decades has been the mastery of techniques for bringing two high-energy beams into (nearly) head-on collision. The advantage of the colliding beams approach over more conventional fixed-target collisions is that of higher available energies. For the same reason that a head-on collision of automobiles is more violent than a rear-end collision, colliding beams are more effective than the interaction of one beam with a stationary target. To reach several TeV in collisions among the fundamental particles, we may contemplate an electron-positron collider with beam energies of 1 to 3 TeV, or a proton-(anti)proton collider with beam energies of 5 to 20 TeV. The higher beam energy required for protons simply reflects the fact that the proton's energy is shared among its quark and gluon constituents. Very roughly, each constituent carries on average about one-tenth of the proton's total energy. The third combination, an electron-proton collider, does not seem appealing for initial exploration because no such machine has been operated, and it appears difficult to achieve the high interaction rates necessary to study rare phenomena.

While both the electron-positron and proton-proton colliders can in principle access the 1 TeV scale, the physics to be studied is by no means identical. The proton machine provides a wider variety of constituent collisions, which allows for a greater diversity of phenomena. The well-defined initial state of the electron machine simplifies the experimental task of detecting and measuring the many particles produced in a high energy collision. Whether richness or simplicity is to be preferred is impossible to decide in advance. There is, however, a decided difference in the feasibility of the two styles of machines. The superconducting magnet technology won by the investment of more than two decades of research and development effort and brought to practical reality for the Fermilab *Tevatron* can be exploited in a very high energy proton synchrotron [10]. In contrast, it seems quite unlikely that a practical electron synchrotron can reach TeV energies. New developments, along the lines being explored in the Stanford Linear Collider, appear essential to the creation of TeV beams of electrons. Because the required technology is in hand, the proton collider is the instrument of choice for the first exploration of the TeV regime.

The *SSC*[11] will have two counter-rotating beams of protons guided by superconducting magnets along circular orbits about 100 km in circumference within evacuated metal beam pipes about 4 cm in diameter. Each beam will be accelerated by radio-frequency cavities to 20 TeV, and the two beams will be brought into collision at approximately six different interaction regions around the accelerator ring. Sophisticated detectors will be installed at the collision points, to analyze the products of the very high-energy interactions. The supercollider itself will be the final stage in a complex of cascading accelerators, each optimized for acceleration of protons in a particular energy range. Injection of the proton beams into the *SSC* itself will occur at roughly 1 TeV. A sketch of the proposed *SSC* complex is shown in Fig. 2.

The large-scale utilization of superconductivity will be essential to the supercollider, for the greater field strength of superconducting magnets, as well as the low power consumption implied by the absence of resistive heating. The magnets will use a Niobium-Titanium alloy cooled to about 4 K, requiring major cryogenic systems. The resulting magnetic fields of about 6 Tesla ($\sim 100,000$ times the Earth's magnetic field) are three times higher than can be attained with conventional warm-iron electromagnets. The radius of the accelerator tunnel is therefore a factor of three smaller than would be required with conventional magnets.

The *SSC* has captured the imagination of the U. S. high energy physics community. Since a commitment to the *SSC* project was recommended in 1983, many elementary particle physicists have contributed to studies of the scientific issues to be addressed, the feasibility of experiments, and the design of the accelerator itself. As a result of design studies conducted since 1982, it is believed that the *SSC* could be operational by 1994, at a cost of $3 Billion. A Central Design Group funded by the Department of Energy has been formed by Universities Research Association, a consortium of 56 major universities in North America, and charged with formulating a specific construction proposal. Considerable progress in the development of accelerator components has been made in the national laboratories, the universities, and industry, and a complete conceptual design of the supercollider is underway.

The challenge before us is the same one met in the past by Galileo, Newton, Einstein, and our other illustrious ancestors: to build a complete understanding of Nature, from the structure and interactions of the fundamental particles of matter to the origin and evolution of the Universe. To meet this challenge we require a powerful new scientific instrument — the *SSC*. The commissioning of the Supercollider in the mid–1990s will come at the end of a century during which society has made immense investments of material and human resources toward the advancement of scientific knowledge; investments that have reaped unprecedented returns in technology and basic knowledge. The *SSC* will affirm our commitment to continue the exploration of Nature as we enter the twenty-first century.

We expect that great discoveries will be made at the *SSC*. Perhaps the discoveries will be the ones anticipated, but we may find instead that Nature is subtler and more beautiful than we now imagine, and be forced to revise today's standard models of particle physics and cosmology. Our successors in the next century may find amusement in our models in much the same way that we look upon the descriptions of Nature of the middle ages. We hope that our efforts will not be found lacking in boldness, imagination, and commitment in our quest for knowledge in areas once thought to lie forever outside the realm of human comprehension.

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[2] A convenient unit of energy is the electron-volt (eV), the energy acquired by a unit (electron) charge falling through a potential difference of 1 volt. We use the abbreviations 1 MeV (= 10^6 eV), 1 GeV (= 10^9 eV), and 1 TeV (= 10^{12} eV). Masses are expressed in terms of their relativistic equivalents in units of eV/c^2, where c is the speed of light *in vacuo*.

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Figure Captions

Figure 1: A schematic history of the Universe, from the Big Bang to the present.

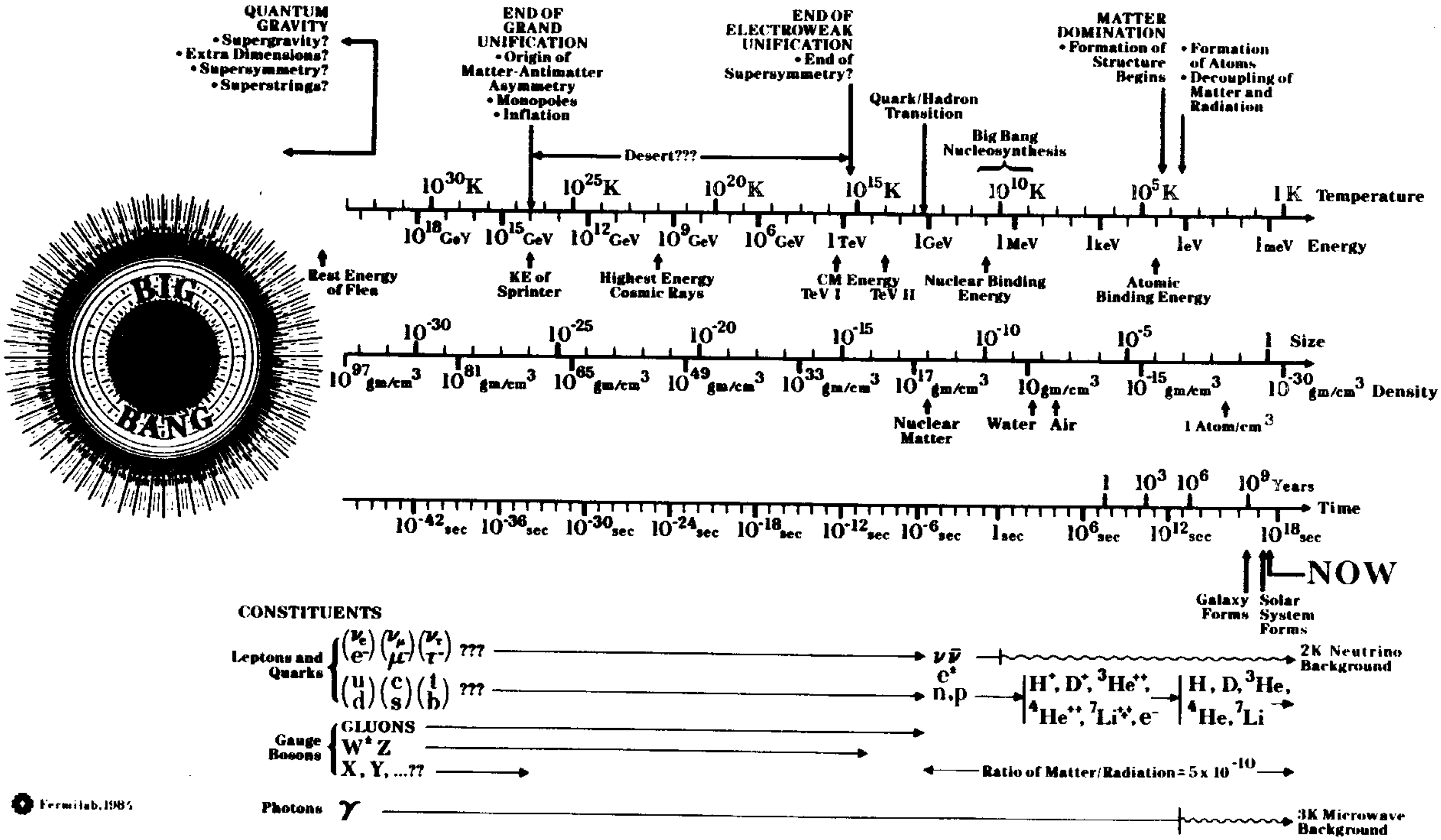
Figure 2: Artist's conception of the proposed accelerator, the Superconducting Super Collider, which will make it possible to study interactions among the fundamental particles at energies of more than 1 TeV.

Table 1. The Elementary Constituents of Matter

LEPTONS (Color Neutral)				**QUARKS (Color Triplets)**			
Particle name	Symbol	Mass (MeV/c^2)	Electric Charge	Particle name	Symbol	Mass (MeV/c^2)	Electric Charge
electron neutrino	ν_e	~ 0	0	up	u	310	2/3
electron	e or e^-	0.511	-1	down	d	310	−1/3
muon neutrino	ν_μ	~ 0	0	charm	c	1500	2/3
muon	μ or μ^-	106.6	-1	strange	s	505	−1/3
tau neutrino	ν_τ	< 164	0	top/truth	t	$\gtrsim 22,500$	2/3
tau	τ or τ^-	1784	-1	bottom/beauty	b	5000	−1/3

Table 2. The Fundamental Forces and Their Carriers

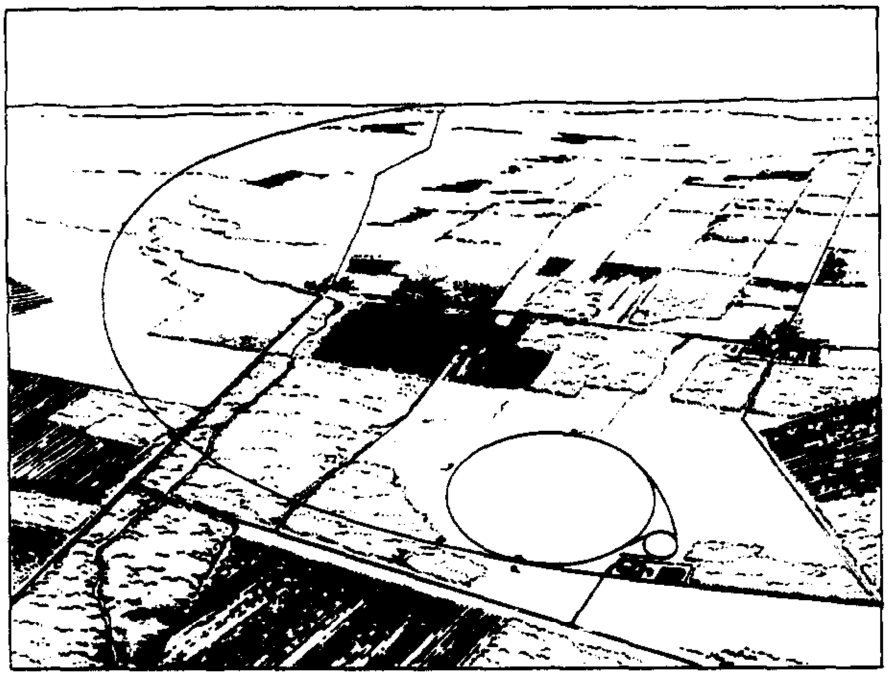
Force	Behavior over distance	Relative Strength at 10^{-13} cm	Carrier	Mass (GeV/c^2)	Spin	Electric Charge	Color Charge	Remarks
Gravity	Extends to very large distances	10^{-38}	graviton	0	2	0	0	*conjectured*
Electro-magnetism	Extends to very large distances	10^{-2}	photon	0	1	0	0	observed directly
Weak	Limited to less than 10^{-16} cm	10^{-13}	intermediate bosons: $W^{\pm}$ Z^0	81 93	1	± 1	0	observed directly
Strong	Limited to less than 10^{-13} cm	1	gluon	0	1	0	octet	permanently confined

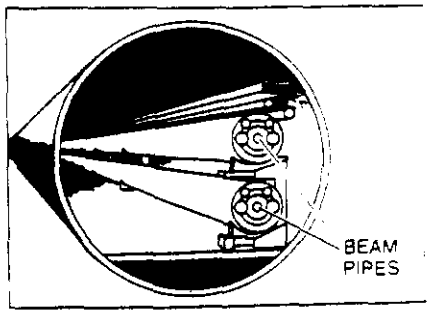


QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
Desert???
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
BIG BANG
10^30 K
10^25 K
10^20 K
10^15 K
10^10 K
10^5 K
1 K
Temperature
10^18 GeV
10^15 GeV
10^12 GeV
10^9 GeV
10^6 GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I TeV II
Nuclear Binding Energy
Atomic Binding Energy
10^-30
10^-25
10^-20
10^-15
10^-10
10^-5
1
Size
10^97 gm/cm^3
10^81 gm/cm^3
10^65 gm/cm^3
10^49 gm/cm^3
10^33 gm/cm^3
10^17 gm/cm^3
10 gm/cm^3
10^-15 gm/cm^3
10^-30 gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^3
10^6
10^9 Years
Time
10^-42 sec
10^-36 sec
10^-30 sec
10^-24 sec
10^-18 sec
10^-12 sec
10^-6 sec
1 sec
10^6 sec
10^12 sec
10^18 sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
(ν_e e^-) (ν_μ μ^-) (ν_τ τ^-) ???
(u d) (c s) (t b) ???
ν ν̄
e^±
n, p
2K Neutrino Background
H^+, D^+, ^3He^++, ^4He^++, ^7Li^+++, e^-
H, D, ^3He, ^4He, ^7Li
Gauge Bosons
GLUONS
W^± Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^-10
Photons γ
3K Microwave Background
Fermilab, 1984

Fig. 1

Figure 2 will be a revised version of this.





PROPOSED ACCELERATOR, the Superconducting Supercollider, will make it possible to study interactions at energies of more than 1 TeV. In the design depicted (one of many) the accelerator ring has a diameter of 30 kilometers and is buried 100 meters underground: smaller rings feed protons into the large ring. A cross section of the main tunnel (*above*) shows the two pipes, each about five centimeters in diameter, which will contain the counterrotating beams of protons. Superconducting magnets supercooled with liquid helium to increase their power and efficiency surround each of the pipes, focusing and confining the beams.