THEORETICAL INTERPRETATION OF e^+e^- RESULTS

Haim Harari
Weizmann Institute of Science, Rehovot, Israel
and
Stanford Linear Accelerator Center, Stanford University
Stanford, California, U.S.A.

Summary

Recent experimental results and theoretical ideas related to e^+e^- scattering are reviewed.

1. INTRODUCTION: A Long List of Answerable Questions

The study of electron-positron collisions has gradually become the most productive experimental method of uncovering new particles and new phenomena. Beginning with the "November revolution" of 1974 and continuing at an incredibly rapid pace since that time, the ψ family, the τ-lepton, the D^+ and D^o, various D^*'s and possibly F^+ were discovered in e^+e^- collisions, while the Υ-states, the charmed baryons as well as quark jets and now gluon jets have been studied.

Our present theoretical picture of the fundamental particles and their interactions is very compact. We describe everything in terms of twelve gauge bosons (W^+, W^-, Z^o, γ and eight gluons) and twelve quarks and leptons, neatly arranged in three "generations": (u, d, ν_e, e); (c, s, ν_μ, μ); (t, b, ν_τ, τ). All interactions of these bosons and fermions are described by an $SU(3)_c \times SU(2) \times U(1)$ gauge theory, in which $SU(3)_c \times U(1)$ is an exact symmetry while the remaining symmetries are spontaneously broken, presumably by the Higgs mechanism. A very long list of theoretical questions accompanies this "standard" picture. Some of these questions have been answered during the last five years. Others are still open. However, every single one of them relates to past, present or future experiments in electron-positron scattering. An incomplete list of these questions, arranged according to the various gauge fields or the relevant fermionic "building blocks" includes:

QED: Are electrons "pointlike"? Up to what energies is QED valid?

Weak Interactions: Do W^+, W^- and Z^o exist? Do they have the predicted masses? Are there additional, heavier, W and Z bosons? Is $SU(2) \times U(1)$ the full electroweak group? Do Higgs mesons exist and if so, are they composite?

QCD: Do gluons exist? Do they have J=1? What are the properties of gluon jets? Are gluons "flavor-blind"? What is the value of α_s? Does it "run" as a function of momentum? Is there a three-gluon coupling?

First Generation Fermions: Are quarks and leptons pointlike? Do quarks come in three colors? Do they have the "usual" charges of $\frac{2}{3}$ and $-\frac{1}{3}$?

Second Generation Fermions: Is the right-handed muon in an $SU(2) \times U(1)$ singlet? Is the $\bar{c}s$ current a V-A current? What is the $c\bar{c}$ potential? Where are the pseudoscalar charmonium states? Do semileptonic D-decays proceed mainly to strange particles, as predicted by GIM? What are the features of nonleptonic D-decays? What are the properties of F^+, Λ_c^+, Σ_c etc?

Third Generation Fermions: Does the top quark exist, and if so, what is its mass? Do B-mesons and T-mesons exist? Are the charged currents involving t and b, left-handed? What are the values of the generalized Cabibbo angles θ_2, θ_3 and the Kobayashi-Maskawa phase δ? Can these parameters account for all weak transitions among the three generations of quarks? What are the properties of τ? Is ν_τ massless?

Beyond: Are there additional generations, following the same pattern? Are there "exotic" quarks and leptons?

Our list of questions seems almost endless. However, as we shall see in this report, all of them are related to recent experimental e^+e^- results or to e^+e^- experiments which will be performed during the next few years. We will review the present theoretical situation in view of the new experimental data which were presented at this conference, and will pose some answerable questions to future experiments.

A schematic "map" of present and future e^+e^- energies is shown in figure 1. Every new energy range has, so far, yielded some entirely new features. We are almost guaranteed that this will continue to be the case, at least up to energies of 200 GeV or so. I, personally, believe that beyond that range, many surprises are awaiting us.

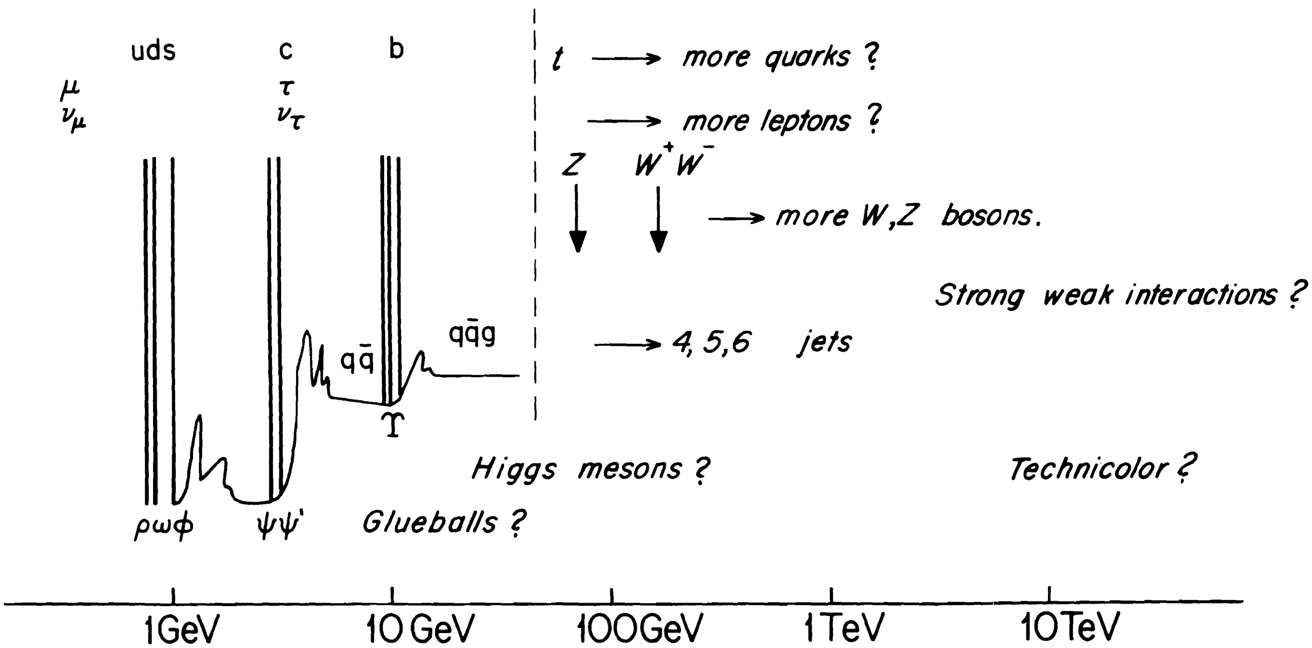

Fig. 1: A schematic "map" of e^+e^- scattering. An impressive array of major discoveries covers the left half of the map. Speculations and hopes for the future are on the right.

2. The Pattern of Fermion Generations

2.1. "Exotic" Quarks and Leptons.

Electron-positron collisions are particularly suitable for the discovery of new types of quarks and leptons. One of the most remarkable experimental facts is actually the absence (up to $E_{c.m.} \sim 30$ GeV) of any "exotic" quarks and leptons. All known quarks have charges $\frac{2}{3}$ or $-\frac{1}{3}$ and are, presumably, color triplets. All known leptons have charges 0 or -1 and are colorless. All known quarks and leptons are probably $J = \frac{1}{2}$ objects. The observed pattern of generations involves unexplained repetitions of these quantum numbers, reminding us of the repeated discoveries of SU(3) octets, decuplets and singlets of hadrons in the 1960's. In analogy with the concept of exotic hadrons we may define "exotic quarks and leptons" to be any such particles which do not repeat the existing pattern. Exotic leptons might have $Q = \pm 2$ and/or spin $\frac{3}{2}$. Exotic quarks might be color sextets and/or have spin $\frac{3}{2}$ and/or have $Q = \frac{5}{3}, -\frac{4}{3}$ etc. Fortunately, all such objects should be relatively easy to detect in e^+e^- collisions, and should contribute to the R-value more than their nonexotic counterparts. Various authors have suggested that the b-quark may be a color sextet[1] or that the τ-lepton has[2] spin $\frac{3}{2}$. There is neither theoretical need nor experimental evidence for these proposals, but some of them cannot yet be definitely excluded. The observed values of R at $E_{c.m.} \sim 30$ GeV indicate that,[3,4,5,6] at most, an additional $Q = -\frac{1}{3}$ quark may exist below that energy, and that any "exotic" quarks and leptons are unlikely. It is extremely important to pursue the search for such states. While we do not understand the generation pattern, we at least have a well-defined puzzle. It would be useful to know whether the puzzle is stated properly!

2.2. Where is the Top Quark?

The PETRA experiments indicate that the $T\bar{T}$ threshold has not been reached until $E_{c.m.} = 31.6$ GeV.[3,4,5,6] This means that the lowest lying $t\bar{t}$ ("topponium") bound state cannot be below, say, 29 GeV and that the mass of the t-quark must be above 14 or 15 GeV. Most (but not all) theoretical predictions place the t-quark between 11 and 15 GeV.[7] However, none of these predictions are based on any fundamental principle or serve as a serious test of important new ideas. One popular relation among quark masses which has been derived from various sets of assumptions is:[8]

$$\frac{m_u \cdot m_c \cdot m_t}{(m_t - m_c + m_u)^3} = \frac{m_d \cdot m_s \cdot m_b}{(m_b - m_s + m_d)^3}$$

Using the "current masses" for the light quarks, this gives $m_t \sim 13$ GeV. However, an important ingredient in all the derivations is the "technical" assumption that there are only two Higgs multiplets. With three, one could get almost any value of m_t. If m_t is well above 14 or 15 GeV, it would simply mean that some of the technical assumptions are not valid.

It would be very nice if the $t\bar{t}$ state is found somewhere around 34 GeV, at the highest luminosity point of PETRA and PEP and at the highest available energy which still allows the production of $T\bar{T}$ pairs and, at the same time, offers the best opportunity of studying the gluon jets in topponium decay. Let us hope that this will be the case, and that the t-mass will turn out to have the "most profitable" value of 17 GeV.

2.3. How Many Generations?

The present list of quark and lepton mass-values reads almost like a table of random numbers. We cannot make any sense out of it. The discovery of additional generations might eventually give us some clues concerning mass regularities. There are several arguments which place limitations on the number of quarks and leptons or on their maximal allowed mass values. Such arguments are based on asymptotic freedom,[9] on calculations of helium abundance in cosmological models,[10] on radiative corrections[11] to the Weinberg mass relation $M_W = M_Z \cos\theta_W$ and on the properties of the Higgs potential.[12] None of these arguments is totally compelling and it is not completely unthinkable that we actually have a very large number of generations. One point of view which has recently been emphasized by several authors, states that the actual number of generations is an important parameter, related to the size of some large group whose representation incorporates all generations.[13] A different opinion, which I, personally, believe in, is that the number of generations is not a particularly relevant parameter. It may be very large, in which case the physics of the first few generations will not depend on whether or not the 10th generation exists and on its mass value. On the other hand, the number of generations may be relatively small (say 3,4 or 5) and the limitation may be some "critical" maximal mass value which is analogous to the "ionization" energy of a composite system. (After all, the number of energy levels of the deuterium nucleus is not a fundamentally important parameter even as far as the N-N force is concerned!).

In any event - future e^+e^- machines such as LEP should help clarify these issues.

3. Second Generation Physics

3.1. "Charmonium".

A year ago, the main remaining experimental puzzles of the ψ-family were the peculiar properties of the two candidates for the $J^{PC} = 0^{-+}$ $c\bar{c}$-states. The X(2.85) and $\chi(3.45)$ were too far below the ψ and ψ', respectively. Much more puzzling and difficult to explain was the claim that X(2.85) had a substantial branching fractions into $\gamma+\gamma$ while $\chi(3.45)$ liked to decay into $\gamma+\psi$. Theoretically, one would expect that the hadronic widths of these states are of the order of a few MeV and that their radiative decays are quite rare.

It is with great relief that we have now heard[14] about the disappearance of these two states. The beautiful results of the crystal ball experiment[14] provided us with new upper limits for $B(\psi\to\gamma+X)\cdot B(X\to\gamma\gamma)$ and for $B(\psi'\to\gamma+\chi(3.45))B(\chi(3.45)\to\gamma+\psi)$. These limits convince us that the simple theoretical notions are, again, reasonable and that the X(2.85) and $\chi(3.45)$ puzzles were either unfortunate statistical fluctuations or experimental errors (or both).

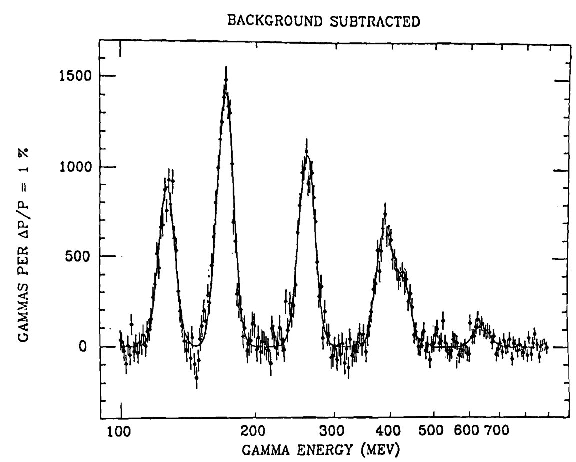

Fig. 2: The new candidate for η_c : the U(2.98) of the crystal ball group

But the crystal ball experimenters did not stop at "killing" previous particles. They have now found evidence[14] (figure 2) for a new candidate for η_c at 2.98 GeV. They use the (hopefully temporary) name U(2.98). The mass is much more in line with naive theoretical expectations (although still a little low) and the $\gamma\gamma$ decay mode is not observed, so far. The branching ratio for $\psi'\to\gamma$+U(2.98) is not yet quoted but is probably a substantial fraction of 1%. Theoretically, it is hard to estimate this rate because it represents a small overlap integral of almost orthogonal wave functions. However, numbers in the general neighbourhood of 1% were quoted by various authors.[15] It is more easy to calculate the decay width for $\psi \to \gamma + U(2.98)$. The obtained numbers are of the order of 1 keV or so, well within the present sensitivity of the crystal ball experiment. It will be extremely surprising if this decay is not observed soon. The simplest hadronic decay modes of the new state are expected to be 4π, $4K$, $\pi\pi KK$, $\rho\rho$, $\phi\phi$ etc.

The η_c' should now have a mass around 3.61 GeV (the ψ'-η_c' splitting should be somewhat smaller than the ψ-η_c splitting in the simple potential picture). Its observation will be experimentally very difficult. The decay $\eta_c' \to \pi^+\pi^-\eta_c$ may be useful as a means of identifying η_c' in the process $\psi' \to \gamma + \eta_c'$, $\eta_c' \to \pi^+ + \pi^- + \eta_c$, $\eta_c \to$ anything.

Qualitatively, the charmonium spectrum looks better than ever, and no major outstanding puzzles remain.

3.2. Prompt Photons from ψ-decay.

A simple-minded theorist who did not hear about QCD might argue that the decay $\psi \to \gamma$+hadrons should be supressed by a factor of α relative to $\psi \to$hadrons. QCD tells us that, in lowest order, the ratio is actually[16] $\frac{16}{5}\frac{\alpha}{\alpha_S} \sim 0.1$. The single γ spectrum is predicted[16] to be "hard", i.e. most photons have $x > \frac{1}{2}$, and the resulting hadronic system should often have J=2. These predictions can be tested in the near future. Preliminary results from the lead-glass wall[17] and the Mark II[18] experiments indicate a substantial branching ratio for $\psi \to \gamma$+hadrons, in accordance with the QCD expectation (although the theoretical higher-order corrections may be quite large). More data should soon come from these and other ψ experiments as well as from Υ decays. These radiative decays are very interesting and we would like to encourage their investigation.

3.3. Semileptonic D-decays.

The most direct test of the GIM prediction[19] for charm decay is, of course, the statement that semileptonic D-decays should mostly proceed into strange-particle final states and that the ratio $\Gamma(c \to d + e^+ + \bar{\nu}_e)/\Gamma(c \to s + e^+ + \bar{\nu}_e)$ is given by $\tan^2\theta_c$, if we neglect the mixing with third-generation quarks. Experimentally, we now know that most nonleptonic D-decays go into K-mesons but we still do not have a good measurement of the K/π ratio in semileptonic D-decays. We appeal to the various groups which study D-decays and ask them to confirm this basic GIM prediction. Once this is done, it would be nice to see whether the $c \to s + e^+ + \nu_e$ decay goes through a V-A current and, eventually, even to learn something about the generalized Cabibbo angles, θ_2 , θ_3. The best data on this issue, so far, comes from bubble chamber neutrino experiments[20] in which μeK combinations are observed. However, an accurate measurement can come only from e^+e^- experiments. This is a typical important experiment which remains to be done in the energy range of SPEAR and DORIS. Many such experimental questions are still open and should provide us with a rich and fruitful program for these machines for the next several years.

3.4. Nonleptonic D-decays

Many new results have been presented by the MARK II[21] and DELCO[22] groups, concerning D-decays. Two interesting theoretical puzzles have been provided to us, one by each group. MARK II has measured the Cabibbo suppressed nonleptonic decays $D^o \to K^+K^-, \pi^+\pi^-$. Both decays are indeed strongly suppressed relative to, say, $D^o \to K^-\pi^+$. However, their relative rate is surprising. While most simple mechanisms predict a 1:1 ratio (with small corrections due to phase space and to the θ_2 and θ_3 mixing angles), the MARK II group found:[23]

$$\frac{\Gamma(D^o \to K^+K^-)}{\Gamma(D^o \to \pi^+\pi^-)} \sim 3\text{-}4$$

The second puzzle is provided by the DELCO group which finds[22] a large discrepancy between the semileptonic branching ratios of D^+ and D^o, leading to the conclusion that:

$$\frac{\Gamma(D^o \to \text{Nonleptonic})}{\Gamma(D^+ \to \text{Nonleptonic})} \gtrsim 5$$

Here, again, we would probably guess that the nonleptonic rates are, more or less, comparable.

Like all theoretical problems in nonleptonic decays, these two puzzles are probably not of great fundamental importance. Nonleptonic decays involve a complicated interplay between the weak current-current interaction and strong interaction (QCD?) effects. Each nonleptonic decay may proceed by several mechanisms, none of which can really be calculated, at present. There are still many open theoretical problems concerning nonleptonic decays of strange particles, where data have been available for twenty years or more!

It is interesting, however, to speculate on possible explanations of the two surprising ratios mentioned above. The decays $D^o \to K^+K^-, \pi^+\pi^-$ proceed via two classes of mechanisms. In one class (figure 3a) the W-boson is exchanged between two different quark lines. In the other mechanism the W is emitted and reabsorbed

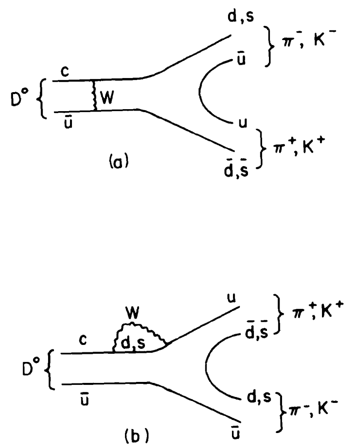

Fig. 3: Two possible mechanisms for the Cabibbo suppressed nonleptonic decay $D^o \to \pi^+\pi^-$, K^+K^-. The surprising branching ratio follows from interference between the two mechanisms.

by the same quark (figure 3b). In both cases, of course, gluons are exchanged (not shown in the figure). Each mechanism, by itself, would predict a ratio of 1 between the two rates (except for small corrections). However, the relative phase of the K^+K^- and $\pi^+\pi^-$ amplitude is opposite in the two mechanisms. Hence the relative decay rates are given by:

$$\frac{\Gamma(D^o \to K^+K^-)}{\Gamma(D^o \to \pi^+\pi^-)} = \left|\frac{b+a}{b-a}\right|^2$$

where a,b are, respectively, the amplitudes due to the mechanisms of figures 3a, 3b. It is clear that the branching ratio can vary over a wide range of values, depending on the relative amplitudes for the two mechanisms. In particular, if $a/b \sim 3$-4, the experimental branching ratio is reproduced. Since we do not know how to estimate a, and especially b, we cannot consider this to be an explanation of the observed ratio. However, we suspect that the substantial deviation of the ratio from one is due to the interference between the two mechanisms, and that it tells us that their relative strength is approximately 3:1 in amplitude.[24]

The second puzzle indicates that D^o nonleptonic decays are substantially enhanced. In fact, the branching ratio $\Gamma(D^+ \to e^+ + \text{anything})/\Gamma(D^+ \to \text{all}) \sim 20\%$ is in agreement with the most naive considerations which suggest equal decay probabilities of the charmed quark into $se^+\nu_e$, $s\mu^+\nu_\mu$ and the three $su\bar{d}$ channels. It would therefore appear that D^+ nonleptonic decays are neither enhanced nor suppressed while D^o decays are enhanced by a factor of five or more. The <u>relative</u> nonleptonic branching ratios of D^o into $K\pi$, $K\pi\pi$, $K\pi\pi\pi$ are roughly similar to those of D^+ into the analogous channels.[21] It, therefore, appears that the enhancement of nonleptonic D^o-decays is common to all or most decays and is not specific to any particular final state. One possible reason may be the enhancement of the diagram in figure 4 which has no analogue in D^+ decay, and which exsists for all final hadronic states in D^o decay.[25] Again, we do not know how to calculate the enhancement of this diagram with great confidence.

It appears that with increasing experimental information on nonleptonic decays we may be able to have at least a better phenomenological, if not a theoretical, understanding of the role played by the different mehcanisms.

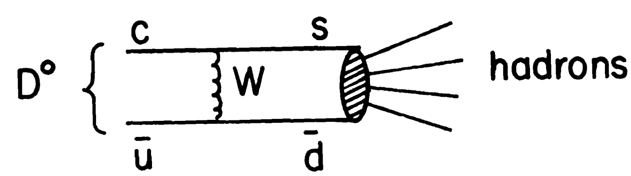

Fig. 4: One contribution to D^o nonleptonic decays, which is probably responsible for the enhanced width.

3.5. Charmed Baryons.

The MARK II collaboration has presented beautiful confirmation of the production of Λ_c^+($\equiv$ cud) baryon in e^+e^- collisions.[21] They quote a mass value of 2285 ± 6 MeV, inconsistent with almost all earlier experiments[26] which found values around 2260. This is a clear experimental discrepancy, which will be settled, sooner or later. Normally, such a difference would not be particularly interesting. However, there are indications that Σ_c is around 2420 MeV.[27] If this is so, $m(\Sigma_c) - m(\Lambda_c) < m(\pi^\pm)$ for the MARK II mass, but $> m(\pi^\pm)$ for the "older" mass. In the latter case $\Sigma_c^{++} \to \Lambda_c^+ + \pi^+$ is an ordinary strong decay. However, if the MARK II value is correct and if the difference is less than $m(\pi)$, Σ_c^{++} is a "stable" doubly charged baryon, decaying only by weak interactions. It would provide for interesting emulsion and bubble chamber events.

3.6. A Pleasant Situation.

The overall picture is that both the charmonium system and the charmed hadrons are behaving as predicted. We, of course, would like to confirm the F^+ and η_c, find η_c' , find more charmed baryons, and understand various features of the charmonium potential and the nonleptonic charm decays. However, no serious crisis exists and we may happily pursue the various details without worrying about any fundamental puzzles, at this stage.

4. Third Generation Physics

4.1. The T Family.

There are no great news from the T-family. The decay of T into hadrons is consistent with the picture of three gluons but cannot prove it. The energy is simply not high enough to enable us to observe three distinct jets. A spherical phase space and a two-jet picture for hadronic T decay are clearly excluded.[28] Planarity is consistent with the data, but in our opinion, this is as far as one can go. We will have to wait for the $t\bar{t}$ states in order to clearly see three gluon jets.

No new data are available on $T \to e^+e^-$, $T' \to e^+e^-$, $T' \to T\pi\pi$ etc. Each of these processes is interesting in comparison with their analogues in the ψ-family. QCD predicts different quark-mass dependences for different processes, and it would be interesting to see whether these are obeyed. Discovery of η_b and other $C = +1$ states will presumably have to wait for CESR.

4.2. B-Mesons

Direct detection of B-mesons is most likely in decays into $D\pi$, $D\pi\pi$,..., and ψK, $\psi K\pi$,... . The two classes of decays are expected to be equally difficult to observe in e^+e^- collisions. Some indications for a B-meson at 5.3 GeV have been presented by an experiment using a π-beam and the Goliath magnet at CERN[29] (one of the authors is David!). The evidence is not yet statistically convincing and the claimed production cross section is extremely large. It would be interesting to see whether the evidence is improved with increased statistics. Searches for B-mesons could be conducted at e^+e^- energies above 10.5 GeV, and are especially suitable for the CESR energy range. However, above the t-quark threshold, most T-mesons should decay into B-mesons (following the chain $t \to b \to c \to s$) and the percentage of hadronic events containing B-mesons should reach 30% (as opposed to 9% immediately above B-threshold). Indirect detection of B-mesons should be relatively simple by observing multilepton events. Assuming a 20% total semileptonic branching ratio for both b and c decay, the chain $b \to c + \ell^- + \bar{\nu}$, $c \to s + \ell^+ + \nu$ should yield a couple of four-lepton events, 25 three-lepton events and 150 two-lepton events for every 1000 $B\bar{B}$ pairs. A particularly clear signal would come from two equal-sign leptons, one from $b \to c$ and one from $\bar{c} \to \bar{s}$ (or from $\bar{b} \to \bar{c}$ and $c \to s$). Approximately 5% of all $e^+e^- \to B\bar{B}$ events (or 0.5% of all hadronic events at, say, $E_{c.m.} = 11$ GeV) should have such lepton pairs. The above numbers assume that the bottom quark decays predominantly into a charmed quark. This is not yet experimentally verified, and would be very interesting to see.

4.3. T-mesons and the Full Six-Quark Scheme.

T-mesons should, of course, exist above the $b\bar{b}$ threshold and are predicted to decay mostly into mesons containing the bottom quark. Interesting decays would be $T \to B\pi$, $B\pi\pi$... . None of these are easy to detect. The leptonic cascades from T-decay should be even more impressive than those of B-decay and the chain $t \to b \to c \to s$ may yield up to six-lepton events (at a rate of one for every 1500 $T\bar{T}$ events). One of every 70 $T\bar{T}$ events should contain four charged leptons! It would be extremely interesting to use this proliferation of lepton events for the study of B and T-decays.

The real excitement should come when we have data for a sufficient number of c,b and t decays and we will be able not only to determine the generalized Cabibbo angles θ_2 and θ_3 (and their relative sign) but also to test the entire six-quark scheme by expressing a large number of decay amplitudes in terms of the same three angles.[30] Only then, will we know whether the generalized GIM picture is correct. Unfortunately, many of the necessary experiments are extremely difficult and a decade will probably pass before all the returns are in.

4.4. The τ-Lepton and its Neutrino.

All is well with τ. New measurements of $\tau \to \pi\nu$ and $\tau \to \rho\nu$ are in magnificent agreement with theory.[21] The decays $\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$ looks more and more like a normal V-A decay.[22] We have reached the stage in which most of the "routine" properties of the τ-lepton are confirmed. The next stage would be a much more accurate investigation of fundamental properties such as the pointlike nature of τ (best probed by the energy dependence of $e^+e^- \to \tau^+\tau^-$), improved bounds on the mass of ν_τ and improved limits on τ-number violating decays such as $\tau^- \to e^-\gamma, \mu^-\gamma, \ell^-\ell^-\ell^+$ where $\ell = e$ or μ. The MARK J collaboration[3] at PETRA presented a first measurement of $\sigma(e^+e^- \to \tau^+\tau^-)$ (figure 5). While the statistics are still modest, it is very likely that within a few months we will be able to use this process for meaningful tests of QED and of the pointlike behaviour of τ.

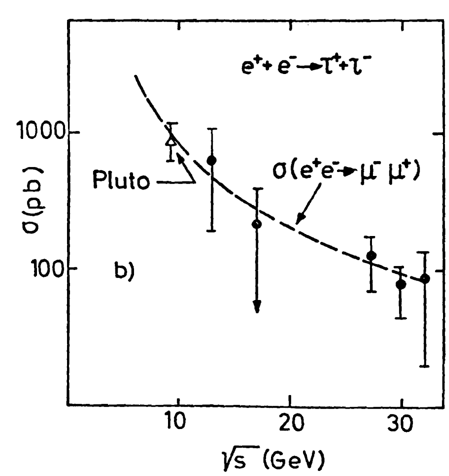

Fig. 5: Preliminary MARK J results on $e^+e^- \to \tau^+\tau^-$, testing QED and the pointlike nature of τ.

5. Quantum-Chromo-Dynamics

5.1. Confronting QCD With Experiment

QCD is the only description of the strong interactions which deserves the name "theory". At present, it has no real competition. This may mean that it is the correct theory, but it may also mean that our imagination is not yet sufficient for finding the correct theory. It is extremely important to confront well-defined predictions of QCD with experimental data. As we shall see below, such predictions are not easy to derive. However, before we discuss the art of extracting meaningful predictions from QCD, we would like to address a few words of caution to our experimentalist colleagues. It serves no purpose to compare data with non-existing dead "theories" such as "scalar gluon theory", "spherical phase space" and the like. These "theories" do not exist in any meaningful way, and their so-called predictions are manifestly wrong everywhere. The fact that some data "is not consistent with scalar gluon theory" or with phase space, teaches us little or nothing. Whenever QCD leads to a well-defined prediction, data of better and better accuracy should be obtained, trying to narrow the maximal possible discrepancy between theory and experiment. This is the way we treat QED (no one makes a fuss about the muon g-2 not agreeing with scalar QED or about $\sigma(e^+e^- \to e^+e^-)$ not agreeing with spherical phase space). This is also the way we should treat QCD, as long as no other theory is available. During the last few years a substantial number of unjustified claims "proving" or "confirming" QCD were made by several experimental groups, especially in deep inelastic scattering experiments and in Υ-decay, but also in other cases. We would like to suggest much more caution in the analysis of such data.

Deriving meaningful, testable, predictions from QCD is not easy. The difficulties are encountered on two different levels. The first level is the quark-gluon level. Here, lowest order QCD predictions are not difficult to obtain but are subject to three types of doubts: (1) There may be important nonperturbative effects. (ii) So called "higher-twist" terms may contribute. (iii) Higher order corrections may be important, or even dominant. A common feature of all of these effects is the fact that they are expected to diminish when the momentum increases. While we cannot yet handle nonperturbative effects and higher twist terms, we expect both types of problems to disappear rapidly with increasing momentum. On the other hand, higher order corrections are calculable and are expected to decrease only logarithmically. We suspect that above

$q^2 \sim 10$ or perhaps $q^2 \sim 100$, most corrections are small. There are, however, important exceptions. One of them is the branching ratio $\Gamma(\eta_Q \to gg)/\Gamma(\eta_Q \to \gamma\gamma)$ where η_Q is the lowest-lying pseudoscalar quarkonium state of a heavy quark Q. In this case, the second order correction[31] is of the order of 100% even at the T mass ($q^2 \sim 100$ GeV^2). It is important to calculate higher-order corrections in many other processes in order to develop a feeling for the validity of the simplest perturbative predictions.

The second level of difficulty involves the translation of predictions for quark and gluon processes into measurable quantities concerning hadrons. This involves either specific "parton distributions" or integrated quantities such as moments or jet properties. In the first case, what is tested is not really QCD. In the second case, large amounts of data are "lost" and the quality of the experimental moments sometimes reflects the quality of the poorest measurements performed over the relevant integration range.

All of these problems are well-known, but it is important to remember that they prevent us from performing a very large number of decisive experimental tests of QCD. The net result is a situation in which QCD faces no outstanding conflict with experiment, but also few, if any, convincing quantitative confirmations.

5.2. The Ingredients of QCD.

When we test QCD we must remember that the complete theory incorporates several distinct elements. Most experimental tests probe specific aspects or components of the theoretical framework. Only the grand total of all components represents the full theory, and only a convincing confirmation of every one of them can be viewed as a confirmation of QCD.

QCD is a gauge theory of quarks and gluons. In order to be convinced that QCD is the correct theory, we must have evidence for the existence of quarks and gluons, we must prove that they have the desired spin and color properties, we must detect the couplings which appear in the basic Lagrangian (namely: $q\bar{q}g$ and ggg) and we must prove that these couplings vary with momentum as predicted. Thus we must prove experimentally:

(i) Quarks "exist."
(ii) Quarks have spin ½
(iii) Quarks are color triplets.
(iv) Gluons "exist."
(v) Gluons have spin 1.
(vi) The $q\bar{q}g$ coupling exists.
(iii) The three-gluon coupling exists.
(viii) The coupling constant "runs" logarithmically as a function of momentum.

The first three items have been established long ago. We have ample evidence for quarks (not free, of course!). The spin ½ of the quark is supported by the spin-parity systematics of the baryon and meson spectrum, by the σ_L/σ_T ratio in deep inelastic electron and neutrino scattering and by the angle-dependence of the production of two quark jets in $e^+e^- \to q\bar{q}$ hadrons.[32] The q^2-dependence of deep inelastic σ_L/σ_T is still somewhat obscure,[33] but the evidence from e^+e^- collisions is quite convincing. In fact, the observation of two jet final states with the correct angular distribution in e^+e^- collisions above, say, 7 GeV provides us with one of the strongest pieces of evidence for the existence of $J = ½$ quarks.

The experimental arguments for the color of quarks are also well known. They include the π^0-lifetime, the value of $R_{e^+e^-}$ and, again, the systematics of hadron spectroscopy.

We, therefore, believe that $J = ½$, tricolored quarks, exist. Important evidence for both their spin and color comes from e^+e^- collisions.

5.3. Gluons Exist.

Until this summer we have had a variety of indirect indications for the existence of gluons. The first hint was, of course, the "missing momentum" in the parton model description of deep inelastic scattering. The total momentum carried by the "valence" and "ocean" quarks in the proton was only 50% of the total proton momentum. The rest is presumably carried by the gluons.

Since then, additional indirect evidence came from several sources, including the pattern of scaling violations in deep inelastic scattering, various features of hadron and photon production at large transverse momenta in hadronic collisions and the data on the Drell-Yan process. All of these data provided extremely indirect evidence. Typically, the existence of gluons would enable us to find an acceptable parametrization of the data, and it would be very hard to fit the data without gluons. However, in none of these processes was it possible to isolate a clear direct effect which must be due to gluons and cannot be due to anything else.

It has been clear for sometime that the most direct way of "discovering" the gluon would be to observe "gluon jets". Assuming that gluons, like quarks, are permanently confined, free gluons cannot be detected. Gluon jets, like quark jets, would be the next best thing.

Three different processes, all of them most easily observed in e^+e^- collisions should yield one, two or three gluon jets, respectively:

(i) $e^+ + e^- \to q + \bar{q} + g$. While most e^+e^- collisions above, say, 7 GeV, yield two clear jets $(q + \bar{q})$, we expect at higher energies a cross section of the order of 5% or so, for three distinct jets. These are obtained from the emission of a hard gluon by the produced quark or antiquark. If such three-jet events are clearly identified, they can come only from a $q\bar{q}g$ final states and one of the jets must be a gluon jet. This would provide convincing evidence for the existence of the gluon.

(ii) $(Q\bar{Q})_{C=1} \to g+g$. The decay of $C = +1$ quarkonium states should usually proceed via a two gluon state. This should be observed in clear contrast to the following case.

(iii) $(Q\bar{Q})_{C=-1} \to g+g+g$. Vector quarkonium states such as ψ,T,($t\bar{t}$) etc., should decay into three gluons, exhibiting a three-jet structure.

Any one of these processes, but especially (i) and (iii), would provide, if observed, conclusive evidence for the existence of gluons. For a while, it was hoped that it would be possible to detect three jets is T decay. However, it has become clear that the mass of the T is not sufficiently large. The decays are consistent with a three-jet mechanism, and they are inconsistent with the standard two-jet pattern of hadronic events off-resonance.[28] However, three jets are not seen explicitly.

The main experimental news of this conference is the observation[3,4,5,6] of several dozens of three-jet events at energies around 30 GeV at PETRA. Preliminary indications based on a few events were already presented[34] in June 1979, but the new data appears to be much more conclusive.

One should clearly distinguish between two separate issues:

(a) Have we really seen three-jet events in e^+e^- collisions?

(b) If we did, does that confirm the existence of the gluon?

Our answer to both questions is a cautious, qualified yes.

Let us start with the first question. The TASSO[5] and PLUTO[4] collaborations have both presented a sample of events which simply look like three-jet events. One spectacular PLUTO event is shown in figure 6. The TASSO group has 18 such events, approximately 5% of their total sample. That, by itself, is fairly convincing.

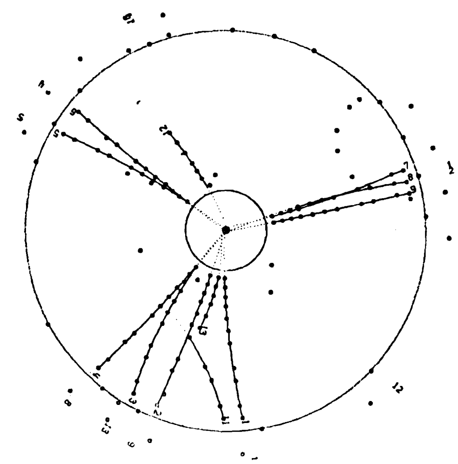

Fig. 6: A "typical" spectacular three-jet event from the PLUTO group.

The events are definitely planar, as expected for three well-collimated jets. When treated as three-jets, the transverse momenta relative to the three axes are comparable to the transverse momenta of the typical two-jet events. Perhaps the most convincing single plot[5] (other than the events themselves) is the P_T plot of figure 7 (from TASSO). Here we see that, around $E_{c.m.} \sim 15$ GeV, the transverse momentum relative to the "best" jet-axis, inside the plain of the event, is always small ($\langle p_T^2 \rangle \lesssim 0.4$ GeV^2). At $E_{c.m.} \sim 30$ GeV, most of the events show a similar pattern, but a very long tail contains approximately 30 events with $\langle p_T^2 \rangle > 0.5$ GeV^2. This tail cannot be explained by simply suggesting that the two jets are much wider. Even if one increases the average p_T in the jet from 250-300 MeV to 450 MeV, the long tail remains unaccounted for. On the other hand, if these events are three-jet events, the large p_T-tail is immediately understood, and one should really plot the transverse momentum relative to the three jet-axes. As we have already mentioned, this gives the usual low p_T-cutoff.

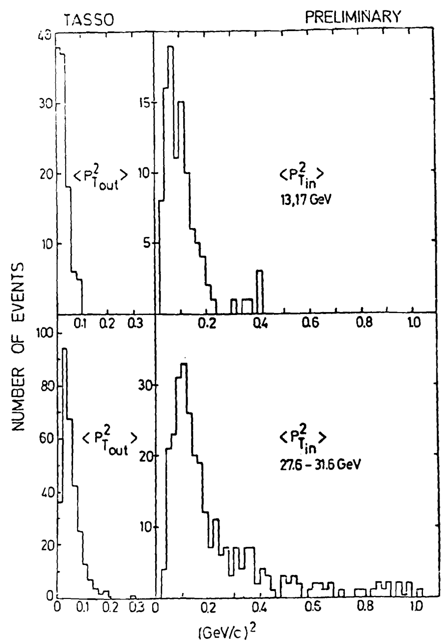

Fig. 7: Transverse momentum distributions outside the event plain and inside the plain. The 30 GeV data for P_{in} shows a significant tail with approximately 30 events beyond $0.5(GeV/c)^2$. Data from TASSO collaboration.

The analysis of the other groups proceed along slightly different lines, but with similar conclusions. Thus, the PLUTO detector[4] has the advantage of better neutral detection, assuring us that the gaps between the jets are not filled with neutrals. The MARK J group[3] presented an energy-flow analysis which is consistent with the picture outlined here. The JADE detector[6] which only started operating, also yielded results which agree with these conclusions.

It is extremely important to improve the statistics of these data samples, and to try some additional "devil's advocate" distributions in order to see whether the data really force us into the three-jet conclusions. This will be, undoubtedly, accomplished during the coming year. In the meantime, our tentative conclusion is that the experimental evidence for three jets is quite good.

Assuming that three-jets are found, is the gluon "discovered"?

Since the bulk of the events at 30 GeV continue to be two-jet events, presumably due to a $q+\bar{q}$ final state, we believe that the three-jet events also contain $q+\bar{q}$. It is then clear that the third jet cannot be a quark jet (spin and baryon conservation would not allow it). The third jet presumably represents a strongly interacting, integer spin object with no baryon number. It is not a heavy meson. The most likely explanation is the gluon.

It is especially encouraging that the rate of the three-jet events is roughly consistent with expectation. The next important test will be the question of the spin. In the same way that the angular distributions of the two quark-jets confirm the spin of the quark, we would hope that various angular distributions of the three-jet events will confirm that the spin of the gluon is one. These tests[35] have not yet been performed, and we are eagerly awaiting their results. It is absolutely crucial to confirm the spin of the gluon.

At the present time we may tentatively conclude that, assuming that the spin test will be positive, the three-jet events provide us with good, almost direct, evidence for the existence of the gluon.

We fully realize that many indications for gluons existed in the past, and that several important checks and tests are yet to be performed. We believe, however, that five years from now, when we look back, we will all agree that the gluon was discovered in the summer of 1979.

The final confirmation should come from the spin tests as well as from quarkonium decays (hopefully from the soon-to-be-discovered $t\bar{t}$ states).

A separate, interesting, issue is the possible existence of "glueballs". Glueballs are colorless bound states of gluons. Their existence has not been proven from QCD, but is very likely. If such states can be discovered and positively identified as glueballs, they would probably provide us with the best possible evidence for the existence of gluons. However, there is no principle which prevents the mixing of pure glue states with $q\bar{q}$, $qq\bar{q}\bar{q}$ etc. Consequently, pure glueballs may not exist, and possible candidates could have confusing features. We are not able to describe an experimental scenario in which we could have enough data to rule out the existence of glueballs. It is almost equally difficult to think of a scenario by which a new particle is found, is proven to be a glueball and cannot be described by complicated combinations of quarks. This issue clearly requires more theoretical work.

5.4. The Couplings of QCD.

Once the existence of spin ½ quarks and spin 1 gluons is confirmed, we have the complete list of fundamental fields in the QCD Lagrangian. The next step is to confirm the existence, and measure the magnitude of the quark-antiquark-gluon coupling and the three-gluon coupling.

The $q\bar{q}g$ coupling can, in principle, be measured in many different processes. However, in some processes (e.g. the Drell-Yan process) too many different mechanisms participate. In other processes (such as quarkonium decays), higher-order corrections are very large.[31] In deep inelastic scattering, the possible effects of "higher-twist" terms confuse the issue. The best two places for a measurement of α_s are in e^+e^- collisions:

(i) The quantity $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ is given by the expression:

$$R = \sum_i Q_i^2 \left[1 + \frac{\alpha_s}{\pi} + 0\left(\frac{\alpha_s}{\pi}\right)^2\right]$$

where $\sum_i Q_i^2$ is the sum of the squared quark charges. The second order term has now been calculated by several authors[36] and is both very small and well-known. The prediction itself is probably the "cleanest" prediction of QCD, requiring the smallest number of dubious assumptions. An accurate determination of R in the range between, say, 5 and 9 GeV, should provide us with the best quantitative test of QCD as well as with an approximate determination of α_s. Present data[37] are consistently higher than the predictions for any reasonable value of α_s, but the systematic errors are still quoted as 15%-20% and are therefore consistent with QCD. It is extremely important (and experimentally feasible[38]) to perform a 5% measurement of R. Such a measurement could be done at SPEAR or DORIS. It would provide us with a very important test of QCD, and, if successful, would determine α_s within a factor of two or so, better than our present knowledge. It is interesting to note that two of the sources of systematic error in the SPEAR and DORIS energy range, can be reduced by using information from PETRA and PEP. These are the errors due to radiative corrections (which will diminish if higher energy cross sections are better known) and the error introduced by subtracting τ-events (which will improve when the branching ratios are measured more accurately at higher energies).

(ii) A second, more direct, method of determining α_s is from the relative rate of three-jet events and two-jet events at PETRA and PEP energies. For any well-defined characterization of these jets in term of energy fraction flowing into a certain opening angle, QCD predictions could be derived and compared with the data, leading to an approximate determination of α_s. Here, the next order correction should be calculated, before we can trust the results.

A more difficult problem is the direct detection of the three-gluon coupling. There are many processes in which quantitative QCD predictions depend on the contribution of this coupling. However, it is hard to isolate qualitative effects whose existence would directly prove the existence of the coupling and, hence, the nonabelian character of the theory. The most direct (or, perhaps, the least indirect) indication could come from a comparison of the properties of quark jets and gluon jets. Because of the three-gluon coupling, gluon jets are predicted to be wider[39] and to possess larger hadron multiplicities, than quark jets. This distinction should become clear at higher energies. Once it is confirmed, it could provide us with an experimental method of determining whether an observed jet originates from a quark or a gluon. All other effects of the three-gluon coupling involve more detailed calculations and additional assumptions (e.g. large p_T hadron production, quarkonium decay, etc.).

Only when and if the $q\bar{q}g$ and ggg couplings are observed and measured, we may seriously begin to chase the logarithmic momentum dependence of the couplings. This would, of course, be the ultimate test of QCD. We believe that, at present, it is premature to do it, when we do not even know the value of α_s at any given point, and when higher order effects and higher twist terms are at least as important as the logarithmic variation of α_s.

QCD can be considered confirmed only when we have evidence for quarks and gluons with the correct spin and color properties, $q\bar{q}g$ and ggg couplings with the correct magnitude, and a confirmation of the predicted momentum dependence of these couplings.

5.5. A Fascinating (but Speculative) Scenario.

Let us assume that every energetic quark or gluon materializes into a hadronic jet. Let us further note that, at present energies, the observed jets in e^+e^- collisions are well-collimated and have p_T of the order of a few hundred MeV. Let us suggest that as the energy of the jet increases, its angular width will diminish (p_T may increase, but as long as it increases less than the longitudinal momentum, the opening angle decreases). If these assumptions are correct, we obtain a fascinating picture of the hadronic final states in e^+e^- collisions at very high energies. Imagine a 10 TeV e^+e^- collision. A large number of hadrons are produced. We ignore "soft" hadrons with energies below, say, 10 GeV. All other hadrons may form narrow jets and the event can be defined, by inspection, as an n-jet event. At sufficiently high energies, the jets will be so narrow that the hadrons forming them will not be resolved by the detector. Detectors may, in fact, detect jets rather than hadrons. Sophisticated detectors may even tell a gluon jet from a quark jet by measuring the energy and the opening angle of the jet and correlating them. There should be one energy-angle curve for gluons and a different one for quarks, and the separation could resemble a time-of-flight π-K spearation today. We may want to measure and to discuss specific cross sections such as $\sigma(e^+e^- \to q\bar{q}gg)$ etc. In some pragmatic sense we will "see" the "tracks" of quarks and gluons (although the question of confinement may remain unsolved).

The above scenario is exciting and promising. It is not clear, however, that it is a necessary consequence of QCD. The variation of hadronic p_T as a function of energy[40] is not fully understood in QCD, and the presently observed p_T of 300 MeV or so can, presumably, be derived only by understanding the same nonperturbative QCD effects which are responsible for quark confinement. It would be extremely interesting to assess the validity of our futuristic picture within QCD.

In the meantime, it would be useful to study the properties of jets at present energies. With enough statistics we should be able to tell whether gluon jets are indeed wider and have higher multiplicities than quark-jets. We might also find other, unexpected, differences. Perhaps gluon jets have a higher (or lower) percentage of neutral energy, of K-mesons, or of η-mesons?

Our favorite three-jet event (figure 6) presumably contains one gluon jet. We do not know which one it is. If we have to bet, we would probably bet on the wider one, at the bottom of the figure (The CBS-TV station in Chicago paraphrased this statement as follows: "Scientists do not know which of the three jets is the gluon, but the smart money is on this one").

6. The Future

A brief look at the future of e^+e^- collisions at higher energies shows almost unlimited horizons. From PETRA and PEP we have well-defined expectations. We hope for the t-quark and, possibly a new lepton. We expect to see weak-electromagnetic interference effects in measurements such as the asymmetry in $e^+e^- \to \mu^+\mu^-$. With some luck and very hard work, we may even obtain indirect evidence[41] concerning the actual mass of Z^0 and the possible existence of more than one Z^0, allowing masses of the order of 60 GeV for the lowest lying Z^0. We should get acquainted with gluon jets, determine the gluon spin, and study the weak decays of the b-quark and, hopefully, t-quark. Any new e^+e^- machine, including PETRA and PEP, holds the promise of finding the Higgs particle. Where? We do not know.

The next generation of machines (LEP and its possible poorer brothers, the so-called "Z-factories") should find Z^0 and possibly $W^\pm$ (if they are not found earlier in hadron machines). We may find some more quarks and/or leptons, and the perrenial Higgs particle may wait for the Z-W mass range. Four and five jet events may appear and a clear trend concerning the collimation of jets as a function of their momenta should emerge. By studying Z^0 decays, very rich information concerning the properties of quarks and leptons should be obtained.

Beyond LEP one may envisage higher-energy machines, utilizing new technologies. There, anything goes. Excited W and Z states, "techniquarks" and "technileptons", possible deviations from pointlike quarks and leptons, more flavors, many Higgs particles, new bound states due to "strong" weak interactions and many totally unexpected features.

Somewhere around $E_{c.m.} \sim$ 100-200 GeV, we expect to cross from the domain of $SU(3)_c \times SU(2) \times U(1)$ and three generations of quarks and leptons in which we understand almost everything, into the new land of surprises. The surprises may appear immediately or may wait several orders of magnitude in energy. The connection between quarks and leptons, as well as the puzzling pattern of generations will have to be deciphered. Whether it will happen along the lines of grand unification models or whether quarks and leptons will turn out to be composite, we do not know. Grand unification is discussed elsewhere in this conference.[42]

Our own personal prejudice is in the direction of compositeness. We imagine a short distance world in which all of matter is made of new building blocks called "rishons".[43] They may act on each other by some "primary interaction", perhaps mediated by gauge bosons. All known quarks and leptons are composites of rishons or of antirishons. Gauge bosons such as $W^{\pm}$ and, perhaps, the gluon are composites of the primary bosons or of rishons. Quark and lepton properties such as color or flavor may be determined by the specific combinations of rishons and cannot be attributed to the rishons themselves.

Such a scheme has several attractive features. It "explains" why only certain charge and color combinations are found among the quarks and leptons; it provides a natural explanation for the vanishing sum of charges for the quarks and leptons of each generation; it indicates that, at the rishon level, there may be equal amounts of matter and antimatter in the universe. However, many serious problems are not solved. How can we have a massless (or almost massless) bound state? What distinguishes the generations from each other? Is it possible to construct a local gauge theory with composite gauge bosons? Do the rishons obey conventional statistics?

These and many other deep questions are still open and all composite models for quarks and leptons are still in an embryonic stage. They may look crazy, but they are probably not crazy enough, at present.

7. Final Comments

High energy physics has reached a remarkable and unusual stage of development. We have a certain range of problems and phenomena in which we understand almost everything. Using $SU(2) \times U(1)$ and QCD, we can make predictions with great self-confidence and, at least so far, the predictions have always been right. In fact, we may compile a remarkable list of experiments which, during the last five years, have disagreed with the standard theoretical wisdom. In all cases the experimental results turned out to be wrong! They include the high y-anomaly in $\bar{\nu}N$ scattering, the absence of the decay $\tau \to \pi + \nu$, the mass and the $\gamma\gamma$ branching ratio of X(2.8), the mass and the $\psi\gamma$ branching ratio of $\chi(3.45)$, one measured cross section for $\nu_\mu e \to \nu_\mu e$, the absence of parity violation in Bismuth atoms, and several less important cases. This list is not intended as a theorist's attack on experimentalists. Many theorists did not fare any better, and the results of each incorrect experiment were "explained" by several theoretical papers... The fact remains that the standard theory has survived many challenges, and it continues to survive.

At the same time, we have an entire range of questions about which we know next to nothing. The quark and lepton mass spectrum, the pattern of generations and their number, possible extensions of $SU(2) \times U(1)$, possible compositeness of quarks and leptons and the connection with gravity are just some of the problems which are completely open. We have almost closed one important chapter in the development of high energy physics, while the next chapter is still wide open.

It is a pleasure to thank John Peoples and Chuck Brown for their hospitality at Fermilab. All the experimental speakers from DESY and SLAC have been extremely kind in sharing their unpublished data with us. Helpful discussions with many theoretical colleagues at SLAC are gratefully acknowledged.

This work was supported in part by the U.S. Department of Energy and by the U.S.-Israel Binational Science Foundation

References

1. See e.g. E.Ma, Phys. Letters 58B, 442 (1975); H. Fritzsch, Phys. Letters 78B, 611(1978); F. Wilczek and A. Zee, Phys. Rev. D16, 860 (1977); G.L. Shaw, Phys. Letters 81B, 343 (1979); H. Georgi and S.L. Glashow, Harvard preprint, HUTP 79/A027, May 1979; S. Pakvasa and S.F. Tuan, Hawaii preprint 1979.
2. For a recent suggestion in this direction see e.g. G.L. Kane and S. Raby, Michigan preprint, July 1979.
3. H. Newman, MARK J collaboration, these proceedings.
4. C. Berger, PLUTO collaboration, these proceedings.
5. G. Wolf, TASSO collaboration, these proceedings.
6. S. Orito, JADE collaboration, these proceedings.
7. A more or less complete compilation of predictions and guesses concerning the t-mass is given in the review by M. Krammer and H. Krasemann, DESY 79/20, April 1979.
8. This relation was first derived by M.A. de Crombrugghe, Phys. Letters 80B, 365 (1979). It was later derived from other sets of assumptions

by H. Georgi and D.V. Nanopoulos, Nuclear Phys. B155, 52 (1979); H. Fritzsch, Nuclear Phys. B155, 189 (1979).

9. H.D. Politzer, Phys. Rev. Letters 30, 1346 (1973); D.J. Gross and F. Wilczek, Phys. Rev. Letters 30, 1343 (1973).
10. See e.g. G. Steigman, D.N. Schramm and J.E. Gunn, Phys. Letters 66B, 202 (1977).
11. M. Veltman, Nuclear Phys. B123, 89 (1977), Acta Phys. Polonica B8, 475 (1977); M.S. Cahnowitz, M.A. Furman and I. Hinchliffe, Phys.Letters 78B, 285 (1978); Nucl.Phys. B153, 402 (1979).
12. H.D. Politzer and S. Wolfram Phys.Letters 83B, 421 (1979); P.Q. Hung, Phys.Rev.Letters 42, 873 (1979); N. Cabibbo et al, CERN preprint TH-2683, June 1979.
13. See e.g. E. Farhi and L. Susskind, SLAC-PUB-2361, July 1979; F. Wilczek and A. Zee, preprint, August 1979; P. Frampton, preprint 1979.
14. E.D. Bloom, Crystal ball collaboration, these proceedings.
15. E. Eichten et al, Cornell preprint, 1979.
16. For a recent review see e.g. M. Krammer and H. Krasemann, DESY preprint 79/20, April 1979, and references therein.
17. M.T. Ronan, Lead-glass-wall collaboration, these proceedings.
18. Private Communication from G.J. Feldman, MARK II collaboration.
19. S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2, 1285 (1970).
20. See e.g. C. Baltay et al, Proceedings of the Oxford Neutrino Conference, July 1978.
21. V. Luth, MARK II collaboration, these proceedings.
22. J. Kirkby, DELCO collaboration, these proceedings.
23. G.S. Abrams et al, Phys.Rev. Letters 43, 477.
24. For various theoretical considerations related to Cabibbo suppressed D^o-decays see e.g. L.F. Abott, P. Sikivie and M.B. Wise, SLAC-PUB-2355, July 1979, M. Fukugita, T.Hagiwara and A.I. Sanda, Rutherford Lab. preprint RL-79-052, Revised August 1979; L.L. Wang and F. Wilczek, Brookhaven preprint, BNL-26276, June 1979, G.L. Kane, SLAC-PUB-2326, May 1979; V. Barger and S. Pakvasa, Hawaii preprint, 1979; M. Suzuki, Berkeley, preprint, 1979.
25. I wish to thank J. Kirkby and P.C. Bosetti for discussions on this point.
26. E.G. Cazzoli et al, Rhys.Rev. Letters 34, 1125 (1975); B. Knapp et al, Phys.Rev.Letters 37, 882 (1976) and many other experiments.
27. E.G. Cazzoli et al, Phys. Rev. Letters 34, 1125 (1975); C. Baltay, Phys. Rev. Letters 42, 1721 (1979).
28. H. Meyer, PLUTO Collaboration, these proceedings.
29. R. Barate et al, SISI Collaboration preprint, July 1979.
30. For a review see e.g. H. Harari, Phys. Reports 42C, 235 (1978).
31. R. Barbieri et al, Nuclear Phys. B154, 535 (1979).
32. G. Hanson et al, MARK I SLAC-LBL collaboration, Phys.Rev.Letters 35, 1609 (1975).
33. See e.g. W. Atwood, to be published at the proceedings of the 1979 SLAC summer institute.
34. B.H. Wiik, TASSO collaboration, to be published in the proceedings of the Bergen neutrino conference, June 1979; R. Cashmore, P. Soding and G. Wolf, TASSO collaboration, to be published in the proceedings of the Geneva EPS conference, June-July 1979.
35. G. Kramer, G. Schierholz and J. Willrodt, Phys. Letters 79B, 249 (1978); 80B, 433 (1979); P. Hoyer et al, DESY preprint 79/21, April 1979.
36. K.G. Chetyrkin, A.L. Kateev and F.V. Tkachov, Phys. Letters 85B, 277 (1979); M. Dine and J. Sapirstein, Phys. Rev. Letters 43, 668 (1979).
37. See e.g. G. Wolf, DESY 79/41, to be published in Proceedings of the Geneva EPS conference, June-July 1979.
38. I wish to thank G.J. Feldman and R. Schwitters for discussions on this point.
39. See e.g. M.B. Einhorn and B. Weeks, SLAC-PUB-2164 (1978); K. Shizuya and S. -H.H. Tye, Phys. Letters 41, 787 (1978); Fermilab preprint Pub-79/16-THY, January 1979.
40. For a related discussion see e.g. A. Bassetto, M. Ciafaloni and G. Marchesini, Pisa preprint, 1979; K. Konishi, Rutherford Lab. preprint RL-79-035, 1979; W. Furmanski, R. Petronzio and S. Pokroski CERN preprint TH-2625 (1979). I wish to thank D. Amati and A. Schwimmer for discussions on this subject.
41. For a recent discussion see e.g. E.H. de Groot, G.J. Gounaris and D. Schildknecht, Phys. Letters 85B, 399 (1979). Earlier discussions include J. Pati and S. Rajpoot, Trieste preprint IC/78/71; Q. Shafi and C. Wetterich, Phys. Letters 73B, 65 (1978).

42. F. Wilczek, These proceedings.
43. H. Harari, Phys.Letters 86B, 83 (1979). Some of these ideas have been independently proposed by M.A. Shupe, Phys. Letters 86B, 87 (1979).

Discussion

Q. (Ralph Roskies, Univ. of Pittsburgh). One of the indications of the spin-1/2 character of the quark that you mentioned was the value of σ_L/σ_T in deep inelastic scattering. For a while that was in question and numbers as high as 1/2 were quoted for it. What is the situation there?

A. As far as I know, (and perhaps someone from the SLAC-MIT group can correct me), the situation is somewhat confused. σ_L/σ_T is small. If one is trying to decide between zero and infinity, (the two "favorite" options) it certainly looks more like zero. However, if you would like to use it as a test of QCD, which predicts a specific Q^2 behaviour, then it really doesn't look so good. But then there are all kinds of QCD effects which you don't really know how to calculate, and it is not difficult to invent excuses. I would say that the Q^2 dependence is still an open question.

Q. (S. Ting, DESY/MIT) I was wondering if you have any comment or guess about what could be the mass of the next lepton? Or would you care to write it down?

A. No.

Q. (Snow, U. of Maryland). Is the charge of the quark still an issue? That is, whether it is fractionally or integrally charged and how can you measure that?

A. That is a difficult question. Historically, there's been a repeating sequence of situations in which we decided that we had a test for the charge of the quarks. The test would prove that the charge of the quark is -1/3 and 2/3, and then somebody would find a clever theoretical way around the test involving integer charged quarks whose charge would be observed at very high energies, but at present energies everything would imitate the effects of fractionally charged quarks. Then somebody else would find a way around this and say, well, let's go to second order electromagnetic process, that's a more sensitive way to measure the charge of the quarks. Then the experiment is done and agrees with the fractionally charged quarks and then somebody else finds another theoretical argument around it and so forth.

I would say that every single test, to the extent it was a test, indicated fractionally charged quarks. But whether one can really claim with absolute confidence that you cannot invent some theoretical concoction that would go around all of these arguments, is hard to say. Personally, I am totally satisfied. I don't lose one moment of sleep on that question. I believe that the charges are -1/3 and 2/3 but, as you know, various people, and especially Pati and Salam, for instance, do not necessarily agree.

Q. (G. Preperata, CERN). There were very interesting results on the gluon jets and so you sound confident about the existence of jets. But judging only form what the evidence you have given today, my personal reaction is that all we are witnessing is the fact there are large p_T objects in the final hadron states in e^+e^- interactions the same way we have learned that in pp collisions there are large p_T objects coming out, and that those processes increase with energy in some particular fashion. And so I wouldn't see anything very dramatic for the existence of gluons there. I think you seem to neglect a problem with the word "existence". Presumably we shouldn't say that gluons exist, but only that we are using them in a good way to describe some facts of nature. But that's a question of epistimology. Maybe we shouldn't bring this up here. In this connection the existence of glueballs is a problem. Now if the gluons should be thought of as degrees of freedom the same way we think about quarks, then glueballs should be free and they should not have evaded searches at low mass. Now I think there isn't any shred of evidence that there is such a thing and I think this should be brought out. Experiments should worry about this, should look for them and be very suspicious of half-baked theoretical ideas that get rid of unwanted objects where you don't want them and that make very strong statement for wanted objects when in fact there is no evidence for them.

A. I want to comment briefly. I find the evidence for jets quite compelling and maybe some of the experimentalists may comment on it. I think I said quite clearly at the beginning that one should be very careful about proving QCD and I think I was quite sharp in saying things about various experimental groups who were claiming this without justification etc. At the same time I do think that the overall picture is very, very impressive, especially this business of the gluon jets. Concerning glueballs, I agree. It is an important theoretical prediction that such states are likely to exist. It is important to look for them. However, I don't want to be in the situation in which an experimentalist finds something and then we say, well, that's not conclusive and he says but you said it's important to look. I want to be very clear about this. It's important to look for them but it is very hard to imagine a scenario in which somebody will show me data discovering, say, a 2GeV particle with $J^{PC}=0^{++}$, that would be conclusively a glueball. There will always be someone else who will explain it as a 2-quark and 2 antiquark state or a fifth excitation of some $q\bar{q}$ state or this or that. No matter how you think of it, it is very hard to find a convincing set of properties that will be properties of a glueball and of nothing else. So it is a very difficult business. But, still, one should look for it because there may be something that we do not think about which will identify it as a glueball. And this is a low energy business and the low energy machines are now looking for exciting things to do. So experimentalists, go ahead.

Q. (Wolf, DESY). I want to make a comment to Giuliano on the experimental results from TASSO. The evidence for jets is twofold. First, we see that ${p_T}^2$ is rising. Secondly we see that this rise is connected to a planar event. That means the ${p_T}^2$ doesn't rise azimuthally isotropically around the jet axis but there are planar events of a kind that cannot be understood with normal $q\bar{q}$ production and fragmentation.

Q. (Veltman, ITP, Rijksuniversiteit). I would like to give an answer to the question concerning the measurement of the charge of the quarks. I think you will get a very clean, even satisfying to you I hope, measurement if in the future the LEP machine starts measuring the interference between electromagnetically produced quark pairs and weakly produced quark pairs. You have a virtual photon that makes a quark pair in an e^+e^- machine. You can also produce the pair with a virtual W^0, and at some energy these two will interfere and you will get a minimum. And such minima are very precise functions of the quarks and the weak coupling of quarks. And there I think you would really have a clean sort of measurement of the charges and the weak interaction coupling constants.

Q. (Ting, DESY/MIT). I just want to comment on Giuliano's remark. In addition to the p_T distributions from TASSO and Pluto there are also completely independent analyses of the major axis distribution and minor axis distribution as functions of energy and functions of thrust and analyses of energy flows, all showing three lobes, all in agreement with gluon emission.