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e^+e^- COLLISIONS : WHAT REMAINS TO BE DONE ?

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ABSTRACT : I discuss some questions which remain to be answered by e^+e^- experiment in the pre-Z^0-factory era. In addition to ruminating on the general state of our knowledge, I emphasize the importance of certain high-precision measurements.

RESUME : Je discute des questions auxquelles les expériences e^+e^- peuvent répondr avant l'entrée en service des fabriques de Z^0. Outre des considérations générales sur l'état actuel de notre connaissance, je mets l'accent sur l'importance de certaines mesures précises.

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After several years of operation of the high-energy electron-positron storage rings PETRA and PEP and of the CESR machine and the ever-productive SPEAR, and with definite plans for 100 GeV collisions taking form, it is interesting to assess the physics prospects of the facilities now in operation. The commitment to this line of research being imposing, both in terms of funds and of physicists' energies, it is worthwhile to consider what return we should expect from further experimentation, and to identify issues that are receiving too little attention. In a brief talk it would be folly to attempt a complete treatment. I shall instead take this opportunity to explain why it seems to me important that certain measurements be done very well. The topics I will discuss here bear on particular aspects of the contemporary paradigm of fundamental fermions interacting through the agency of gauge bosons, and touch on our implicit assumptions. I shall deal in turn with the spectrum of fermions, the weak and electromagnetic interactions, and quantum chromodynamics. The presentation will be largely in the form of a series of questions, which are intended to have some overall structure and organization.

The focus of this talk is narrow, in that only the physics of e^+e^- annihilations is emphasized, and within that framework some important topics (charmed-particle decays and quarkonium, for example) are omitted. I acknowledge, but have done little to avoid, the danger of being too conventional. Some supersymmetric possibilities will be discussed later in the week1), and searches for the canonical unconventional particles have been reviewed here2) and at the Bonn Conference3).

1. THE FERMION SPECTRUM

(a) Do quarks exist ? The evidence, though circumstantial, is overwhelmingly affirmative, and will not be reviewed here. I shall assume that the answer is yes.

(b) Do free quarks exist ? The answer is not known, either in theory or in experiment. It is widely believed, but not proved, that QCD is a confining theory. Assuming that to be the case, we do not know whether a gentle deformation of the theory which preserves its desirable features will lead to quark liberation. On the experimental side there are many unsuccessful searches and one persistent observation of fractionally-charged matter4). The importance of this issue cannot be overstated.

(c) Are all quarks color triplets ? We have strong and diverse evidence that the known quarks (u, d, s, c, b) are color triplets, but little understanding of the origin of their color charge. In some unifying groups, there is room for quarks in larger color representations. Like the small dimensionality of $SU(3)_{\text{flavor}}$ representations of hadrons, which found its explanation in the quark model, the observed restriction requires explanation.

(d) Are (all) quarks fractionally charged ? The best evidence that the light quarks are fractionally charged comes from the two-photon decay rates of η and η', but one may be slightly squeamish about current algebra extrapolations or gluonium admixtures. We are on the verge of having definitive evidence on the light quarks from the reaction $\gamma\gamma \rightarrow$ hadrons, the rate for which measures the mean fourth power of quark charges and thus distinguishes between fractionally- and integrally-charged quarks. I do not know whether it is in fact possible to build a consistent theory based upon integrally charged quarks.

(e) Are quarks and leptons fundamental ? This is important not only because of the МАТРЁШКА Hypothesis, but also because the requirement of renormalizability has become an important guiding principle in the selection of theories. If quarks and leptons are composite, and their interactions thus damped by form factors, it is less natural to demand that our theories of the interactions among quarks and leptons be renormalizable. On present evidence[5)] the charged leptons e, μ, and τ and the quarks u, d, s, c, and b are pointlike on a scale of about 2×10^{-16} cm, and there is no indication of neutrino structure. For the electron and muon the minuteness of the magnetic anomalies $(g - 2)$, which are precisely calculable in QED, is another indicator of elementarity on the present distance scale. As a spur to greater efforts, I offer a prize of one bottle of Marc de Savoie for a direct experimental determination of $(g - 2)_\tau$, within errors of ± 10%.

(f) Are the weak interactions of quarks and leptons universal ? Explaining the universality of the light quarks and leptons is one of the basic achievements of the unified theory of the weak and electromagnetic interactions, in which charge current couplings are implied by the weak isospin assignments. With precise measurements of the lifetimes and semileptonic branching ratios of the charmed particles[6)] and the tau lepton[7)] on the horizon, we may await stringent tests of universality for these particles as well. It is already apparent that universality holds within a factor of 2 for τ and c. The absence of flavor-changing neutral currents supports the correctness of the GIM mechanism and thus the universality hypothesis. Direct checks that the neutral current interactions are of universal strength, given in terms of the weak isospin and electric charge of the fermions, are also becoming increasingly precise, as described by Sakurai[8)]. Precise measurements of the magnitude and energy dependence of the forward-backward asymmetry in $e^+e^- \rightarrow f\bar{f}$ are of particular importance in this regard.

(g) What are the fermion mass matrices ? The spectrum of the fundamental particles is one of the areas in which our ignorance (at the level of explanation) is most complete. Experimental clues are consequently of great value. The most immediate questions concern the lifetime of particles containing the b-quark and the relative strengths of the $b \rightarrow c + W^-$ and $b \rightarrow u + W^-$ transitions. At this point, it is not easy to make the latter determination in a manner free from poorly controlled assumptions, and it is therefore important to exploit several independent methods. I continue to believe that a multilepton analysis[9)], though vulnerable to inefficiencies for low-momentum tracks, may be a tool of considerable value.

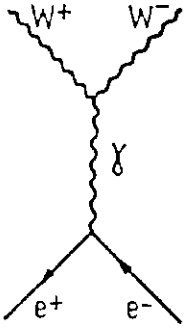
2. WEAK AND ELECTROMAGNETIC INTERACTIONS

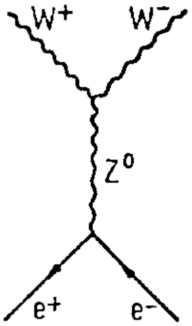
(a) Do the intermediate vector bosons $W^{\pm}$ and Z^{0} exist, with the desired properties ? Confirmation of the detailed Weinberg-Salam model predictions for these objects evidently awaits production of the intermediate bosons as real particles. In the interim one need not be idle, however. Tests of the single-Z^{0} boson hypothesis by means of checks of factorization in the neutral current sector are of prime importance because many extensions of the minimal model imply the existence of several neutral weak bosons$^{10)}$. Measurements of the magnitude of the forward-backward asymmetry in $e^{+}e^{-} \to f\bar{f}$ provide discrimination against some of the simplest schemes for Z^{0} proliferation.

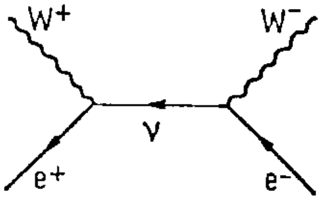
(b) Where are the right-handed intermediate bosons $W_{R}^{\pm}$, or in other words, wh is parity maximally violated in the charged-current interactions ?

(c) Are the intermediate bosons fundamental ? This is at least approximately equivalent to asking whether they have the self-interactions prescribed by local gauge invariance. It is frequently advertised that the energy dependence of the cross section for $e^{+}e^{-} \to W^{+} W^{-}$ will confirm that the three-gauge-boson couplings are as they should be. I have my doubts that any such test will provide quantitati evidence during this century. Instead, I am persuaded that the systematic and careful study of electroweak radiative corrections, as advocated in many places by Veltman, is of comparable importance to the study of radiative corrections in QED. Once more, the meticulous measurement of forward-backward asymmetries seems an ide experimental probe.

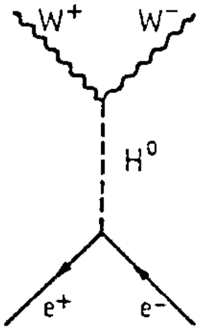
(d) Does the Higgs boson exist ? Although I have no good idea to add to the canonical list of ways to search for the Higgs scalar, I am confident that it will be discovered whether it exists or not. This Delphic pronouncement requires explanation. In the standard formulation of spontaneous symmetry breaking an elementary Higgs boson appears in the Lagrangian of the unified theory of the weak and electr magnetic interactions, but this is not mandatory. The Higgs field is the analog of the order parameter in the Ginzburg-Landau description of superconductors, which may be identified as the density of Cooper pairs in BCS theory. Similarly, as for example in technicolor schemes, one may imagine the Higgs boson to be a composite object which is dynamically generated. In any case, an S-matrix argument makes it apparent that a scalar particle —whether elementary or resonant— must occur. The production of longitudinally-polarized W-bosons in fermion-antifermion collisions is a favorite process for the discussion of unitarity and high-energy behavior. Consider for definiteness the reaction $e^{+}e^{-} \to W^{+} W^{-}$, for which the direct-channel γ- and Z^{0}- graphs and the t-channel ν-exchange graph







give a well-defined $J = 1$ partial-wave amplitude. The $J = 0$ partial-wave amplitude, corresponding to "wrong helicity" leptons, is proportional to the square of the c.m. energy. To enforce unitarity at the level of tree diagrams it is necessary to add the contribution of an s-channel scalar particle H^0,



which cancels the offending behavior. The $He\bar{e}$ coupling is naturally proportional to m_e, the familiar parameter of helicity suppression. If such a term is not added to the Lagrangian, I am assured by a childhood spent in the study of hadronic interactions that unitarity will be protected by the formation of a $J = 0$ s-channel resonance with Yukawa coupling proportional to the fermion mass. I believe it nearly inevitable that a Higgs scalar or its doppelgänger must be found with a mass less than a few hundred GeV/c^2. It is important to look !

3. STRONG INTERACTIONS (QCD)

(a) Do gluons exist ? Not so thoroughly proved as the reality of quarks, the existence of gluons nevertheless naturally explains a number of observations, and will be assumed in what follows. It is an interesting (and not entirely idle) intellectual exercise to ask whether the evidence for gluons can be interpreted otherwise.

(b) Do free gluons exist ? As for quarks, the conventional wisdom says no, but the foundation for such a statement is not particularly firm, and searches are essential.

(c) Do gluons interact with quarks ? Departures from Bjorken scaling and the existence of three-jet events in e^+e^- annihilation into hadrons confirm that they do. The flavor-independence of quarkonium potentials provides evidence that color, rather than flavor, determines the strength of the interquark interaction. To find the first evidence for a one-gluon-exchange Coulomb interaction in a still heavier quarkonium system ($t\bar{t}$) would be a delight.

(d) Do gluons interact with other gluons ? As for the intermediate bosons, this is an essential consequence of a non-Abelian gauge theory. Although it may someday be possible to construct a case for the three-gluon vertex by means of detailed studies of $\geqslant$ 4-jet events in e^+e^- annihilations, I expect that less direct methods are required. To me, observing the q^2-variation of the "running coupling constant" $\alpha_s(q^2)$ and confirming a tendency toward asymptotic freedom would constitute reasonably decisive evidence for the three-gluon interaction, since it is gluon bubbles that give rise to the antiscreening of the color charge. (My fascination with radiative corrections thus persists in the strong-interaction sector.) The most satisfactory way to measure the variation of α_s is to measure the energy-dependence of the hadronic cross section ratio $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-$ This may now be done over a meaningful range in energy thanks to the large mass of the t-quark. To perform an adequate measurement of the variation of R will require imagination as well as extensive running time, but it must be done.

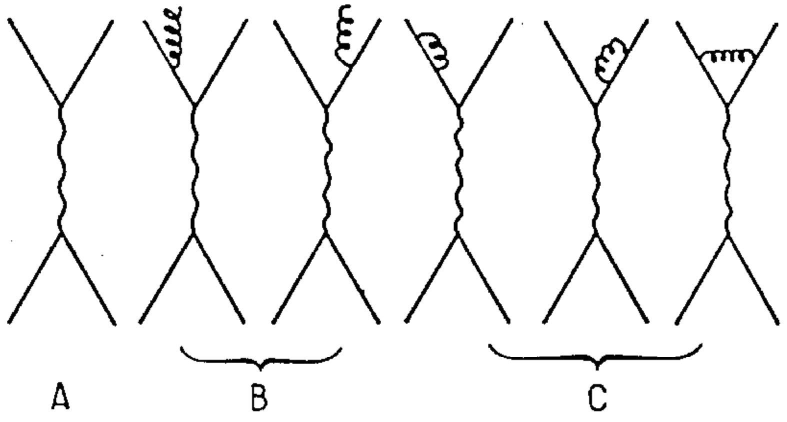
Prima facie evidence for interactions among gluons would be provided by the discovery of quarkless states, or glueballs. The evidence that the state $\iota(1440)$, seen in the cascade decay

$$\begin{array}{l}\psi \to \gamma + \iota(1440)\\ \qquad\qquad\quad \hookrightarrow K\bar{K}\pi\ ,\end{array}$$

might qualify as gluonium has been reviewed at this meeting$^{11)}$. What has been learned from 2 million ψ events is extremely suggestive, but not definitive, and has required a very detailed examination of the hadron spectrum in this region. Evidently improvements in statistics are unlikely to advance the argument soon. To clarify the nature of the iota and other glueball candidates will require meticulou and painstaking work —both experimental and theoretical. In my view, the potential rewards warrant the required investment of effort. One obvious component of this activity should be a comparison of meson states formed in $\gamma\gamma$ collisions with those produced in $\psi \to \gamma$ + anything or in hadronic interactions. Two-photon collisions should favor the production of $(q\bar{q})$ states over gluonia, whereas the radiative decays of quarkonium states may favor glue-bearing hadrons. Line shapes and branching ratios for the mesons produced in a variety of ways may yield important insight to a comprehensive analysis.

(e) Can anything be calculated in perturbative quantum chromodynamics ? Mueller's excellent review talks at this meeting$^{12)}$ give a measure of the progress being made and of the prospects for those elusive "clean tests" at still higher energies. The uncertainty introduced by higher-twist contributions, which reflects our inability to solve the bound-state (quark confinement) problem, is particularly vexing for processes with hadrons in the initial state. In addition, I would acknowledge two other technical issues which interfere with direct or precise comparisons of theory and experiment : infrared troubles and the problem of multiple mass scale

It is well known, but worth reiterating, that the total cross section for electron-positron annihilations into hadrons is calculable, whereas the cross secti for production of two, three, or an arbitrary number of jets is not. The distinctio is easily seen in lowest nontrivial order in QCD. The cross section for $e^+e^- \to$ hadrons is described, to order α_s , by six Feynman graphs :



the parton model diagram (A), two gluon radiation graphs (B), and three graphs (C) involving virtual gluon lines. In a schematic but self-evident notation, the cross section given by

$$\sigma(e^+e^- \to \text{hadrons}) \sim \underbrace{|\,A\,|^2}_{\alpha_s^{\,0}} + \underbrace{|\,B\,|^2 + |\,A \otimes C\,|}_{\alpha_s^{\,1}}$$

is well-defined, whereas the two-jet or three-jet cross sections given by

$$"\sigma_2" \sim |\,A\,|^2 + |\,A \otimes C\,|$$

and

$$"\sigma_3" \sim |\,B\,|^2$$

are separately infrared divergent. It is for this reason that it is necessary to study various sorts of energy-weighted cross sections, for which an intuitive motivation may not be entirely evident, in order to make sense of multijet events.

The photon structure function is a second quantity calculable from first principles in QCD. The parton-model result,

$$F_2(x,\ Q^2) \sim \alpha \log(Q^2/m_f^2).\ f(x)\ ,$$

arises from the QED evolution of the photon and the virtual dissociation into pointlike charged constituents. The subsequent QCD evolution has the effect of modifying ,

$$\log(Q^2/m_f^2) \rightarrow \log(Q^2/\ \Lambda^2)\ ,$$

for $Q^2 \gg m_f^2$. In the kinematical regime of experimental interest, it is necessary to take into account the contributions of charmed (and eventually b-) quarks, for which this strong inequality is not satisfied. Uncertainty surrounding the general issue of thresholds, especially in processes involving several mass scales, inhibi a precise confrontation between theory and experiment. It is important that means be found to minimize this uncertainty.

4. CONCLUSIONS

I have reviewed some of the studies of basic issues which remain topical in electron-positron annihilations into hadrons. Precision experiments to measure the energy dependence of weak-electromagnetic interference and of the strong coupling constant have particularly high promise. For these questions, and for the similarl important task of measuring the photon structure function, it is not difficult to specify in quantitative terms the criteria for significance. For the long term, I attach great importance to a broad assault on meson spectroscopy, where the experimental issues are not yet sharply defined. The developing tool of $\gamma\gamma$ collisions has a key role to play in extending our knowledge of the spectrum of hadronic states.

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