SLAC-PUB-2366
August 1979
(T/E)

ELECTRON-POSITRON ANNIHILATION: SOME REMARKS ON THE THEORY*

James D. Bjorken
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA.

ABSTRACT

We review some topics in e^+e^- annihilation, including high-quality QCD tests, jet production, production of old and new leptons and quarks, gluonium, Higgs-bosons, and unconfined quarks.

It is difficult for me to try to review the status of e^+e^- theory; I feel very much an amateur at this point. Since the early days, the field has matured and flourished a great deal. More than a half dozen very large experimental groups are well prepared to exploit the expected physics forthcoming from PETRA and soon from PEP. These groups are served by a large number of theoretical gurus, e.g., one expert on sphericity, another on spherocity, another for thrust, and so on. So the phenomenology expected from QCD and the Kobayashi-Maskawa six-quark version of electroweak $SU(2) \otimes U(1)$ has been rather thoroughly worked out, and it is now a matter of waiting for the returns to come in. We have had abundant evidence at this meeting that thus far there is no trouble for the theory. It is a far cry from the early ADONE days, when existence of a large multihadron cross section was considered something of a surprise, or the days of the CEA and SPEAR startups. Then the most popular hypothesis had R less than $s^{-1} \log s$, while $R = 2/3$ was considered a large estimate[1)]. This time around, everything is working remarkably well — almost too well. It is tangible evidence of the great progress that has been made in the last decade.

This talk will not try to be a detailed or balanced review of the phenomenology, and will consist only of remarks on a few aspects I feel may be important, along with others that are perhaps a bit neglected. The topics are listed below:

(1) Gold-plated tests of QCD.
(2) Comments on jet properties.
(3) Leptons, old and new.
(4) New quarks.
(5) Higgs.
(6) Gluonium.
(7) Unconfined quarks.

1. GOLD-PLATED TESTS OF QCD

Many QCD calculations are actually judicious mixtures of the parton-model and QCD perturbation theory. Others stretch the limits of applicability of the short distance, perturbative quark-gluon aspect of the theory. But there are a few tests which appear to be especially clean, and therefore deserve special attention. The best candidate is the colliding beam total cross section, or R. The theoretical value is

$$R = \left(\sum_i Q_i^2\right)\left[1 + \frac{\alpha_s}{\pi} + (1.98 - .12N_f)\left(\frac{\alpha_s}{\pi}\right)^2 + \ldots\right] \qquad (1)$$

---

* Work supported by the Department of Energy under contract number DE-AC03-76SF00515.

(Talk given by the 1979 EPS High Energy Physics Conference, Geneva, Switzerland, June 27 - July 4, 1979.)

The second order term has only been recently calculated[2]. The result above is expressed in a modified minimal-subtraction renormalization scheme, one which allows a definition of α_s comparable to the one used in analyses of deep inelastic lepton-nucleon scattering.

It is probably better to evaluate the real part of the vacuum polarization at spacelike Q^2; this has been recently carried out by Sanda[3]. It should come as no surprise that the agreement with QCD is satisfactory. Nevertheless the systematic errors in the experiments are still large ($\Delta R \gtrsim 0.5$) and it is important to refine, if possible, the measurements to sharpen the comparison as much as possible. For example, it is not ruled out that there is a $J = 0$ pointlike integer-charged boson ($R = 0.25$) being produced along with the quarks.

Another test which appears quite clean is the production of energy (gluon jets) at large angles to the quark-jet direction[4]. A gluon with finite fraction ϵ of the total energy and large angle (greater than some fixed angle δ) relative to the quark jet is emitted at very short distances $\sim s^{-\frac{1}{2}}$, and therefore calculable in perturbation theory[5]. This short-distance process should lead to a distinct 3-jet final state. Hence measurement of the cross section and distribution in the Dalitz plot of these "gold-plated" 3-jet events should lead to an especially clean test of QCD perturbation theory and an independent determination of α_s.

Another candidate for a clean test is annihilation of onium into three gluons. However recent calculations[6] show very large radiative corrections for these processes, $\sim(10\text{-}20)\ \alpha_s/\pi$. Thus doubt is shed on quantative tests based on hadronic width. However, the data[7] on 3-jet final states in Υ decay remain of course a nice piece of general evidence in support of QCD.

We may also mention in this connection recent work of Peskin[8], who constructs a strict multipole expansion for gluon systems coupled to massive onia, based on operator product expansions. However in this case, it can only be applied to extremely heavy onia (which are essentially Coulombic), with level spacing large compared to the confinement scale Λ (Peskin optimistically estimates $m_Q \gtrsim 25$ GeV, but this number could well be considerably higher). This again suggests that QCD tests involving onia may not be all that gold-plated.

2. JET PROPERTIES

It takes a distance scale ~10-20 f for a PETRA/PEP jet to evolve from its parent parton into a group of distinct, approximately collinear hadrons. After the original $q\bar{q}$ pair have separated by no more than 1 fermi, one must expect that non-perturbative confinement effects are operative, in order that each jet screens the fractional charge and color it possesses at birth[9]. It is not clear to what extent (if any) such effects influence, say, the inclusive distribution of leading hadrons. Nevertheless, one must exercise extra caution in interpreting inclusive hadron distributions (parton fragmentation) in terms of perturbative QCD.

The question of the time-evolution and screening of QCD jets has recently attracted theoretical attention. The tree-structure of quark and gluon emissions present in the leading-logarithm approximation to QCD suggests a time-evolution for jet formation similar to the Weiszacker-Williams approximation in QED. The QED evolution does occur on a long time scale[10] (proportional to $\sqrt{s}$) so that one may suspect perturbative QCD to be deficient in being able to account for the evolution of color confinement[11]. However, the situation appears to be not that bad[12]. Owing to the high multiplicity of low-rapidity gluons emitted at short times — times short enough ($t \ll 1f$) for the perturbative calculations to be trusted — there is enough filling of the central rapidity-region to allow soft confining effects to easily proceed at early times[13]. Indeed it has been found by Amati and Veneziano[14] that the distribution in rapidity of virtual quarks produced at early proper time (i.e., very near the light cone) allow — in the $1/N_c$ approximation — the quarks to be grouped into color-singlet combinations of relatively low mass. This phenomenon, which is dubbed "preconfinement," sets the stage for the action of only soft confining forces in producing the observed hadrons out of the groups of virtual quarks and gluons.

However, these calculations are strictly valid only in the very asymptotic limit of high multiplicity of virtual gluons ($n_g \sim \exp \sqrt{Q^2/\mu^2}$) and thus very high Q^2. It would also be nice to see a more explicit space-time description of how the jets evolve. Another interesting question concerns what role would be played by pre-confining processes in a world without light quarks u,d,s. On the one hand, at sufficiently high energies $\sqrt{s}$, the time-evolution of the perturbative QCD jet should be insensitive to quark masses m_Q for times $t < m_Q^{-1}$. On the other hand, one intuitively suspects that in a world with only heavy quarks, confinement is implemented at all energies via strings connecting the heavy quarks, and not by pair-creation of $Q\bar{Q}$. Is this intuition wrong?

While jet structure has its theoretical uncertainties, it does mean we might learn more about non-perturbative aspects of QCD by studying it. The approximate scaling behavior of the leading hadrons is compatible with parton model ideas, suggesting that use of perturbative methods may be applicable. This phenomenology has had some success and is discussed here[15] by M. K. Gaillard. An important experimental question concerns charge correlations of the leading hadrons. The observed hadron distributions in neutrino-nucleon interactions are in good agreement with the general notions of parton fragmentation[16]. While much of the observed correlations of leading hadrons with parent-quark charge in charged-current ν and $\bar{\nu}$ processes may be attributed to phase-space and overall charge-conservation effects[17], this criticism cannot be made for the neutral-current processes, where a distinct difference in the π^+/π^- ratio for leading mesons has been seen in νN vs. $\bar{\nu} N$ processes. [In fact, it may now be time to use neutral currents as a tool in studying QCD and parton-model dynamics, accepting the applicability of the Weinberg-Salam effective Lagrangian for the basic coupling.] In colliding-beam reactions, one must therefore expect a negative charge correlation of the leading hadron in the quark jet with that of the antiquark jet, reflecting the negative charge correlation of their parents. A search for such an effect was made in SPEAR data, with results somewhere between inconclusive and negative[18]. It seems hard to find an excuse for this effect not being present at the higher energies now available.

Another question of considerable interest concerns the inclusive production of D and D^*. One naturally expects that their momentum distributions should be flatter than the pion distribution because of the heavy quark inside, which is difficult to decelerate. Existing SPEAR data[19] is too close to threshold to give a good inclusive distribution. The situation in the neutrino data is consistent with a flat D spectrum; however, the arguments are rather indirect[20].

3. LEPTONS, OLD AND NEW

The e^+e^- physics of μ and e centers about the QED tests. Of course we now expect QED to break down. The photon is supposed to die at a distance scale of ~100 GeV, presumably to be replaced by the U(1) generator of electroweak $SU(2) \otimes U(1)$ at shorter distances.

The most salient tests are well known and well studied, namely $\delta R_{\mu^+\mu^-}$ and the front-back asymmetry in $e^+e^- \to \mu^+\mu^-$.

The τ lepton is by now almost an "old" lepton. But it should not be taken for granted; we saw already[21)] that PEP/PETRA should be especially clean sources of τ's. What is interesting?

(i) Lifetime: Georgi and Glashow have recently played with assigning τ to a higher grand-unified SU(5) representation[22)], leading to a reassignment of τ to an electroweak triplet $(\nu_\tau\, \tau^-\, L^{--})_L$. This leads to a τ lifetime a factor two shorter than the standard value. On the other hand, were ν_τ mixed with a massive neutral lepton, the lifetime could be longer.

(ii) Branching ratios: Kane, motivated by the apparently large branching ratio of $D \to K\bar{K}$ observed at SPEAR, has suggested[23)] that charged Higgs-exchange contributes to this weak decay as well as the usual $W^\pm$ exchange. His scheme then implies that this Higgs should contribute to τ-decay. This leads to branching ratios for $\tau \to K\nu$ and $\tau \to \pi\nu$ at variance with the standard (gold-plated) predictions coming from W-exchange. The effect is a factor ~1.4 for $K\nu$ and ~1.1 for $\pi\nu$.

(iii) Rare decays: We know so little about intergeneration relations that one should watch for other unanticipated rare decays such as $\tau \to eee$, μee, $\mu\gamma$, $e\gamma$, $\mu\pi$, μK, $e\pi$, eK, ...

Given the cloning of fermions into three generations, we cannot rule out the possibility of a fourth charged sequential lepton λ. If the trend $m_\mu/m_e > m_\tau/m_\mu > m_\lambda/m_\tau$ is correct[24)], there is a good chance that λ production would be within the PETRA/PEP energy range. The final states and branching fractions would be (for $E_{CMS} \sim 30$ GeV)

$$\begin{aligned} e^+e^- \to \lambda^+\lambda^- &\to q\,q\,q\,q\,\nu\,\nu \sim 45\% \\ &\to q\,q\,\ell\,\nu\,\nu\,\nu \sim 45\% \\ &\to \ell\,\ell\,\nu\,\nu\,\nu\,\nu \sim 10\% \end{aligned} \tag{2}$$

Signatures are high sphericity, relatively low visible energy, and considerable numbers of energetic associated charged leptons which are not correlated with the quark jets. It seems unlikely that such a particle has been already produced at PETRA unless the threshold is rather near 27.4 GeV.

Neutral leptons, while less conventional, should not be forgotten. They naturally appear, for example[25)], in the grand-unified theory based on the exceptional group E6. [This model can be arranged[26)] so as to give just as satisfactory a value for $\sin^2\theta_W$ as SU(5).] There was a time when a neutral lepton N^o, paired with the right-handed electron in a weak doublet, helped in understanding the null result of the Seattle and Oxford atomic parity violation experiments. Such an N^o could be produced in $e^+e^- \to N_0\nu_e$ via W-exchange, or in $\tau^- \to \nu_\tau \bar{N}_0\, e^-$. A search[27)] at SLAC for the latter mode set a limit $M_{N^o} > 1.2$ GeV. However, the SLAC polarized electron-scattering experiments[28)] have disallowed this assignment. The remaining way to produce an N_0 in e^+e^- annihilation is pair production via an intermediate Z^o (or Higgs). The R for such a process[29)] is $\lesssim 10^{-2}$ at $E_{CMS} \sim 30$ GeV. Provided N_0 communicates with μ or τ, a good signature is two leptons (+ other charged particles as well) in the final state. If N_0 is of low mass, the $\pi^\pm\mu^\mp$ channel is an especially nice signature. If N_0 is of high mass, the high sphericity (plus two leptons), or more than two charged leptons are good signatures.

4. NEW QUARKS

The signatures for new-quark production have been much discussed[30)] and will not be reviewed here again in detail. They include increases in sphericity, $\bar{n}_{ch}$, inclusive lepton yields, and various multilepton configurations as one crosses the production threshold. As one has seen[31)], the detection is relatively easy for tops, and difficult for bottoms.

While one may discover such quarks without too much grief, it is harder to do something with them once one has them. For example, the decay

$$t \rightarrow q\,q\,q \tag{3}$$

with $m_t \sim 15\text{-}20$ GeV will yield a better 3-jet final state than $\Upsilon \rightarrow qqq$. But with two t-quarks per event, it will be hard to disentangle all those jets.

For the bottom-quark the situation is similar. There is expected to be a flavor cascade

$$b \underset{W}{\rightarrow} c \underset{W}{\rightarrow} s \underset{W}{\rightarrow} u \tag{4}$$

and inclusive properties as well as multilepton, multikaon events will provide a fair amount of information. But it will be rather indirect. To find direct exclusive decay channels of B will probably be harder than for D. Leading candidates are $B \rightarrow D\pi\pi$ or $D^*\pi\pi$. An interesting idea[32)] is to use the decay channel $b \rightarrow c(\bar{c}s)$ which is not too badly repressed by phase-space effects. One has modes $B \rightarrow D\bar{D}\bar{K}$ or $B \rightarrow \psi\bar{K}$. Observable branching ratios, however, are not better than 10^{-3}, so that one needs $> 10^4$ bottom-mesons just to enter the game[33)].

The orthodoxy gives a reasonably definite picture of bottom-quark properties, but these properties could change radically were the orthodoxy to be abandoned. If bottom is an electroweak singlet, one does not understand at all the decay-mechanism, and the lifetime could be anything. Even within the doublet assignment, crazy things might happen. For example, Derman[34)] uses permutation symmetry to relate fermion generations to each other, and ends up, because of multiplicative conservation laws, with b decaying only semileptonically, e.g., $b \rightarrow q\mu e$. It will not take long to settle that issue.

5. HIGGS

The final, least understood, and least established piece of the orthodoxy is the Higgs sector. The minimal scheme has one neutral Higgs-boson of mass somewhere between ~10 GeV and ~10^3 GeV. There has been increased enthusiasm[35)],[36)] of late for supposing that the only mechanism which gives the Higgs-boson its mass is essentially the virtual emission and absorption of $W^\pm$ and Z. With the present value of $\sin^2\theta_W \cong 0.23$, this puts the Higgs-mass at ≅ 10 GeV, approximately degenerate with the Υ system. This mass range for the Higgs is rather advantageous from the point of view of early detection[35)]. If toponium does turn up at a mass ~30 GeV, the branching ratio for $(t\bar{t}) \rightarrow h^0 + \gamma$ is $\sim 5 \times 10^{-3}$. In addition, the decays of Υ states (especially Υ' and Υ'') into $h^0 + \gamma$ is enhanced by mixing of the h^0 with the 0^{++} P-wave bottomonium states. Branching ratios are $\sim 10^{-4}$, and with some luck could even be bigger. The situation is summarized in Fig. 1.

The Higgs sector might suffer proliferation, just like the fermion-sector does. If so, there should exist charged Higgs particles, which should be pair-produced by e^+e^-, with an $R = 0.25$. However, not much guidance can be given on masses, coupling constants, or decay modes[37)].

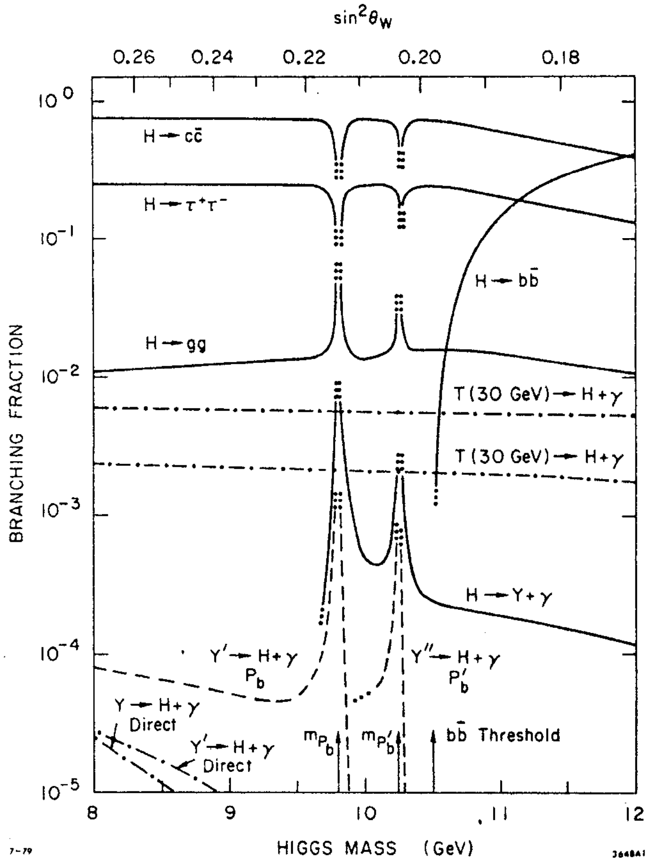

Fig. 1. Properties of a standard model Higgs-boson of mass ~10 GeV (the "scalon"). Taken from Ref. 35).

6. GLUONIUM

We now turn to a less-discussed feature[38)] of the orthodoxy — that of gluonium. Gluonia are the physical quanta of pure QCD (i.e., QCD without the quarks): quarkless, colorless, flavorless mesons with mass probably in the range of 1 to 2 GeV. We emphasize that QCD implies that they should exist. Why? Let us start with pure QCD and consider the well known process

$$\nu + \bar{\nu} \rightarrow g + g \tag{5}$$

This is neutrino-antineutrino annihilation into two gluons via a virtual graviton. At short distances asymptotic freedom tells us that the cross section can be calculated perturbatively. Let

$$R_\nu = \frac{\sigma(s)}{\sigma(s)_{\text{point}}} \tag{6}$$

be defined as usual, and consider the behavior as s decreases. As s approaches the confinement scale, perturbation theory breaks down, and we expect some wiggles in the true R_ν along with possible discrete resonances, as shown in Fig. 2. There are two choices for the mass scale M: either it is small (1-2 GeV) or it is large. If it is large, gluonia could be heavy, but then perturbation theory breaks down at an unexpectedly high mass scale. Such

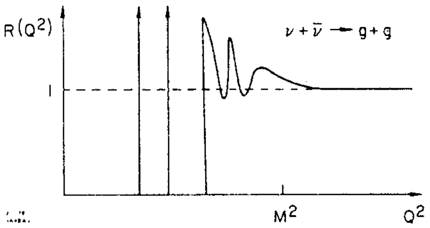

Fig. 2. Hypothetical cross section for the process $\nu + \bar{\nu} \to$ hadrons (gluonia) in pure quarkless QCD, normalized to the point cross section.

a conclusion would undermine the applicability of perturbative QCD at a moderate mass scale. On the other hand, if the mass scale is small, then the gluonia have small masses and there is no problem with convergence of perturbation theory.

However, this is still pure, quarkless QCD, not the real world. What happens when the quarks are introduced? Again, there are two possibilities: either the gluonia mix strongly with the ordinary $q\bar{q}$ meson states, or else the mixing is small. Consider the first possibility. The gluonia (some of which were stable) become very broad and difficult to see as resonances. But this threatens to introduce large violations of the OZI rule, with possibly large violations of the ideal nonet mixing in the 1^{--} ($m_\rho \approx m_\omega$) and 2^{++} ($m_{A2} \approx m_f$) nonets, along with broadening of ψ and ψ' widths.

Despite these problems, a group at ITEP in Moscow have recently advocated this viewpoint[39]. Their basic starting point is the set of QCD sum rules used not only to successfully describe the charm sector, but even to determine the parameters of ρ^0 and ω resonances[40]. Emboldened by this success, they analyze two-point functions such as $\langle 0|F^2(x)\ F^2(0)|0\rangle$ and $\langle 0|F\tilde{F}(x)\ F\tilde{F}(0)|0\rangle$ in the same way as the electromagnetic vacuum polarization, and conclude that the sum rules which they construct should (or could) be saturated by the 0^{++} ε meson (the broad $\pi\pi$ "resonance" at ~700 MeV) for F^2, and the η' for $F\tilde{F}$. They estimate the radiative decays $\psi \to \eta\gamma$ and $\psi \to \eta'\gamma$ with this picture[41], finding satisfactory agreement with experiment. Nevertheless the calculations do not look too clean (for example, instanton effects enter in a poorly controlled way). The success of the straightforward quark-model estimate[42] of $\Gamma(\eta' \to \gamma\gamma)$ is no longer understood. And one wonders whether a systematic study of OZI forbidden processes (e.g., $\psi' \to \psi\pi\pi$) would allow compatibility with this scheme[43].

I think it fair to say that most QCD theorists favor the second alternative, that gluonia mix very little with ordinary $q\bar{q}$ mesons and are narrow. This is a feature of the topological expansion or 1/N expansion[44]. [An eloquent exposition and summary of this line of argument has been recently given by Witten[45].] What then are the properties? Theory is hard put to give a sharp answer to this question (it is a challenge for nonperturbative, pure QCD to give us a spectrum — even qualitative — in terms of α_s). As a first terribly simple-minded attempt, we may try a naive gluonium model[38], at least as naive as the naive parton model, naive Drell and Yan, or naive SU(6) quark spectroscopy. Just take two or three massive "constituent gluons" and bind them together into an S-wave bound state with spin-independent central potential. One gets a plethora of candidate states (cf., Table I), not all of which need be low-lying — or even exist — in the real world. Some typical decay channels are also listed in the table. Nothing very distinguished emerges. One must have (approximate) SU(3) — singlet states, suggesting that channels with η, η', ϕ, K's may be advantageous. Robson[38] suggests a 1^{-+} gluonium decay into $\eta + \eta'$ might be a good possibility.

Where should gluonia be produced? No doubt in hadron collisions (are "clusters" gluonia?), but they may be hard to dig out of the background. $\pi\pi$ and $K\bar{K}$ phase-shift analyses might be promising places to look for narrow 0^{++} and/or 2^{++} states. Resonant e^+e^- annihilation is of course good for any 1^{--} gluonium state. However, one has to go rather far down the list of candidates in Table I to find one, and the leptonic width would be hard to estimate and quite likely rather small.

TABLE I

	Type	J^{PC}	Typical Decays
1.	E_iE_j	0^{++}, 2^{++}	$\pi\pi, KK, \eta\eta, \eta'\eta', \rho\rho, \omega\omega, K^*K^*, \phi\phi$
2.	E_iB_j	0^{-+}, 1^{-+}, 2^{-+}	$\pi\delta, K\kappa, \eta S^*, \eta'\varepsilon, \rho B, K^*Q; \pi A1, KQ, \ldots$
3.	B_iB_j	0^{++}, 2^{++}	Same as (1)
4.	$E_iE_jE_k$	0^{-+}, 1^{--}, 3^{--}	$\pi\delta, K\kappa, \eta'\varepsilon, \pi\rho, KK^*, \eta\omega, \eta'\phi, \omega f, \phi f', \ldots$
5.	$E_iE_jB_k$	0^{++}, 1^{++}, 2^{++}	Same as (1); $\pi\delta, K\kappa, \eta S^*, \ldots$
		1^{+-}, 2^{+-}, 3^{+-}	$\pi\rho, KK^*, \eta\omega, \eta'\phi, \pi B, KQ, \eta D, \ldots$
6.	$E_iB_jB_k$	0^{-+}, 1^{-+}, 2^{-+}	Same as (2)
		1^{--}, 2^{--}, 3^{--}	$\pi B, KQ, \rho A2, K^*K^{**}, \omega f, \phi f', \ldots$
7.	$B_iB_jB_k$	0^{++}, 1^{+-}, 3^{+-}	Same as (1); $\pi B, KQ, \rho A1, \rho A2, \ldots$

The best chance for finding gluonia probably lies in radiative ψ decays$^{46)}$: $\psi \to \gamma +$ gluonium. In QCD the branching ratio is estimated to be ~10% although the aforementioned large radiative corrections makes this at best a semiquantitative guess. The γ-ray spectrum from the lowest order perturbative calculation is shown in Fig. 3(a); it is essentially 3-body phase-space. Radiative corrections$^{6)}$ will change it to something like Fig. 3(b), while replacing the low-mass gg parton final-states with a more realistic resonance spectrum (assuming duality) will provide something like Fig. 3(c).

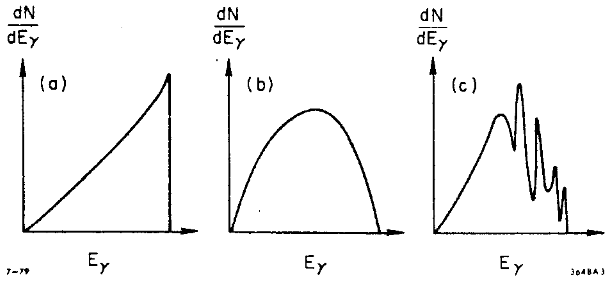

Fig. 3. (a) Lowest-order γ spectrum as calculated for $\psi \to \gamma gg$.
(b) The γ-spectrum (schematic) only after radiative corrections.
(c) The conjectured real spectrum after inclusion of gluonium resonances (with use of duality).

The known decays $\psi \to \gamma\eta$, $\gamma\eta'$, γf give a total width of $\lesssim 1\%$. The Mark I lead-glass wall collaboration at SPEAR has reported[47)] a single-γ continuum contribution (with mass recoiling against the γ of $\lesssim$ 1.7-1.8 GeV) consistent with a total radiative branching ratio of ~5%. If this result holds up, the gluonia may in fact be already observed.

A large fraction of the final gg state is expected[48)] to be 0^{++} and 2^{++}. Krammer[49)] has estimated the $\pi\pi$ angular correlation in the decay $\psi \to \gamma gg \to \gamma f \to \gamma\pi\pi$ expected from QCD. The correlation observed experimentally agrees nicely with expectations. However, only a quite weak $q\bar{q} \leftrightarrow gg$ coupling is needed, so that this does not imply that the f is a gluonium state. It is also curious that $\psi \to \gamma f'$ has not been seen.

7. UNCONFINED QUARKS

Unconfined quarks may seem a radical departure from orthodox QCD, but it may not be so at all. De Rujula, Giles and Jaffe[50)] have studied a slightly multilated version of QCD which appears to produce unconfined quarks of large mass and large size. The procedure is as follows:

(1) Give gluons a small "Lagrangian" mass μ_g (we will be considering $\mu_g \sim$ 5-20 MeV, of order the bare-quark "Lagrangian" masses).

(2) Do this by the Higgs-mechanism. [Otherwise nonrenormalizable effects probably occur at an unacceptably low mass scale.] The Higgs representation(s) must be $\underline{8}$ (or $\underline{10}$, $\underline{27}$,...), not $\underline{3}$ (or $\underline{6}$, $\underline{15}$,...) in order to avoid low-mass colorless fermions of fractional charge built from quarks bound to the Higgs-bosons[51)].

(3) Unbroken QCD (omitting temporarily the light quarks) probably implies a quite stable string connecting a widely separated pair of very heavy quarks Q. If the distance exceeds the gluon Compton wavelength μ_g^{-1} it is plausible (but not self-evident and far from proven) that this string breaks, owing to the replacement of a power-law potential with a Yukawa-like potential. A single quark Q with a piece of broken string then has a mass $M \sim m_Q + T\mu_g^{-1}$, where T is the energy per unit length of the string (string-tension), ~1 GeV/f. If this picture can be maintained, it implies that both size and mass of unconfined quark are $\sim\mu_g^{-1}$, i.e., tend to infinity as the breaking tends to zero.

(4) Adding in the light quarks u,d,s may profoundly change the situation. Vacuum structure is probably modified, and in unbroken QCD the string breaks by Heisenberg-Euler pair creation[52)]. This probably means that the color field surrounding the unconfined quark contains a large component of virtual pairs of light quarks. It may even be that a degenerate sea of q's and $\bar{q}$'s form in order to suppress further pair creation. However this is at best wild speculation.

In addition to the large size, large mass, and complicated internal structure, such an unconfined quark would accrete nucleons in its passage through matter. The mass of the resultant system versus baryon number A is estimated by De Rujula, Giles and Jaffe[50)] to look like Fig. 4(a). McLerran and I, motivated by a desperate effort to understand the Centauro cosmic-ray event, have tried going one step further[53)]. We considered a situation (Fig. 4(b)) where the primeval quark with $|A| < 1$ can spontaneously decay into a lighter system of large A with emission of ~A antibaryons. This might happen were the region of color field surrounding the quark source stabilized from pair-creation by the presence of a degenerate sea of either light quarks or light antiquarks, but not both (thereby avoiding the cost of the extra kinetic energy). Again, this is wild speculation.

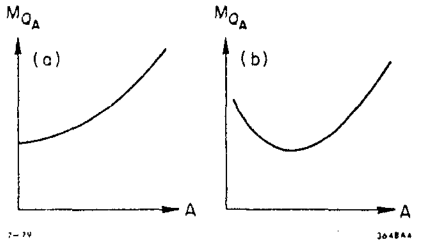

Fig. 4. (a) Mass of an unconfined quark + baryonic matter system as function of A according to De Rujula, Giles and Jaffe (Ref. 50). (b) Extreme variant used by McLerran and me (Ref. 53) as model of Centauro event.

If large, heavy quarks do exist, how might they be produced? In e^+e^- annihilation, probably a necessary condition is that a newly formed $q\bar{q}$ pair separate by a distance μ_g^{-1} without any quark pair breaking the string. Since the probability per unit time of Heisenberg-Euler pair creation is some constant, say

$$\frac{d\Gamma}{dz} \sim 20 \text{ MeV/f} \quad , \tag{7}$$

then the survival probability $P_{Q\bar{Q}}$ will be

$$P_{Q\bar{Q}} \sim \exp - \left(\frac{M_Q}{m}\right)^2 \tag{8}$$

with the scale factor m^{-2} proportional to $d\Gamma/dz$ in Eq. (7). With the above guess for the decay rate of the string, one gets $m \sim 3$ GeV. This would lead, for $M_Q \sim 10$ GeV, to a yield $R_{Q\bar{Q}}$ of unconfined quarks in e^+e^- annihilations of

$$R_{Q\bar{Q}} \sim 10^{-4} \tag{9}$$

But this is clearly very uncertain; the exponent is not reliable to better than a factor ~3-10.

What is the mass of the unconfined quark? Recently Steigman and Wagoner[54)] have reconsidered the problem of quark production in the big bang. They estimate the quark/baryon fraction by regarding, at the time when quark matter makes the phase transition to nuclear matter (temperature $T \sim 100$-200 MeV), those quarks of energy $E > m_Q$ as the remanent physical quarks. This results in a quark mass estimate of ~15-30 GeV, provided the quark abundance is to be $\sim 10^{-18}$-10^{-20} per nucleon, as indicated by the Stanford experiments[55)]. It may not make sense to identify in that epoch those energetic quark-partons with the heavy, large unconfined quarks we discussed. If one only allows non-equilibrium quark production by hadron-hadron collisions after the phase transition, the mass estimate goes down[56)] to ~10 GeV. In either case the mass range is of experimental interest.

What messages are there in all this crazy speculation? For theorists there is a challenge: one clearly need not believe a word of what we have said. But if anyone really claims to understand confinement in QCD, he should also be able to understand what happens were QCD to be slightly broken in the way we described.

And what is the message for experimentalists? It is simply that, were they to observe an e^+e^- event with two highly charged heavy tracks, accompanied by fireballs composed of several baryons and antibaryons, they should let us all know about it. After all, it may turn out to be another test of QCD.

8. SUMMARY

The present experimental situation exhibits a remarkably good agreement with theoretical expectations. There exists opportunities of making truly incisive tests of QCD by study of R and of gold-plated 3-jet events. Somewhat less incisive, but still an important issue for QCD, is the search for gluonium in radiative ψ decays and elsewhere. And while it is somewhat premature to draw any firm conclusion from the new data, it already appears that if truly new and surprising phenomena exist in the energy range 13-27 GeV, they do so at best at a rather low level. One should of course pursue the search for possible kinds of low-level hidden phenomena, such as charged Higgs-bosons, or the standard neutral Higgs in onium-decays, or neutral lepton production, or even unconfined quarks. And we may still have major surprises as the energies increase from the 28 GeV at present to ~40 GeV in the near future.

* * *

REFERENCES

1) J. Bjorken, Proc. of the 6th Internat. Symp. on Electron and Photon Interactions at High Energies, ed. by H. Rollnik and W. Pfeil, North-Holland (Amsterdam), 1974; also J. Ellis, Proc. of the 17th Internat. Conf. on High Energy Physics, London, 1974.

2) M. Dine and J. Sapirstein, SLAC preprint SLAC-PUB-2332; K. Chetyrkin, A. Kataev and F. Tkachov, Moscow INR preprint P-0126.

3) A. Sanda, Rockefeller preprint COO-2232B-178, also Phys. Rev. Lett. 42, 1658 (1979). See also G. Moorhouse, R. Pennington and G. Ross, Nucl. Phys. B124, 285 (1977).

4) P. Hoyer, P. Osland, H. Sander, T. Walsh and P. Zerwas, DESY preprint DESY 79/21 and references therein.

5) This infrared freedom of jet properties has been especially emphasized by G. Sterman and S. Weinberg, Phys. Rev. Lett. 39, 1436 (1977).

6) R. Barbiera, E. d'Emilio, G. Curchi and E. Remiddi, CERN preprint CERN-TH-2262, January 1979.

7) See the talk of P. Söding, these proceedings.

8) M. Peskin, Harvard preprint HUTP-79/A008, March 1979; G. Bhanot and M. Peskin, Harvard preprint HUTP-79/A015, March 1979.

9) I have in mind the inside-outside cascade picture of particle production; cf., J. Kogut and L. Susskind, Phys. Rev. D10, 732 (1974); also J. Bjorken, in Lecture Notes in Physics 56, "Current-Induced Reactions," ed. by J. Korner, G. Kramer and D. Schildknecht, Springer-Verlag (N.Y.), 1975.

10) A nice exposition is given by E. Feinberg, Zh. Exp. Teor. Fiz. 50, 202 (1966) [English translation, JETP 23, 132 (1966)].

11) C. Chiu and J. Szwed, Max Planck Institute preprint MPI/PAE/PTh 15/79 (May 1979).

12) L. Caneschi and A. Schwimmer, Weizmann Institute preprint WIS-79/24 Ph.

13) K. Konishi, A. Ukawa and G. Veneziano, Phys. Lett. 78B, 243 (1978) and Rutherford Laboratory preprint RL-79-026.

14) D. Amati and G. Veneziano, Phys. Lett. 83B, 87 (1979).

15) M.-K. Gaillard, these proceedings.

16) For reviews, see R. Field, Proc. of the 19th Internat. Conf. on High Energy Physics, Tokyo, Japan, 1978 (CALT 68-696); L. Sehgal, Proc. of the 19th Internat. Symp. on Lepton and Photon Interactions at High Energies, Hamburg, Germany, August 1977.

17) For example, cf., J. Vander Velde, Michigan preprint UMBC-78-9; J. Bell *et al.*, Phys. Rev. D19, 1 (1979).

18) G. Hanson, Proc. of the 13th Rencontre de Moriond, Les Arcs, France, March 1978; also SLAC preprint, SLAC-PUB-2118, May 1978.

19) M. Piccolo, I. Peruzzi and P. Rapidis et al., SLAC-PUB-2323, May 1979; P. Rapidis et al., SLAC-PUB-2184, August 1978.

20) R. Odorico and V. Roberto, Nucl. Phys. B136, 333 (1978).

21) G. Wolf, these proceedings.

22) H. Georgi and S. Glashow, Harvard preprint HUTP 79/A027.

23) G. Kane, SLAC preprint SLAC-PUB-2326, May 1979.

24) For example, see J. Bjorken, SLAC-PUB-2195 (unpublished); A. Barut, Phys. Rev. Lett. 42, 1251 (1979); T. Walsh, DESY preprint DESY 78/58.

25) F. Gursey, P. Ramond and P. Sikivie, Phys. Lett. 60B, 177 (1976).

26) Y. Achiman and B. Stech, Phys. Lett. 77B, 389 (1979).

27) D. Meyer and H. Nguyen et al., Phys. Lett. 70B, 469 (1977).

28) C. Prescott et al., Phys. Lett. 77B, 347 (1978) and SLAC-PUB-2319, May 1979; also C. Prescott, these proceedings.

29) A. Ali, Phys. Rev. D10, 2801 (1974); C. Ragiadakis, Strasbourg preprint CRN/HE 77-15 (1977).

30) J. Ellis, M.-K. Gaillard, D. Nanopoulos and S. Rudaz, Nucl. Phys. B131, 285 (1977); A. Ali, J. Korner, G. Krammer and J. Willrodt, DESY preprints DESY 78/47, 78/51, and 78/67.

31) G. Wolf, these proceedings.

32) H. Fritzsch, CERN preprint CERN-TH-2648, March 1979.

33) A positive signal in π^- production at 150 GeV is reported by the Goliath collaboration; cf., D. Treille, these proceedings.

34) E. Derman, Phys. Rev. D19, 317 (1979) and references therein.

35) J. Ellis, M.-K. Gaillard, D. Nanopoulos and C. Sachrajda, Phys. Lett. 83B, 339 (1979).

36) I. Bars and M. Serardoglu, Yale preprint COO-3075-188; S. Weinberg, Phys. Lett. 82B, 387 (1979).

37) H. Haber, G. Kane and M. Sterling, Michigan preprint UM HE-78-45, December 1978.

38) D. Robson, Nucl. Phys. B130, 328 (1977), provides a nice survey of the subject and references to other work; see also P. Roy and T. Walsh, Phys. Lett. 78B, 62 (1978). We follow here the arguments of H. Fritzsch and P. Minkowski, Nuovo Cimento 30A, 393 (1975).

39) V. Novikov, M. Shifman, A. Vainstein and V. Zakharov, ITEP preprint, 1979.

40) M. Shifman, A. Vainstein and V. Zakharov, Nucl. Phys. B147, 385,448 (1978).

41) See also M.-K. Gaillard, these proceedings.

42) G. Abrams et al., SLAC preprint SLAC-PUB-2331.

43) Studies of the connection of the OZI rule with gluonium states have been made by J. Bolzan, K. Geer, W. Palmer and S. Pinsky, Phys. Rev. Lett. 35, 419 (1975); also J. Bolzan, W. Palmer and S. Pinsky, Phys. Rev. D14, 3202 (1976).

44) G. Veneziano, Nucl. Phys. B117, 519 (1976).

45) E. Witten, Harvard preprint HUTP 79/A007.

46) M. Chanowitz, Phys. Rev. D12, 918 (1975); S. Brodsky, D. Coyne, T. deGrand and R. Horgan, Phys. Lett. 73B, 203 (1978); see M. Krammer and H. Krasemann, DESY preprint DESY 79/20, for a nice review.

47) See M. Davier, these proceedings.

48) A. Billoire, R. Lacaze, A. Morel and H. Navelet, Phys. Lett. 80B, 381 (1979).

49) M. Krammer, Phys. Lett. 74B, 361 (1978).

50) A. De Rujula, R. Giles and R. Jaffe, Phys. Rev. D17, 285 (1978).

51) Here we differ from Ref. 50), which allows color-triplet Higgs breakings.

52) A recent discussion is given by A. Casher, H. Neuberger and S. Nussinov, Tel-Aviv preprint TAUP-747/79; cf., also H. Neuberger, preprint TAUP-721/79.

53) J. Bjorken and L. McLerran, SLAC preprint SLAC-PUB-2308.

54) G. Steigman and R. Wagoner, Stanford preprint ITP-633, April 1979.

55) G. LaRue, W. Fairbank and A. Hebard, Phys. Rev. Lett. 38, 1011 (1977); G. LaRue, W. Fairbank and J. Phillip, Phys. Rev. Lett. 42, 142,1019 (1979).

56) This result is contained in work of J. Bahcall, S. Frautschi and G. Steigman, Ap. J. 175, 307 (1972). I thank G. Steigman for useful discussions and clarifications of all these points.