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IMPACT OF ELEMENTARY PARTICLE PHYSICS ON STORAGE RINGS*

J. D. Bjorken†

I. Status of Elementary Particle Physics

The prevailing viewpoint[1] on the present status of elementary particle physics can be expressed quite succinctly. First, the basic building-blocks of matter (discovered thus far) are pointlike spin 1/2 leptons and quarks, arranged according to Table I:

Table I. The table of elementary spin -1/2 building-blocks. The top quarks, while not yet discovered, are expected to be found soon.

	Q = 0	Q = -1	Q = 2/3	Q = -1/3
Generation I	ν_e	e^-	$u_1u_2u_3$	$d_1d_2d_3$
Generation II	ν_μ	μ^-	$c_1c_2c_3$	$s_1s_2s_3$
Generation III	ν_τ?	τ^-	$(t_1t_2t_3)$	$b_1b_2b_3$

The first generation particles (electron e and its neutrino ν_e, up and down quarks u_i and d_i) account for the constituents of ordinary matter. The second and third generations seem to be clones of the first generation, with the main distinction simply being increasingly larger mass with each increase in generation.

These constituents interact with each other via the various known forces. The well-understood electromagnetic force mediated by the photon is generally believed to be synthesized with the weak force. The weak interaction in turn is believed to be mediated by three J = 1 intermediaries W^+, W^-, Z^0 whose masses are expected to be ~80-100 GeV. And the strong force is believed to be associated with the three-fold (color) degeneracy of the quarks. An octet of J = 1 colored massless gluons, coupled to the color quantum numbers of the quarks, is assumed to mediate the strong force between quarks -- at least at short distances. Together with this picture of the interaction comes the dogma of confinement: only color-neutral states (e.g., baryons composed of combinations $q_1q_2q_3$ or mesons composed of combinations $\sum_i \bar{q}_i q_i$) can be realized physically. Thus quarks and gluons should not exist as isolated states.

All of these forces can be described by theories based on a principle of local gauge invariance. The only exception is an interaction, not mentioned above, mediated by spinless bosons (the conjectured Higgs-particles) needed to account for the masses of $W^\pm$, Z^0, leptons and quarks and for the existence of inter-generation (Cabibbo) mixing of quark types. Very little is really known about the properties of this interaction (not to mention its very existence) and it remains one of the most unsatisfactory elements of the present viewpoint.

II. How the Machines Have Contributed

Most of the information on the new building-blocks c_i, τ, ν_τ has come from the e^+e^- rings. Information on the bottom-quark b originated with the discovery at Fermilab of the Υ particles: presumably bound states of b and $\bar{b}$, analogous to the relationship of ψ and ψ' to charm. But we can expect that PETRA and PEP will play the dominant role in elucidating the detailed properties of this constituent.

On the other hand, information on the forces has come more from fixed-target experiments than from storage rings. Confidence in the gluon theory of the strong force (now known as quantum chromodynamics, or QCD) rests in large part on the successes of interpreting the many resonant hadron states found in earlier generations of machines in terms of the quark model and on the evidence for (almost) pointlike structures from deep-inelastic lepton-hadron collisions, as manifested in the approximate scaling behavior in the cross sections as well as the pattern of deviations from exact scaling. Colliding beams have also contributed, notably in the value and energy-dependence of the cross section for hadron production by e^+e^- annihilation and in the production of quark "jets" in pp and e^+e^- colliders.

Confidence in the present picture of the weak force rests in large part on the discovery and elucidation of neutral-current neutrino interactions. Here experiements with neutrino beams from all the proton machines -- PS, AGS, FNAL, SPS -- have assembled a wealth of quite accurate data which is in remarkably good agreement[2] with the low-energy effective Lagrangian of the Weinberg-Salam model. The beautiful experiment at SLAC on parity violation in polarized electron-nucleon scattering[3] has provided additional confirmation. It has in fact been very satisfying to see progress realized by experimentation across such a broad range of energies and technique.

III. Implications for Future Storage Rings

The successes of e^+e^- rings in finding fermion building-blocks speaks for itself as far as implications for the future are concerned. The question of verifying the present viewpoint on strong and weak forces is also well addressed by the new generations of e^+e^- rings. The most vital question regarding QCD has to do with finding the gluons. This does not mean they need be seen as isolated physical particles any more than the quarks need be seen. However quarks are already "seen" in the sense that they materialize into jets of hadrons with rather definite properties. For example the process $e^+e^- \to$ hadrons can be viewed as proceeding in two stages: first one has $e^+e^- \to q\bar{q}$; thereafter q and $\bar{q}$ evolve into two jets of hadrons which populate the same regions of phase-space as the parent quarks. Gluons should behave similarly; what one needs is a gluon source with well-defined properties. A quark itself is such a source; it should radiate gluons in a manner very similar to the bremsstrahlung radiation of photons from electrons. The only problem is having sufficient energy and luminosity to cleanly isolate the gluon jet from the jet of the parent quark. At PEP and PETRA, the process

$$e^+e^- \to q + \bar{q} + g$$

is expected to be clearly visible, with a more-or-less calculable cross section. Another potentially clean

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† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305.

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test is annihilation of heavy onium into three gluons, very analogous to the three-photon annihilation of the $J = 1$ state of positronium. A search for gluon jets from the decay of Υ has been carried out by the PLUTO group at DORIS. The results, while marignal, do favor the three-gluon hypothesis better than any other hypothesis. Were top-onium to be found it would provide a much cleaner test than the Υ.

With time the tests of QCD become more and more similar to the tests of QED carried out 15 years ago. There is some difference in detection technique. The shower counters used to convert and detect the produced electrons and photons of interest to QED are not needed. But the vacuum itself is kind of converter: it converts quarks and gluons into a cascade shower of hadrons. The parameters are as follows: radiation length $\sim 10^{-12}$ cm at $E \sim 10$ GeV, and directly proportional to E; critical energy ~500 MeV. The analogy should not be pressed too far; the structure and time evolution of the cascade is in fact somewhat different. In order to cleanly see the quark and/or gluon the energy of the parent must be large compared to the critical energy, $E_{jet} \gg 1$ GeV.

Just as the task in strong interactions is to find the gluon, the quantum purported to mediate the strong interactions, in weak-electromagnetic theory the central task is to find the $W^\pm$ and Z^0 presumed to mediate the weak force. Here both $p\bar{p}$ (or pp) and e^+e^- rings may be used. This has been much discussed and we need not go into detail here. Most notable is resonant production of Z^0 (mass ~90-100 GeV) by e^+e^-, where the peak yield is estimated to be (at 10^{32} luminosity) between 1 and 10 per second. Not only would discovering the Z^0 greatly increase confidence in the orthodox weak-interaction theory, it would also provide a great source of all the building-blocks into which the Z^0 decays.[4]

A Z^0-factory may in fact be one of the few possibilities of finding direct evidence of the conjectured Higgs particles which are supposed to underlie the mechanism of mass generation of $W^\pm$, Z and the building-blocks. The decay $Z^0 \to \text{Higgs} + \mu^+ + \mu^-$ allows its detection provided the Higgs mass is no larger than 40-50 GeV.

IV. Limits to Growth

Where does all this end? Will the cloning of building-blocks continue indefinitely? There are some theoretical indications that if there is indefinite proliferation, it at least must be more imaginative. First of all, astrophysicists object to more two-component neutrinos coupled weakly to more leptons. Such neutrinos would be in equilibrium with matter during the early stages of the Big Bang, and their inertia would affect the expansion rate. This in turn would influence the mechanism of helium production and thereby the primordial helium abundance. With much more than the presently known number of neutrinos, the calculated helium abundance disagrees with observations.

A second limit comes from calculations of virtual radiative corrections to the standard model -- in particular relative mass-shifts of $W^\pm$ and Z^0 coming from massive fermion vacuum-polarization loops.[5] When the quark or lepton masses exceed a few hundred GeV, such corrections become unacceptably large. This also is the case for the mass of the conjectured Higgs-boson; it cannot exceed 1 TeV without drastically affecting the structure of the theory.

Thus center-of-mass energies of hundreds of GeV to the few TeV range may well be a landmark of special significance. This is the old weak unitarity limit

$$E_{cms} \gtrsim \left(\frac{G_F}{\pi^2}\right)^{-1/2} \sim 1 \text{ TeV}$$

a number which has not completely disappeared from the theory, despite the relatively small mass of the intermediate bosons. Building-blocks with masses in this range should be especially interesting. For example, if there is a fourth (final?) generation of quarks and leptons, the quark masses (by simple extrapolation of the existing pattern) may well be in the range of 100 GeV or above. In any event the last generation of quarks may be the most significant: their strong interactions are simplest, and with such large mass, they are most likely the quarks most directly connected with whatever mechanism is responsible for mass generation. For example, within the conventional Higgs-picture, the coupling of Higgs-bosons to a superheavy quark is stronger than the photon-quark coupling and becomes comparable in strength to that of the "strong" QCD quark-gluon coupling when the quark mass is $\gtrsim 300$ GeV.

Could superheavy quarks be produced and detected? The answer appears to be yes; if one scales their production in pp (or $p\bar{p}$) collisions to charm-production using dimensional analysis

$$\frac{(pp \to Q_i + \text{anything})}{(pp \to c_i + \text{anything})} \approx \left(\frac{m_c}{m_Q}\right)^2$$

one obtains a cross section in excess of 10^{-33} cm^2. Thus both the FNAL $p\bar{p}$ collider (at 1 + 1 TeV) and ISABELLE could produce ample numbers of such $Q\bar{Q}$ pairs. The Q should decay into a light quark q and an intermediate boson W

$$Q \to q + W \to q + \bar{q}$$

leading to 6-jet final configurations of very characteristic signature.

V. How Much Color in Our Future?

If QCD is correct, the color quantum number plays a role for strong interactions much like charge of QED. The previous example of heavy-quark production indicated that pp or $p\bar{p}$ collisions are a good source of such objects. This can be generalized: colliding quarks and gluons can produce any colored object, confined or unconfined, by mechanisms completely analogous to the way colliding e^+ and e^- beams generate any charged object. Those cross sections are generally of order α^2; the analogous QCD processes are of order $\alpha^2_{strong} \sim 100\,\alpha^2$. Thus pp or $p\bar{p}$ rings with $\mathscr{L} \gtrsim 10^{30}$ sec^{-2} make colored objects at about the same rate that comparable e^+e^- rings

$$E^{e^+e^-}_{cms} \sim \frac{1}{3} E^{pp}_{cms}$$

with $\mathscr{L} \sim 10^{32}$ sec^{-2} make charged objects.

What are the prospects for actually producing colored objects other than quarks? One must engage in a degree of speculation higher than the orthodoxy we have followed so far. (In the full orthodoxy[1] the only extra colored objects needed for "grand unification" of QCD with the weak force are $J = 1$ lepto-quarks with masses $\gtrsim 10^{14}$ GeV.) Objects which have been mentioned include massive axial gluons,[6] unconfined massive gluons[7] (or quarks) and lepto-quarks of more modest mass.[8] Nevertheless we may expect to be surprised, just as we have been with the rich collection of charged building-blocks. And the range of masses available to the pp and $p\bar{p}$ colliders of the future makes the prospects both promising and exciting.

References

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