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Charge of the Quark

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Occam's razor and recent data from CERN on photon-photon interactions favour a highly charged rival to the Standard Model. Either of two recently proposed linear colliders could make decisive tests.

KEY WORDS: quark charge; photon-photon interaction; electro-strong model.

1. INTRODUCTION

The nature and the magnitudes of the charges of quarks are important quantities in science. They determine the properties of atomic nuclei, and they control the production of the chemical elements in stars. They may be compared in importance to the gravitational constant and the charge of the electron. Despite this, both the nature and the magnitudes of the charges of quarks are open to debate. This is simply because quarks have never been detected in isolation. Only bound states containing multiple quarks have been observed. Assumptions are required to determine the charges of individual quarks from these observations.

Recently, a new type of experiment was performed that can shed light on the charges of quarks from an observational point of view. High-energy interactions of photons with photons were studied at CERN. Measurements of the cross-section for hadron production at large transverse momenta yielded surprising results. The cross-section for the process depends sensitively on the magnitudes of the electric charges of quarks, more sensitively than for any previously observed process. The measurements may be utilised to test various theories of quarks that have been proposed.

In the following sections, the photon-photon experiment that was carried out at CERN is described and discussed in terms of three models. These are the Standard Model (Fritzsch *et al.*, 1973), a model in which quarks are assumed to have the same colour charges as in the Standard Model but unit electric charges

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(Ferreira, 2002), and an electro-strong model in which quarks are assumed to have large electric charges and no colour charges (Yock, 1969). Prospects for carrying out improved photon-photon experiments at higher energies are also discussed. Finally, some epistemological and concluding remarks are made.

2. THE PHOTON-PHOTON EXPERIMENT

The photon-photon experiment was carried out by the L3 collaboration at CERN (Archard *et al.*, 2002, 2003, 2004). The photons were generated by electrons and positrons in the LEP collider that was recently de-commissioned. Cross-sections for hadron production at large transverse momenta were measured in three channels. The transverse momenta were of order some tens of GeV/c, and the three channels were inclusive π^0 and K_s^0 production, inclusive charged hadron production, and inclusive jet production.

The collider was operated at its maximum energy of 200 GeV. At this energy, almost all hadron production occurred in photon-photon interactions. Hadron production by electron-positron annihilation amounted to less than 1% of that from photon-photon interactions (Braccini, 2003). In the photon-photon events, the outgoing electrons and positrons were not observed, as they exited close to the incoming beams. Their energies, and hence the energies of the interacting photons, were deduced by energy conservation and measurements of the energies of the other participating particles. The L3 collaboration was able to do this successfully as a result of employing relatively accurate calorimeters in their detector. Succinct reviews of the experiment are available (Braccini, 2003; Wengler, 2004).

3. COMPARISON OF THE PHOTON-PHOTON DATA WITH THE STANDARD MODEL

According to the Standard Model, the large transverse momenta observed by the L3 collaboration imply that a fundamental interaction involving only a single quark, as shown in Fig. 1, causes the interaction (Berger and Wagner, 1987; Gordon, 1994; Binnewies *et al.*, 1996). It then follows that the predicted amplitude with any quark is equal to the square of the electric charge of that quark multiplied by kinematic factors that are fixed by the Standard Model. The final cross section, obtained by summing over quarks in the usual manner, is thus free of ambiguities.

However, the cross-sections measured by the L3 collaboration in all three channels were considerably greater than the predictions of the Standard Model, with excesses reaching about an order of magnitude at the highest transverse momenta (Braccini, 2003; Wengler, 2004). It follows that either the data in all three channels are invalid, or the Standard Model is.

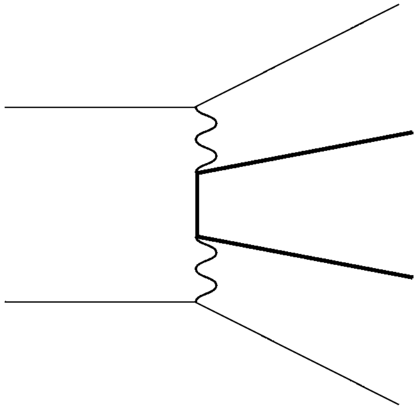

Fig. 1. Feynman diagram for hadron production at large transverse momentum in photon-photon interactions at high energies. The incoming electron and positron (thin lines) radiate photons that produce quarks (thick lines). Because two photons are attached to the quark line, the amplitude is proportional to the square of the electric charge of the quark. In the Standard Model, the above diagram is assumed to apply at present-day energies. In the electro-strong model it is assumed to apply at asymptotically high energies only, as described in the text.

The fact that the discrepancy is largest for those events where the transverse momentum is highest is important, because it is precisely these events that probe the smallest distances. It was, of course, Rutherford's observation of anomalously frequent scattering of 2-particles by gold foil through large angles that led to his discovery of the atomic nucleus. Prior to his observation, the atom had been envisaged (Thomson, 1904) as numerous electrons swarming inside a cloud of massless positive charge, remarkably analogous to today's picture of the proton according to the Standard Model (Shipsey, 2005)

Two further points are noteworthy. First, the fact that the amplitude for the photon-photon process is proportional to the square of the electric charge of the quark is exceptional. The amplitudes for other processes depend at most on the electric charge of the quark raised to the first power. Hence, the photon-photon process provides a uniquely sensitive measurement of the electric charge of the quark. If the charges assigned to quarks in the Standard Model are incorrect, it is not surprising that this error should first show up in a study of the photon-photon interaction.

Second, the analysis that was used to compare the photon-photon data with the Standard Model was based upon the "parton model" (Feynman, 1972). A number of simplifying assumption are made in this model. In particular, quarks are treated effectively as free particles. This is of course at variance with observation. Free quarks have never been detected. Quarks produced in processes such as that depicted in Fig. 1 must undergo final state interactions in which they coalesce with other quarks to form bound states before emerging from the interaction region. In the parton model, it is assumed that the final state interactions have no effect on cross sections. The assumption simplifies analyses enormously, and it is the foundation on which the parton model is based. However, it is both counter-intuitive and unconfirmed. It is not surprising that Feynman referred to the parton model as a "very tall house of cards" (Feynman, 1972). Although the model is in widespread use, results obtained with it must be treated with some uncertainty.

The origin of the uncertainty is historical. The parton model was developed specifically to account for results observed in electron-proton scattering experiments carried out at the SLAC laboratory in the 1960s. In these experiments, only the scattered electron was observed, and it was found that the model could account for the distribution of the scattered electrons observed in the experiments. However, a later experiment carried out the DESY laboratory, in which the distribution of scattered hadrons was also measured, yielded serious disagreement. The DESY experiment provided clear support for Yukawa's old meson model (Yukawa, 1935; Derrick *et al.*, 1996; Yock, 2002).

4. COMPARISON OF THE PHOTON-PHOTON DATA WITH UNIT-CHARGED QUARKS

Ferreira carried out a detailed comparison of the photon-photon data with a modified version of the Standard Model in which quarks are assigned unit electric charges together with the colour charges of the Standard Model (Ferreira, 2002). This model is based on an earlier model with unit electric charges (Han and Nambu, 1965). Ferreira found improved agreement between theory and experiment, but an apparent discrepancy remained at the highest values of transverse momenta observed by the L3 collaboration.

We note that Ferreira utilised the parton model in his analysis, and that he also considered another discrepancy that is present between the photon-photon data and the Standard Model. The measured cross-section for the production of "b-particles" in these interactions exceeds the expectation of the Standard Model by a large factor. Ferreira found that this discrepancy could be resolved with unit-charged quarks (Ferreira, 2002).

5. COMPARISON OF THE PHOTON-PHOTON DATA WITH THE ELECTRO-STRONG MODEL OF HIGHLY ELECTRICALLY CHARGED QUARKS

Comparison of the photon-photon data with the electro-strong model in which quarks are assumed to be highly electrically charged (Yock, 1969) is relatively complicated. This is because no calculational scheme analogous to the parton model has been developed for this model—just rough ideas. As Feynman remarked, it is very difficult to solve quantum field theories of strong interactions (Feynman, 1985).

It was recognized early on that if quarks are highly electrically charged, then they must be tightly bound with mean separations much smaller than the size of the nucleon. Otherwise, they could not have escaped detection in low-energy experiments. It was "guesstimated" that mean separations between them in bound states might be of order 10^{-18} m, and that centre-of-mass energies of order several hundred GeV could be needed to detect them directly (Yock, 1970).

A generalized Yukawa model was proposed with these features (Yock, 2002). In this model, the partons of the parton model are effectively replaced by Yukawa's bare mesons and nucleons. The model is consistent, at least in principle, with a large body of data from nuclear physics. Also, it avoids the puzzle of the parton model whereby partons appear to be both free and yet confined. However, detailed calculations have not been attempted, because such calculations would be severely parameter or model dependent (as are parton model calculations). It was merely noted that, if the electro-strong model is valid, then clear evidence of large electromagnetic effects must eventually emerge at high energies (Yock, 1970).

According to the above ideas, hadrons should behave as if composed of integrally charged parton-like constituents below some threshold energy where the internal structures of the bare mesons and nucleons begin to be resolved. Below this threshold, the constituents might be able to be treated approximately by phenomenological fields. Above the threshold, the high electric charges of the fundamental constituents should lead unmistakably to large, electromagnetic effects. Nowhere should these be more apparent than in the photon-photon interaction, where the amplitude is proportional to the square of the quark's charge. Between the two energy regimes, a transition will occur where electromagnetic effects will grow from normal to large magnitude.

Given that the above scenario is physically plausible, it follows that the extraction of quantities such as the charges of quarks from experimental data is subject to uncertainty. The true charges will only be revealed at energies that are sufficiently high to resolve the fundamental constituents.

As an example of the above, consider the lifetime of the π^0. This is often cited as providing evidence for the charges (both electric and colour) of quarks assumed in the Standard Model. However, in the generalized Yukawa model, the lifetime of the π^0 could be calculated as Steinberger did some years ago (Steinberger, 1949) using phenomenological fields for bare nucleons and pions without recourse to constituents of any specific description.

Consider now the photon-photon data. Clearly, the increasing discrepancy between the Standard Model, or any parton-like model in which the partons do not possess a new level of sub-structure at small distances, and the data with increasing transverse momenta is just what would be expected to occur if the L3 experiment had just entered the transition region described above. The fact that the effect should be seen first in photon-photon interactions is, as noted above, not surprising.

6. PHOTON-PHOTON EXPERIMENTS AT HIGHER ENERGIES

The above scenario can be tested experimentally by repeating the photon-photon experiment at higher energies. Two proposals have been made for larger electron-positron colliders that would enable this. These are the International Linear Collider and the Compact Linear Collider (Abbott, 2004). The first of these is planned to operate at a centre-of-mass energies up to about 1 TeV, the second up to about 4 TeV. Either would offer a significant boost on the 200 GeV reached at CERN. In view of the above discussion, either should be capable of distinguishing unequivocally between the three models that have been discussed here.

If the discrepancy between the data and the Standard Model was found to continue to grow with increasing transverse momentum, the weight of evidence for highly electrically charged quarks could seem to be quite compelling. This would hold true whether or not the threshold for free quark production was reached.

In order to realise the above, the funding proposals for the proposed linear colliders might usefully be broadened. At present, these are based on planned studies of the Higgs boson (Abbott, 2004). This particle is an essential ingredient of the Standard Model (Weinberg, 1999). In contrast, the electro-strong model has inbuilt symmetry breaking, and probably does not need spontaneous symmetry breaking or the Higgs boson (Yock, 2003). This is because the replication symmetry that is present in the Standard Model without the Higgs is absent in the electro-strong model (Yock, 1969). A less-focussed funding strategy for the linear colliders might better be able to take advantage of their physics potential.

On the question of the existence of the Higgs boson, we note that Hawking has bet \$100 that it will not be found at Fermilab (Giles, 2002). This author feels the prospects for finding the Higgs boson with the Large Hadron Collider are similarly unassured.

7. EPISTEMOLOGICAL AND CONCLUDING REMARKS

It has been said of the Standard Model that many of its features seem to have been unpredictable on the basis of general principles of elegance or simplicity (Anderson, 1990). It might be regarded as an "accommodation" rather than a "prediction" in Lipton's terminology (Lipton, 2005). Also, from the viewpoint of a reductionist (Ellis, 2005), it could appear to present a surprisingly large discontinuity in the nature of physical law as one goes from the nuclear to the subnuclear domain. Glashow and Lederman remarked that it might be seen not to relate to the rest of the scientific endeavours of mankind (Glashow and Lederman, 1985).

Are these remarks cause for alarm? How does the electro-strong model fare under such considerations? Consider the three generations of particles that exist according to the Standard Model. The first generation accounts for all normal matter in this model (i.e., for electrons, neutrons and protons). The remaining generations were added to account for extra particles, such as the so-called "strange particles", that appear to have virtually no effect on normal phenomena. Thus, the existence of the extra generations is a mystery in the Standard Model (Feynman, 1985). The suggestion has been made that they are required to account, through mixing between the generations, for the presence of matter in the universe, but we note that the mixing hypothesis has long been inconsistent with the measured lifetimes of the strange particles (Yock, 1970).

Consider now the electro-strong model. This is a gauge theory of strong interactions, as is the Standard Model, but the electro-strong model was proposed first, and, not surprisingly, was based on the simplest possible gauge group. A property of this group is that it requires multiple generations of particles to exist that are not replications of one another. The model cannot account for protons and neutrons without also including additional particles like the strange particles (Yock, 1969). In this sense, the model seems to be in harmony with nature.

Consider the question of confinement. The familiar composite objects of nature (nuclei, atoms and molecules) are of course subdivisible into their constituents—electrons, protons and neutrons. But, according to the Standard Model, although neutrons and protons are composite, they are indivisible. From the reductionist's point of view, the chain is abruptly broken. On the other hand, the electro-strong model posits that neutrons and protons are tightly bound, but not necessarily permanently bound.

Consider also the charges present in nature. In normal matter we find only integrally charged objects—electrons, photons, nuclei, atoms and so on. The highly electrically charged quarks of the electro-strong model would fit naturally into this scheme, especially if they were integrally charged. But, according to the Standard Model, the spectrum of charges changes dramatically when we enter the subnuclear world, with its fractional electric charges and even more bizarre "colour" charges. Again, the Standard Model appears to be at odds with the rest of science.

The significance of the above remarks is hard to assess. They can all be regarded as questions of complexity that disfavour the Standard Model from the point of view of Occam's razor. But nothing beats hard data in science. We conclude therefore that a decisive result on the existence of highly charged quarks could only be obtained from a study of photon-photon interactions at higher energies than those that the L3 collaboration was able to reach, and that this could be achieved with either of the two linear colliders that were proposed recently.

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