Gluon jets

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One of the most interesting problems in the theory of particle structure is the absence of quarks and gluons in the free state. All information on the components of hadrons must be obtained indirectly. Nevertheless, there is now quite a lot of evidence for the existence of quarks in the interior of hadrons. This follows, above all, from the success of the quark model of hadron structure. In addition, it has long been known that the deep inelastic interactions between leptons and hadrons can be explained in terms of the interaction between leptons and point partons which are among the constituents of hadrons, and have fractional charge, and half-integer spin.[1] Convincing evidence for the existence of quarks has also been obtained from electron-positron annihilation processes. Many resonances have been found in the relatively low-energy region. Moreover, the spectrum of charmonium, for example, is quite similar to the simplest atomic spectra and is readily explained in terms of the usual quantum-mechanical ideas as applied to a system consisting of a quark and an antiquark.[2] At higher energies, a collision between an electron and a positron in the center-of-mass system usually results in the emergence of the final hadrons in opposite directions. The common axis of these two hadron jets[1)] is at an angle to the collision axis of the primary electron and positron (according to the expression $1+\cos^2\theta$, where θ is the angle between the axes) as if the electron and positron at first (through the virtual photon stage) were transformed into a point quark–antiquark pair with spin half each. These then determine the direction of emission of the jets, and it is only after this that the quark and antiquark neutralize their color degrees of freedom and undergo fragmentation into the final hadrons through some mechanism as yet unknown (but characterized by small transverse momenta).[3] Thus, by observing the two jets emerging from the electron-positron annihilation process, we are, in effect, witnessing the creation of a quark and an antiquark which we perceive as free before they transform into hadrons. The success of quark models in hadron–hadron reactions has been distinctly less impressive.

As already noted, quarks are colored. They have to be assigned three colors in order to avoid contradictions with Pauli's principle for simple systems such as, for example, the nucleon or Δ^{++} resonance. Color was invoked to ensure the antisymmetry of wave functions for these states, which turned out to be symmetric in the spin and space degrees of freedom. Without tripling the number of quarks by the introduction of color, one cannot understand such facts as the $\pi^0\to 2\gamma$ decay or the ratio of cross sections for electron-positron annihilation into hadrons and a muon pair.

However, it was found that the theory could not be restricted to quarks alone as the structural elements of hadrons. Even older data on deep inelastic lepton–hadron interactions showed that only half the hadron momentum could be assigned to the quarks.[1] One was thus forced to assume that the hadron contained components that did not interact with leptons (i.e., via the electromagnetic and weak interactions) and carried off the missing amount of energy. These components were called gluons, since they were visualized as the "glue" holding the quarks together in the interior of hadrons. It is now believed that gluons have zero mass, that they are vector particles, and that they can be classified as colored bosons. They have to be assigned these properties, in the first instance, to explain the spectroscopy of particles.

The picture of colored quarks and gluons fits well into the framework of non-Abelian gauge theory of strong interactions, which is referred to as quantum chromodynamics.[2,4] There are eight massless gluons in this theory. Apart from the renormalization property, which is attractive from the purely theoretical point of view, quantum chromodynamics has one further important property that enables us to understand the results of experiments on deep inelastic processes. Thus, it is found that, for large momentum transfers (at short distances), the coupling constant that appears in this theory tends to zero (this is the so-called asymptotic freedom). This is why quarks appear as free point particles in processes with large momentum transfers. On the other hand, it must be admitted that we still do not know whether quantum chromodynamics is capable of explaining the absence of free quarks and gluons at large distances.

Nevertheless, theoreticians had such strong faith in this theory that immediate attempts were made to find theoretical predictions that would assist in "seeing" gluons at least with the same confidence as we can "see" the quarks. Since the properties of the gluon are, in many ways, analogous to those of the photon, it is natural to consider processes in which the quark emits a gluon. If the emitted gluons are soft, or travel almost parallel to the primary quark, it is difficult to

[1)]The jets separate only at high energies at which the longitudinal momenta of particles in the jet become much greater than the transverse momenta perpendicular to the common axis of the jet.

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observe them directly. However, such gluons give rise to a very interesting effect: they appear to "spoil" the point property of the quark. This is manifested experimentally[5] as a violation of Bjorken scaling (see, for example, Ref. 1), i.e., the functions describing the distribution of quarks in hadrons begin to depend not on one variable (the ratio of transferred momentum to the loss of lepton energy) but on both these variables separately. Nevertheless, the experimental result is only an indirect confirmation of the existence of gluons.

The emission of a gluon at a relatively small angle leads, in addition, to the broadening of the jet. This broadening is, of course, asymmetric: one of the jets (into which the gluon is emitted) turns out to be thicker than the other. The transverse particle momentum in the thick jet increases with increasing energy whereas, in the thin jet, it remains practically constant. These effects have been confirmed experimentally.

The observed emission of gluons at large angles for which the gluon departs to a "large" distance from its parent quark can be regarded as more direct evidence. Some indications as to the reality of this type of process emerged after the discovery[6] in hadron–hadron collisions of muon pairs which were emitted with large transverse momenta. They can be interpreted as traces of the process in which the initial quark (or antiquark) from the colliding hadrons emits a gluon with high transverse momentum, and then transfers the recoil momentum to the muon pair during annihilation with the antiquark (quark). However, supporters of the point of view, in which quarks in the interior of the hadron have high initial transverse momenta, have disputed this interpretation of experiments on the creation of muon pairs (although the momenta involved were quite high, up to 12 GeV, the accuracy was not very high, and the effect was not well defined).

Moreover, there was some indication that gluons were also emitted in the decay of the upsilon particle. The upsilon particle is analogous to orthopositronium (which decays into three photons) in that it can decay into not less than three gluons (their number must be odd). Unfortunately, the mass of the particle is too small for a clear definition of the jets of each of these gluons, since only about 3 GeV of energy can be attributed to each jet. Although the theoretical analysis supported the three-gluon decay of the upsilon particle and confirmed the vector nature of gluons,[7] the overall situation was not clear. One would hope to see the three-lobe decay mode when and if "toponium" is discovered (its mass should be greater than 30 GeV).

Gluon jets can also, apparently, be observed[8] in events with high transverse momenta in the case of colliding $p\bar{p}$ beams with energy $\sqrt{s} = 540$ GeV. The point is that, at such high energies, the main contribution (even for high transverse momenta) is provided by the parton components of hadrons, which carry a small fraction of the primary momentum (small x), and these are mainly gluons. We shall have to wait another year or two before experimental data become available in this energy range.

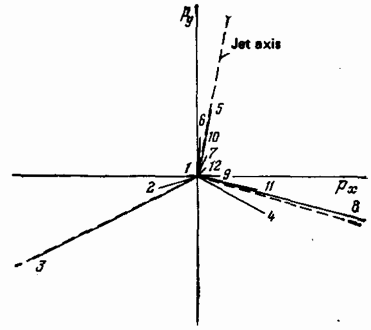

FIG. 1.

The possibility of a new mechanism for the emission of gluon jets at ultrahigh energies, namely, the analog of the Vavilov–Cherenkov effect in the case of photons, is discussed in Ref. 9.

After this rather extensive introduction, let us now consider some of the results[10] which led to the conclusion that gluon jets have been observed for the first time. We have already noted that, to achieve a clear separation of the jets, one must consider events in which glons are emitted by quarks at relatively large angles, i.e., we must consider sufficiently hard gluons. Because of asymptotic freedom in quantum chromodynamics, the probabilities of multijet processes are ordered. The fact that the coupling constant is small at high transferred momenta ensures that the quark–antiquark jets are followed in the next order in the coupling constant by jets with the emission of one hard gluon, then two, and so on. The search for three-jet events in the PETRA installation has occupied the attention of four experimental groups. The first three-jet event in electron-positron annihilation was reported by Wiik[11] in the summer of 1979 during the conference on neutrino physics at Bergen in Norway. It is shown in Fig. 1. It was interpreted as the transition of an electron and a positron into quark + antiquark with the emission of a hard gluon, each of which then fragmented into hadrons. In this interpretation, the axes of the three jets must lie in the same plane, since the gluon and the parent quark are forced by conservation laws to remain is planar with the axis of motion of the quark prior to emission (and, consequently, with the direction of motion of the antiquark as well). At energies of about 30 GeV (in the center-of-mass system), several tens of such coplanar events have been observed (out of a total number of several hundred events). They were characterized by the fact that the distribution of momenta at right-angles to the plane of the event[2)] was sharply restricted, whereas the momenta in the plane of the event could be quite high. Tests on the selected events for anisotropy (sphericity, aplanarity, triple character, and so on) showed that they could be interpreted, with some confidence, as three-jet events. They were very different from possible two-jet events (for example, the two-jet model predicted 4–5 events, whereas the observed number was 18 events in a given

[2)]This plane was, in fact, found by minimizing these momenta.

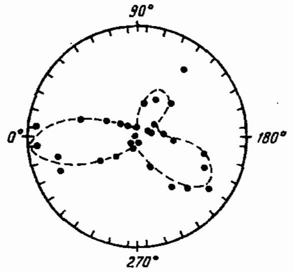

FIG. 2.

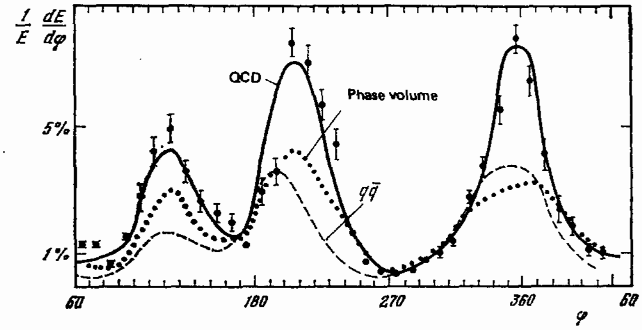

FIG. 3.

range of sphericities and aplanarities, which is in good agreement with the prediction for three jets). Although this method of analysis was applied to individual events, and the individual conclusions could be regarded as unreliable because of possible fluctuations, the *overall* statistics was good enough to eliminate the contribution of such effects.

Moreover, the directions of the chosen events were investigated for the complete available statistics. The result was the three-lobe structure shown in Fig. 2. This picture cannot in itself be regarded as proof, since it is clear that statistical fluctuations of particle energies in two-jet events can give rise to a departure of the axes of these jets from collinearity because of lateral fluctuations. It has been shown (Fig. 3) that the observed structure is better defined than one would expect for fluctuation effects in two-jet events and in ordinary phase volume. It may therefore be concluded that the three-jet structure of electron-positron annihilation at energies of about 30 GeV can be detected in an appreciable fraction of events. According to quantum chromodynamics, one of the jets is initiated by a quark, another by an antiquark, and a third by a gluon. First attempts at a study of correlations between particles and jets are reported in Ref. 12, and first reports of possible observation of events with four jets are given in Ref. 13.

Nevertheless, skeptics will demand more evidence in support of this point of view. This will require, firstly, studies of the angular distribution of jets which should demonstrate that the spin of the gluon is, in fact, 1. Secondly, it will be necessary to investigate the mean effective electric charge transported by each jet. This should be fractional in the case of quarks and zero in the case of the gluon jet. Thirdly, it will be necessary to investigate in detail the properties of the products emerging as a result of the fragmentation of these jets as functions of the square of the total four-momentum of the jet. In particular, current theories suggest that the gluon jet should be more active than the quark jet: it produces approximately twice as many particles, it expands more in the transverse direction, it violates scaling more rapidly, and so on. Fourthly, at higher energies and with better statistics, one should be able to observe the creation of four or more jets. The fraction of such events will enable us once again to improve the value of the chromodynamic constant for different values of the four-momentum.

Whether or not such energies will be attained will depend both on fundamental questions (such as, for example, whether processes involving the collision of two virtual photons from the electron and positron clouds are predominant; first estimates indicate that this is not so)[14] and on important problems connected with radiation losses by highly accelerated electrons.

A more detailed account of the properties of gluons will be found in the review by Ya. I. Azimov, Yu. L. Dokshitser, and V. A. Khoze, entitled "Gluons," to be published in the November 1980 issue of this journal.

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