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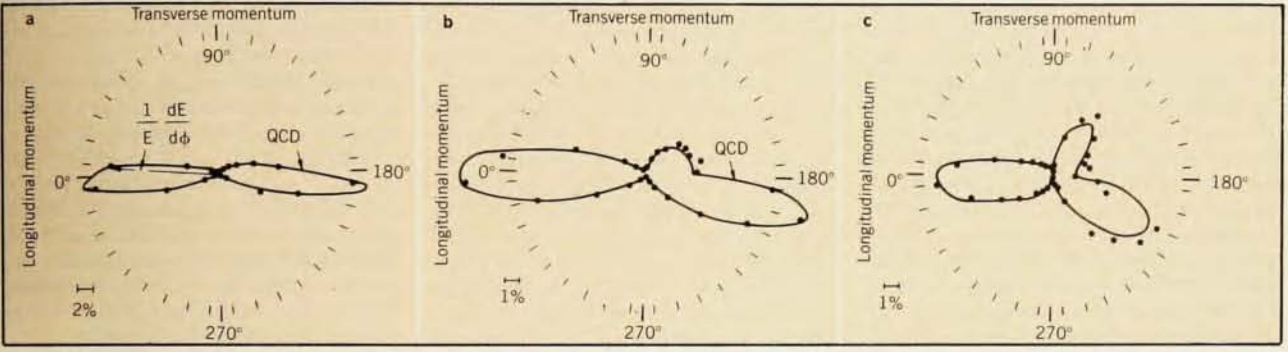
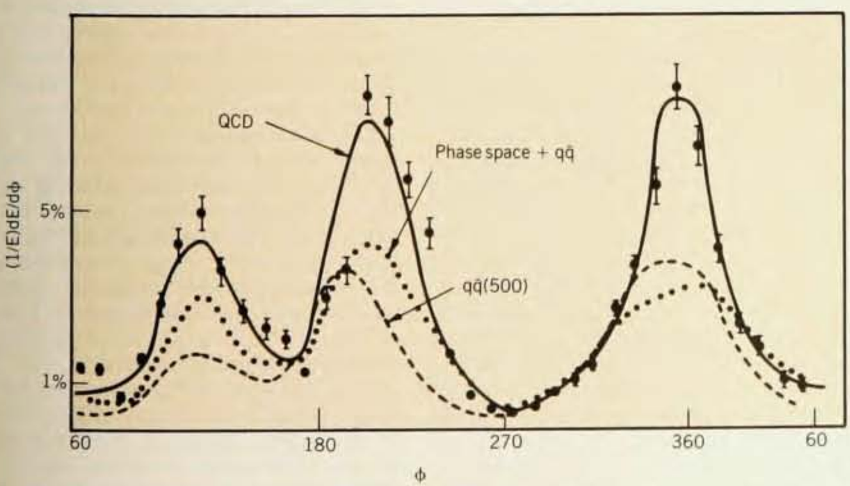
Evidence from PETRA adds support for QCD and gluons



Jets of hadrons produced in electron–positron collisions at PETRA. Each event has been rotated into a frame where both the longitudinal momentum and transverse momentum are maximized. Figures **a**, **b** and **c** are samples where the events become increasingly oblate. The distance from the center of the circle $(1/E)dE/d\phi$ is a measure of the energy of the particles. In **a** the two large lobes are jets from decays of quark–antiquark pairs. The gluons have too little energy to create an additional jet. In **b** the third small lobe is mostly due to the jet from the decays of a low-energy gluon. In **c** the gluon has enough energy to create a distinct jet of its own (in the 90–180° region). (From reference 8.)

Over the past several years a theory of the strong interactions known as quantum chromodynamics has been developing. This theory assumes the existence of fractionally charged quarks of spin ½ and that the force between the quarks is carried by a gluon, a massless spin-1 quantum. Like the quark, it is widely believed that the gluon is not directly observable.

Now experiments at PETRA, the new electron–positron storage ring at DESY in Hamburg, Germany, which started operating last year with roughly 15 GeV in each beam, are showing evidence for the existence of gluons and are in agreement with the general picture of quantum chromodynamics. Very recent analyses of the PETRA data have determined a value of the strong-interaction coupling constant, α_s, which is consistent with earlier measurements involving the inelastic scattering of either neutrinos or muons on protons.



Unfolded energy flow diagram based on figure **c**, compared with QCD, quark-antiquark production (with average transverse momentum 500 MeV/c) and a model mixing $q\bar{q}$ and phase space.

The experiments are being done by four groups at DESY—Jade, Mark J, Pluto and Tasso. Preliminary results were reported last summer and more recently at The American Physical Society meeting in Chicago in January.

At present we have evidence for five kinds of quark—up, down, strange, charmed, bottom—and the strong expectation of a sixth—top. Quantum chromodynamics requires that each kind of quark have a quantum number called color, which comes in three varieties. The three quark colors transform as a functional triplet of the group SU(3). To make this SU(3) symmetry a local gauge symmetry, one introduces eight vector gauge fields—colored gluons. Because the gluons carry color, they interact with each other and thereby lead to a decrease of the coupling as the energy is increased (asymptotic freedom).

Most of the evidence in favor of quantum chromodynamics preceded the theory. For example, the rate of a neutral pion decay into two photons was evidence that up and down quarks must come in three colors. In electron–positron interactions, the ratio of hadron production to lepton production could be explained by having colored quarks. Until QCD, no one could find a quantum field theory that could explain all the experimental results.

At about the same time as QCD was being developed, experiments on deep

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inelastic electron-proton scattering showed that quarks only carry about half the momentum; something else, such as a neutral gluon, would be needed to carry the remainder. The observation that proton-proton scattering yielded lepton pairs with unexpectedly large transverse momentum could be explained in terms of the gluon. Experiments last year on deep inelastic scattering of neutrinos gave further indirect evidence of gluons.

Jet structure. In electron-positron annihilation, the quark idea says that hadrons arise mainly from the production of a quark and an antiquark. At high energies, as quarks and antiquarks move apart in opposite directions, other quark-antiquark pairs are created in the vicinity. The quarks and antiquarks then bind together to form hadrons, some of which can then decay to create more hadrons and other particles. The quark and antiquark form a stream of particles in a narrow cone known as a jet.

Production of two jets was first found about five years ago at SPEAR, by the famous SLAC-Lawrence Berkeley Laboratory collaboration. As electron-positron energies were raised—first at DORIS (roughly 5 GeV in each beam) and then at PETRA—these characteristic two-jet distributions became more apparent (PHYSICS TODAY, January 1979, page 17). The experiments showed that the jet axis distribution around the incident beam varied as $1 + \cos^2\theta$, providing good evidence that quarks have spin $\frac{1}{2}$.

Theorists using QCD predicted that at about 20 GeV in the center of mass, a new process should be observable: One of the quarks produced when the electron and positron annihilate can give up some of its energy and emit a gluon. This process is similar to the emission of a bremsstrahlung photon in quantum electrodynamics. These gluons then fragment into hadrons, which should also appear as a jet. Thus, three jets would be produced: one from the quark, one from the antiquark and one from the gluon. The three-jet events would be much less probable than two-jet events, and the axes of the three jets should appear in a single plane.

Last summer the Pluto group, working at DORIS, reported (at the European Physical Society meeting in Geneva) finding evidence for the upsilon particle decaying into three gluon jets. The decay of the ϒ can be compared to that of orthopositronium, where the electron and positron spins are parallel (net spin of 1) and can only decay into three photons. Similarly, the ϒ, with spin 1, should have two parallel quarks and should decay only to an odd number of gluons. Very recently Karl Koller and H. Krasemann analyzed[1] the Pluto data on the angular distribution of the most energetic jet with respect to the incident beam. They found that the data exclude a zero value for the spin of the gluon and are consistent with a spin of 1 for the gluons.

The CESR device at Cornell University has just started doing experiments in the energy range of the ϒ family (beyond 9 GeV center of mass), but it is too soon for any results to be reported. At DESY, the DORIS ring is running once again in the energy range of the ϒ, according to Herwig Schopper, director of DESY. He feels that confirmation of the earlier analysis of the ϒ decay by Pluto, which indicates spin 1 for the gluon, would be most important.

When PETRA was operated with high energy, deviations from the simple jet picture (quarks without gluons) were observed: The average transverse momentum of hadrons emitted in a jet was found to increase as the energy of the beam was increased, and this increase only occurred in one of the two jets. That is, one of the jets widened. Furthermore, on the average, some of the events had individual particles lying in a fanlike pattern (flat) rather than a cone, and the events showed a three-jet character. These results were reported by the Tasso group at the International Neutrino Conference in Bergen, Norway in June and at the European Physical Society International Conference on High-Energy Physics in Geneva in July.

Late in August, at the International Symposium on Lepton and Photon Interactions at High Energies, held at Fermilab, the Jade, Mark J,[2] Pluto[3] and Tasso[4] groups at DESY all reported evidence for three-jet events in the PETRA energy range (up to about 30 GeV center of mass). Schopper told us[5] that the Mark J group was the first to report statistically significant evidence of the three-jet pattern predicted by QCD. Since then, he said, the other groups have also obtained good evidence.

In December the Jade group submitted[6] a paper to *Physics Letters* reporting they have model-independent evidence that the "wide jet" can be resolved into two jets. They did this by making a Lorentz transformation to the center of mass of the wide jet; in the center of mass, they find two jets.

At this writing, each of the four groups from DESY has more than a thousand hadronic events, of which about 10% are of the three-jet type. Samuel C. C. Ting (MIT) of the Mark J group told us the group has a dozen four-jet events (much less probable than three) in the range 27-32 GeV center of mass.

Technique. The Mark J detector is a calorimeter complemented by drift chambers for muons and by an inner track detector surrounding the intersection region to aid in observing individual charged particles. Mark J can measure the energy distribution in space of both charged and neutral particles and can determine jet direction to about 9 deg.

Jade, Pluto and Tasso all take individual tracks and determine their properties separately.

Tasso is a large general-purpose detector that sees muons, electrons, photons and hadrons. It also has a Cerenkov counter (that hasn't operated yet) to separate pions and kaons. Although the Tasso group used only charged particles in its analysis (and the neutral pions carry off one-third to one-half of the energy) and the Mark J does see all the neutrals, the neutral and charged particles do tend to go in the same direction on the average.

Jade can make good momentum measurements and do very well at measuring photons and electrons (with a lead-glass system) and muons (by a hadron filter). Ultimately, Jade will be able to do detailed studies of jets.

Pluto makes muons, electrons and photons visible but cannot separate pions from kaons (no Cerenkov detection).

Analysis. All four DESY groups must look at a large number of events to compare them with gluon-model predictions on a statistical basis, and each uses its own suitable Monte Carlo calculation. As a guide to understanding the correlations between the individual particles in an event and how they distribute themselves in their angles and momenta, the PETRA experimenters compare their results with a phase-space model (in which no intrinsic correlations are imposed—only those from balance of energy and momentum). Although the phase-space model can produce a collection of particles that resemble three jets, the DESY results do not agree in detail with the phase-space model.

Some particle-physics critics are concerned that when a correlation is found in the analysis, at least some of it may simply have been imposed by conservation of energy and momentum alone. As the PETRA experimenters get more events and experimenters at PEP (almost completed at Stanford) start taking data, they will be able to study angular correlations between the three jets, for example, and presumably verify the spin-1 nature of the gluon. Such a definite determination of the gluon spin would be crucial. Three decades ago, when the muon was found, it was first thought to be the Yukawa meson because its spin was not known.

Coupling constant. Very recently the PETRA groups have reported a measurement of the strong-coupling constant, α_s, the QCD analog of the fine-structure constant, α, of quantum electrodynamics. In the reaction $e^+e^- \rightarrow \mu^+\mu^-$, sometimes a muon also radiates a photon. That process allows one to determine the coupling of a photon to a muon—the electromagnetic coupling constant.

Similarly, for QCD, one wants to know the probability that a quark will produce a virtual gluon, that is, α_s. Unlike QED, whose coupling constant is indeed constant (1/137), QCD theory predicts that as energy is increased, α_s will decrease logarithmically.

By measuring the ratio of three-jet events to two-jet events and using a QCD calculation done[7] by Ahmed Ali, E. Pietarinen, Gustav Kramer and Juergen Willdrodt, the Mark J results yield a value[8] of $\alpha_s = 0.23 \pm 0.02$ (statistical error) and ± 0.04 (systematic error). According to Schopper, Ali and his collaborators also used Tasso data and obtained a similar result. The Jade group, using the calculations[9] of P. Hoyer and his collaborators, found a value of $\alpha_s = 0.17 \pm 0.04$.

Schopper noted that the PETRA measurements are a direct determination of α_s, whereas the earlier determinations (with which the new results agree) are less direct because of large theoretical uncertainties. These earlier values were obtained from the level spacing of particles in the ψ family and from deep inelastic experiments involving neutrino or muon scattering on protons.

This spring Schopper expects PETRA to operate with 19 GeV in each beam. He said, "One might hope the experimenters can find the energy variation of α_s. This was not possible earlier because the logarithmic dependence requires either a wide energy range or a more precise determination than is feasible."

Another interesting—but negative—finding at PETRA is that toponium, a particle containing a top quark, has not been found up to an energy of 31.5 GeV. Many theories had predicted its energy would be in the 28–30-GeV range.

Summing up the situation on QCD, Schopper said, "One of the relevant predictions of QCD is that gluons carry color charge and hence there should be direct interaction between gluons. This has not been demonstrated. But I think the data show that gluons are there." —GBL

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Pulsed molecular-beam sources

A new type of fast, pulsed molecular-beam source for collision studies and molecular spectroscopy appears to have several advantages over the traditional continuous-flow sources. It improves signal-to-noise in the detectors, produces very "cold" beams with little or no rotational or vibrational excitation, and it allows good time-of-flight measurements to determine velocity spectra. The source was developed by W. Ronald Gentry and Clayton Giese at the University of Minnesota.[1] Their work employs two such sources to investigate collisions between two molecular beams.

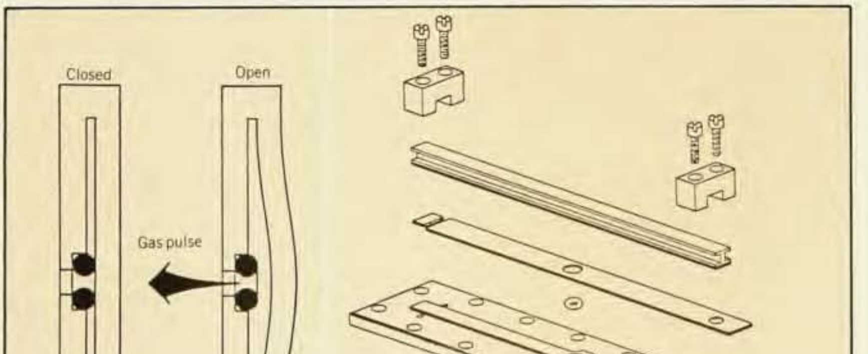
Continuous cooled beams have been in use for some years in single-beam spectroscopy; in a few cases a form of pulsed source had already been adopted to reduce the gas load on the system. Among the spectroscopists who have turned to the Gentry–Giese source for this purpose, in single-beam experiments, are Richard Smalley and his group[2] at Rice University and J. D. McDonald's group[3] at the University of Illinois at Urbana–Champaign.

Gentry summarized some of the latest work in a paper delivered at the 11th International Conference on the Physics of Electronic and Atomic Collisions in Kyoto, Japan, last September.

Technique. For many years the standard technique for studying single-collision cross sections in atoms and molecules has used crossed molecular beams of the reactants. "Chopping" of one or both beams provides an amplitude modulation to help resolve signal from background; each chopper is a rotating or vibrating vane that interrupts the line-of-sight path of the beam but does not stop the effusive flow of gas into the system generally. The method is limited by the attainable signal-to-background ratio, kept as high as possible by several stages of differential pumping of the gases effusing continuously into the system from the two beams. Another drawback, stemming directly from this need for fast differential pumping, is that the hardware—nested vacuum chambers, pumps and so on—often gets in the way of the experiment, limiting the angular range of differential scattering measurements, for example. The newer, pulsed molecular-beam sources increase the signal-to-background ratio, yet consume so little gas that no differential pumping is required. And the supersonic free expansion of gas from the pulsed source yields cooled molecular beams with rotational temperatures down to a few tenths of a kelvin.

For good resolution the pulse duration should be shorter than the flight time of molecules across the apparatus—particularly if a velocity-distribution measurement of the beam molecules is contemplated. For a light gas, such as helium, and a typical flight path of 50 cm the required pulse duration for 10% velocity resolution works out to be around 20 microseconds. The problem of designing a pulsed molecular-beam source is largely that of designing a valve that will open for 20 microsec, close to make a good seal, and repeat indefinitely.

Gentry and Giese solved the problem by clamping a metal bar across a Viton O-ring to make the seal, and springing the bar away from the O-ring by means of the force between short, intense pulses of electric current (about 20 kiloamps for about 2 microsec) flowing through the bar in one direction and the same current flowing back through a fixed faceplate in



Pulsed gas valve designed by Ronald Gentry and Clayton Giese at the University of Minnesota. The two schematic sketches on the left show how a pulse of electric current flowing in two parallel but opposite directions flexes a metal bar and admits a burst of gas through the O-ring seal. On the right we show an exploded view of the construction. This valve generates 10-microsec pulses of light gases (hydrogen and helium) with a 20-pulse-per-second repetition rate. (From ref. 1.)