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## PARTICLES WITH A CHARGE OF $\frac{1}{3}e$

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The SU(3) group, as used to describe the strong interactions of mesons and baryons in the manner of Gell-Mann[1] and Ne'eman,[2] admits representations of dimension 3. If the elements of this representation are associated with real particles, and if the Gell-Mann Nishijima strangeness scheme is not modified,[3] the elements of the "3" representation correspond to three particles, an isotopic spin doublet with charges of $-\frac{1}{3}e$ and $+\frac{2}{3}e$, and a singlet with a charge of $-\frac{1}{3}e$. Elements of the antiparticle representation "3*" have opposite charges. Gell-Mann, who has emphasized the importance of investigating the existence of such particles, has named them quarks.[4]

At least one of the charge-$\frac{1}{3}e$ quarks must either be stable, or decay very slowly by $\beta$ decay into the charge-$\frac{2}{3}e$ quark. It seems likely that, if quarks exist at all, they are coupled but weakly to regular particles or that they have large masses. Otherwise they would probably have been noted, particularly in bubble chamber pictures of high-energy interactions. Interactions producing quarks would show two tracks, with bubble densities of $\frac{1}{9}$ and $\frac{4}{9}$ minimum, which would probably be noted in scanning. This lack of production suggests the conclusion: If quarks have masses not much larger than that of the nucleon, their coupling to regular mesons and baryons must be weak. Such generalizations must be made with care, however. The production of $\Omega^-$ hyperons in such interactions does not seem to be large and the $\Omega$ almost certainly does interact strongly with matter.

Our search for quarks was then divided into two parts following different assumptions as to the interaction of quarks. In each case we lose no generality by limiting our search to quarks of charge $\frac{1}{3}e$. The first method assumes a weak coupling of quarks to regular particles. In particular the assumption is made that the quark-nucleon total cross section is not larger than a few millibarns. For production processes we make the minimal assumption that the only coupling of importance is the electromagnetic coupling which we know is $\frac{1}{3}e$ and $\frac{2}{3}e$.

The very large accelerations of charged particles involved in the strong interactions results in the radiation of photons in nominally strong interaction processes and also results in the production of pairs by virtual photons. The probability of emitting a real photon in an interaction is of the order of $(e^2/\hbar c)$; the probability of emitting a pair will be of the order of $(e^2/\hbar c)(e_q{}^2/\hbar c)$ where $e_q$ is the charge of the particles. These numbers must be modified to allow for phase space factors and for the radiative damping so important at high energies where a very large number of reaction channels are open. We do this by considering the ratio of quarks to antiprotons produced in nucleon-nucleon collisions. For the production of pairs of quarks, where the mass of the quark is about the mass of the proton, the portion of phase space available should be about equal for the two reactions: production of quark pairs, and production of proton-antiproton pairs. The ratio of quarks of charge $\pm\frac{1}{3}$ to antiprotons will then be about $2\times(1/137)^2\times(1/3)^2$. If we take the ratio of antiprotons to charged pions produced by proton-nucleus collisions at proton energies near 25 BeV as,[5] characteristically, 0.005; we have for a quark/pion ratio about $500/10^{10}$. For quark masses greater than a nucleon mass we would expect somewhat smaller production. The threshold, for 28-BeV protons, is about 2.8 BeV/$c^2$.

The details of the experimental setups were dictated by logistic considerations rather than any detailed planning but were little the worse for that. The detector, described in detail below, was first placed 40 meters from a target position in the AGS in the forward direction. Between the target and detector lie the vacuum chamber wall at a mean distance of about 2.0 meters from the target, a sextapole correcting magnet about 5.0 meters from the target, and about 50 cm thick in the beam direction, and just in front of the detector 150 cm of heavy concrete of a density of 4.0, and 50 cm of Pb. The total density of material is about 1.6 kg/cm$^2$. The energy loss by minimum particles, e.g. $\mu$ mesons, is about 2.6 BeV; for quarks it is about 300 MeV.

The complicated geometry of the absorbers, together with the effects of the AGS magnetic field, makes it difficult to understand the beam in detail. However if the quark trajectories are compared to appropriate $\mu$-meson trajectories this detailed knowledge is not so very important. We illustrate the close relationship by these beams and the utility of this relation by considering the evolution of the beam in time or space after production at the target. The beam which concerns us is the mixture of pions and quarks produced at the target. The effects of the magnetic field will be the same for pions of momentum $p$ and quarks of momentum $p/3$. After a flight of perhaps four meters, on the average, the pions will strike the vacuum chamber wall and magnet structures, and will be largely eliminated from the beam. Some will have decayed into $\mu$ mesons which will have almost exactly the same direction and, on the average, about 20% less momentum than the pion, a difference we will neglect. The $\mu$ mesons together with quarks of the appropriate momentum will have nearly the same evolution on their path to the detector as they will be similarly affected both by multiple scattering and by magnetic fields. Therefore, the numbers of muons measured at the detectors provides a measure of the number of quarks to be expected.

The detector consists of seven scintillation counters arranged in a counter logic as CACACAC, where C and A represent, as usual, coincidence and anticoincidence counters. The coincidence counters are plastic scintillators with dimensions of 2 in. $\times$2 in. $\times$6 in.; the anticoincidence counters are 2 in. $\times$3 in. $\times$8 in. and are arranged to cover the coincidence counters. The energy lost by a charge-one particle in a counter is about 11 MeV; a quark will lose about 1.2 MeV. The angular acceptance of the detector was $4^\circ\times12^\circ$. The coincidence counters were set to count on levels corresponding to an energy loss of about 100 keV, the anticoincidence counters were set to count on energy losses exceeding 3 MeV. Measurements of linewidth from the passage of singly charged minimum ionizing particles, made with absorbing screens set between the photomultipliers and the scintillator, showed that about 20 photoelectrons were produced at the photocathode for a quark. To reduce background, largely due to soft photon showers, we also set two large guard counters above and below the detection counters. The counter logic was used to trigger a scope upon which was presented the array of pulses from the thirteenth dynode of all seven 6810 photomultipliers. Inspection of the photographs showed no evidence of a charge-$\frac{1}{3}e$ particle. Not one appropriate pattern was found in a set of photographs corresponding to the passage of $3\times10^7$ $\mu$ mesons through the detector. This flux resulted from the bombardment of a beryllium target by 28-BeV protons.

The $\mu$ mesons which pass through our detector must have had an energy greater than 2.5 BeV or they could not have passed through the absorbers. We estimate that their average momentum is 4.0 BeV/$c$ and that they represent decays from a pion flux of average momentum of about 5.0 BeV/$c$. About 1.5% of such pions would decay into muons before being eliminated from the beam absorbers near the target. Strongly interacting particles are almost completely eliminated by about 15 mean free paths of absorber. For weakly interacting particles the thickness of the absorber is such that the transmission through it is numerically equal to $1/\sigma$ where $\sigma$ is the total cross section for interaction with nucleons measured in millibarns. Since the energy loss by quarks in the absorbers is small, the original spectrum of quarks accepted by the detector is shifted toward lower energies than that of the $\mu$ meson. We believe that this factor together with some effects of multiple scattering in the last stages of the absorber, which increase the angular spread of muons—which have slowed down in the absorber—more than that for quarks and more than the angular acceptance of the detector, result in a factor of five between the acceptance of quarks and muons. In short we estimate that each $\mu$ meson detected represents about 300 pions in a momentum band corresponding to the acceptance band for quarks. Our sensitivity of 1 quark/$3\times10^7$ muons then becomes $\approx$1 quark/$10^{10}$ pions, which is about 0.2% of that which we expect for electromagnetic coupling alone. This small number indicates that quarks do not exist with interaction cross section with nucleons less than 3 mb and mass less than 2 BeV/$c^2$.

The possibility cannot be excluded by the above arrangement that quarks interact strongly with nucleons, but are still produced with small probability—though presumably with a probability much greater than that deduced from the electromagnetic coupling alone. To cover this possibility the same apparatus was set up in a charged beam designed to accept singly ionized charged negative particles produced at an angle of 18° with a momentum of 4.5 BeV/$c$. The corresponding quark momentum will be 1.5 BeV/$c$; the transverse momentum will be 550 MeV/$c$.

Using this technique, a limit was established of one quark in $10^8$ pions through the detector. The flux of pions at 1.5 BeV/c through our channel was about 20 times that at 4.5 BeV. Therefore the ratio of quarks to pions is less than $5/10^{10}$, about one percent of our estimate for electromagnetic production. In terms of total cross section our results suggest a cross section for quark production by 28-BeV protons on nucleons as $<10^{-34}$ cm$^2$. Since these limits are appreciably smaller than our estimate of the production through electromagnetic couplings alone we believe that we have established experimentally that quarks do not exist with a mass less than 2 BeV/$c^2$.

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## ANTIPROTON-PROTON COLLISION IN THE UNITARY SYMMETRY MODEL*

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It has been noticed[1,2] that the branching ratio of the meson pair production in antiproton-proton annihilation is not in accord with the prediction of the Sakata model[3] of the group U(3).

In this note,[4] we point out that the observed cross sections of the baryon pair production in antiproton-proton collisions seem to be also at variance with the prediction of the octet model[5,6] of the group SU(3), if we do not allow for a symmetry-breaking interaction. Further it is remarked that the relations among the transition amplitudes for baryon pair and meson pair production in antiproton-proton collisions have an intimate connection with those among the magnetic moments of the baryon octet.

For the case of complete symmetry in the octet model, we can write the $S$ matrix of the baryon pair production in an antibaryon-baryon collision