Experimental consequences of the existence of quarks

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(Received 15 July 1974; revised manuscript received 29 October 1974)

Reasonable assumptions about quarks and their interactions lead us to expect relatively copious production of these particles through diffraction disintegration of cosmic-ray protons into their constituent quarks. We estimate here the production threshold, cross section, fluxes, and momentum spectra of the quarks.

I. INTRODUCTION

One continuing puzzle of quark models of hadrons is the lack of experimental confirmation of the existence of free quarks. This may be because quarks have very large mass. However, if massive quarks exist, their existence must have experimental consequences, even if their production as free particles by ordinary mechanisms is greatly suppressed. We concentrate on the experimental consequences of the existence of quarks which seem to follow from reasonable and conservative assumptions about the properties of quarks. An earlier and similarly motivated study was done by Adair and Price.[1]

We assume that protons are made up of three quarks, although our conclusions would not be essentially altered if the number of proton constituents were some other small integer. Since the mass of the quark is unknown, we perform our calculations for quark masses of 10 and 100 GeV/c^2 to indicate the dependence of the experimental effects on quark mass.

II. QUARK PRODUCTION PROCESSES

The threshold of laboratory momentum in proton-proton collisions for $Q\overline{Q}$ pair production is 241 GeV/c or 2.04×10^4 GeV/c for a quark mass of 10 GeV/c^2 or 100 GeV/c^2, respectively. However, because of the large mass of the quark compared to ordinary hadrons, $Q\overline{Q}$ production by the usual pair-production mechanisms or by the diffraction-dissociation mechanism

$$p+T\rightarrow p+T+Q\overline{Q} \tag{1}$$

(where T is an arbitrary target particle) is likely to be strongly suppressed by the large number of competing channels of lower mass. Nevertheless, if quarks exist, one process which should have experimental consequences is the diffraction disintegration of cosmic-ray protons into quarks

$$p+T\rightarrow Q_\alpha+Q_\beta+Q_\gamma+T, \tag{2}$$

where $Q_\alpha, Q_\beta, Q_\gamma$ indicate the quark constituents of the proton. This process should take place even if quarks have unusual quantum numbers which prohibit their production in ordinary processes. Since this is a new process, the opening of the disintegration channel (2) will lead to a rise in the proton total cross section above the threshold for reaction (2).

A. Threshold for diffraction disintegration

Diffraction disintegration will take place when the laboratory momentum of a cosmic-ray proton is so large that the energy of the proton differs by only a small momentum transfer from the energy of three free quarks with the same total momentum. Since this occurs only at very high proton laboratory momenta, we neglect any internal motion of the quarks within the proton. The difference in energy between a proton of mass m_n ($m_n\simeq 1$ GeV) moving at a lab momentum P and a (dissociated) three-quark state of mass $3M$ moving at the same total momentum is

$$\Delta E=\frac{9M^2-m_n^2}{2P}\,. \tag{3}$$

If we assume that a momentum transfer on the order of 0.25 GeV can be supplied to an incident cosmic-ray proton colliding with a nucleon at rest in the lab, Eq. (3) gives the threshold for diffraction disintegration of protons into their three constituent quarks as 1.8×10^3 or 1.8×10^5 GeV/c for a quark mass of 10 or 100 GeV/c^2, respectively.

B. Cross section for diffraction disintegration

We have shown[2] that a proton wave function which reproduces the experimental values of the proton electromagnetic form factor (after the appropriate

Lorentz transformations have been made[3]) can be used in conjunction with Glauber's[4] geometric arguments to estimate the asymptotic diffraction disintegration cross section. The resulting estimate is of the order of 5 mb, which agrees with the expectations that it should be about the same as the geometric cross section and is further supported by Dooher's argument[5] indicating asymptotic hadron disintegration cross sections in the few-millibarn range.

Denote the diffraction disintegration cross section as a function of proton lab energy E by

$$\sigma_D(E) = \sigma_A f(E), \tag{4}$$

where σ_A is the asymptotic cross section and $f(E)$ contains the energy dependence. To get an upper bound on the number of quarks produced by proton disintegration, we set $f(E)=1$ for $E > E_{\text{th}}$, where E_{th} is the threshold energy for diffraction disintegration of protons into quarks. Another approach assumes that the matrix element for diffraction disintegration is constant. Consequently the cross section grows like the phase space available to the three final-state quarks up to some energy above E_{th}, at which point the cross section becomes constant at its asymptotic value. For want of a better value, we assume that the cross section rises like available phase space from zero at E_{th} to σ_A at $4E_{\text{th}}$ and remains constant above $4E_{\text{th}}$.[1] In the ultrarelativistic case where the momenta of the reaction products are very much greater than their masses (this is certainly true in our case), a cross section which grows like phase space varies with lab energy as $E^{5/2}$. Thus, we take

$$f(E) = \left(\frac{E}{3E_{\text{th}}} - \frac{1}{3}\right)^{5/2} \tag{5}$$

in the energy range $E_{\text{th}} < E < 4E_{\text{th}}$, and $f(E)=1$ for $E > 4E_{\text{th}}$.

C. Flux of quarks from disintegration of cosmic-ray protons

The number of cosmic-ray protons with lab energy greater than E is given by[1]

$$F(>E) = 1.4E^{-1.67}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}, \tag{6}$$

where E is measured in GeV. We assume that the nucleon-nucleon total cross section σ_{NN} is about 40 mb at energies above 10^3 GeV. Quarks will be produced in the fraction $\sigma_D(E)/\sigma_{NN}$ of proton collisions at energies above the threshold for diffraction disintegration.

To estimate the flux of quarks produced by diffraction disintegration, we assume that three-quark final states predominate in the disintegration process. This is done for two reasons. First, the threshold for disintegration into five quarks is 2.8 times the threshold energy E_{th} for disintegration into three quarks. Owing to the rapid fall of the cosmic-ray flux with energy, only 18% of protons with $E > E_{\text{th}}$ can disintegrate into five quark states. Furthermore, disintegration into five quarks should be strongly suppressed by the high mass of the 5Q state and the resulting competition from lower-mass 3Q and $3Q+n$ hadron channels.

A lower limit on the quark flux can be estimated by assuming that diffraction disintegration takes place only on the first collision at the top of the atmosphere and that only three quarks are produced in each disintegration. The resulting estimate for the flux is

$$F_L = 3\frac{\sigma_A}{\sigma_{NN}} \int_{E_{\text{th}}}^{\infty} f(E) N(E)\, dE,$$

where $f(E)$ is given by Eq. (5) and $N(E)$, the differential spectrum is, from Eq. (6),

$$N(E) = 2.3E^{-2.67}\ \text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}\ \text{GeV}^{-1}.$$

By numerical integration, this flux is 3.2×10^{-7} or 1.4×10^{-10} $\text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}$ for quarks with mass of 10 or 100 GeV/c^2, respectively. By contrast, assuming that $f(E)=1$ gives a flux of

$$F_L' = \tfrac{3}{8}\int_{E_{\text{th}}}^{\infty} N(E)\, dE = \tfrac{3}{8} F(>E_{\text{th}})$$

or 1.3×10^{-6} or 6.3×10^{-10} $\text{cm}^{-2}\ \text{sr}^{-1}\ \text{sec}^{-1}$, respectively, about four times the fluxes F_L obtained using Eq. (5).

An approximate upper limit on the flux of quarks produced by diffraction disintegration of cosmic-ray protons can be estimated by making the following assumptions:

(1) Protons lose half of their energy in each interaction not involving disintegration.

(2) Three-quark states dominate among the final states produced by diffraction disintegration.

(3) The diffraction-disintegration cross section attains its asymptotic value immediately above threshold.

The second assumption may lead to a slight underestimate of the number of quarks produced, but this should be more than compensated by the overestimate involved in the third assumption. The flux is then estimated in the following way: $\frac{5}{40}$ of the protons with energies above threshold should disintegrate into quarks in the first collision. Protons with energies above $2^n E_{\text{th}}$ will be able to produce quarks by diffraction disintegration in their $(n+1)$st collision if they survive the preceding n collisions without disintegrating. Therefore $(\frac{7}{8})^n$ of the protons with initial energy above $2^n E_{\text{th}}$ will have a chance to disintegrate in the $(n+1)$st collision, and of this number $\frac{1}{8}$ will disintegrate. The upper limit on the flux of quarks produced by diffraction disintegration of cosmic-ray protons in the atmosphere is then

$$F_U = \tfrac{3}{8}[F(>E_{th}) + \tfrac{7}{8}F(>2E_{th}) + (\tfrac{7}{8})^2F(>4E_{th}) + (\tfrac{7}{8})^3F(>8E_{th}) + (\tfrac{7}{8})^4F(>16E_{th}) + \cdots], \quad (7)$$

or

$$F_U = \tfrac{3}{8}F(<E_{th})[1 + 0.271 + 0.0735 + 0.0054 + 2.9\times 10^{-5} + \cdots].$$

This gives an upper limit on the quark flux of 1.8×10^{-6} or 9.0×10^{-10} cm^{-2} sr^{-1} sec^{-1} for a quark mass of 10 or 100 GeV/c^2, respectively. The contribution from protons which can produce quarks in their fifth collision (protons with initial energy $>16E_{th}$) is negligible. The inclusion of protons which can produce quarks in their fourth interaction is justified because the weight of the atmosphere is about 1000 g/cm^2 and the nucleon mean free path in air is about 90 g/cm^2, implying that there are about eleven nucleon free path lengths between the top of the atmosphere and the surface of the earth. Therefore, an incident cosmic-ray proton will probably undergo four interactions before reaching the surface of the earth.

These fluxes (see Fig. 1) indicate that, if quarks exist, it is unlikely that their mass is as low as 10 GeV/c^2. Such "low"-mass quarks would be produced copiously in diffraction-disintegration processes and it is hard to see how they could escape detection. It should also be noted that the relatively large fluxes produced by diffraction-disintegration mechanisms make the existence of fractionally charged quarks seem unlikely.

D. Momentum spectrum of quarks produced in diffraction disintegration

When a proton incident with lab momentum P on a target nucleon contained in a nucleus in the atmosphere disintegrates diffractively into three quarks, the laboratory momentum of the resulting quarks is $P/3$. Furthermore, in the rest frame of the incident proton, the target nucleon is approaching with a momentum $-P$, and diffraction disintegration of the target nucleon into three quarks with momenta $-P/3$ in the rest frame of the incident proton is possible. From the symmetry of the situation, half the quarks produced by diffraction disintegration should come from projectile disintegration and half from target disintegration. If we calculate the laboratory momentum of the quarks resulting from disintegration of the target nucleons, we can determine the momentum spectrum of the produced quarks. In these calculations we neglect the internal momenta of the quarks relative to the nucleon center of mass, as well as the internal momenta of the nucleons in the target nucleus. In the incident proton's rest frame, the target nucleon approaches with momentum $-P$ and the quarks resulting from diffraction disintegration of the target have a momentum $p' = -P/3$. The lab momentum p of these quarks is given by

$$p = \gamma\left(p' + \frac{\beta E'}{c}\right)$$

or

$$p = \gamma\left[\frac{-P}{3} + \frac{P}{3}\left(1 + \frac{m^2}{p^2}\right)^{-1/2}\left(1 + \frac{9M^2}{p^2}\right)^{1/2}\right].$$

In order for diffraction disintegration to take place we need $P \gg M$, and we find

$$p \simeq \frac{3}{2}\,\frac{M^2}{m}.$$

This indicates that the quarks produced by diffraction disintegration of *target* nucleons will have momenta in a narrow band around 150 GeV/c if the quark mass is 10 GeV/c^2 or around 1.5×10^4 GeV/c if the quark mass is 100 GeV/c^2. This is purely a kinematic effect. Consequently, the *number* of quarks expected from diffraction disintegration of target nucleons will vary with the

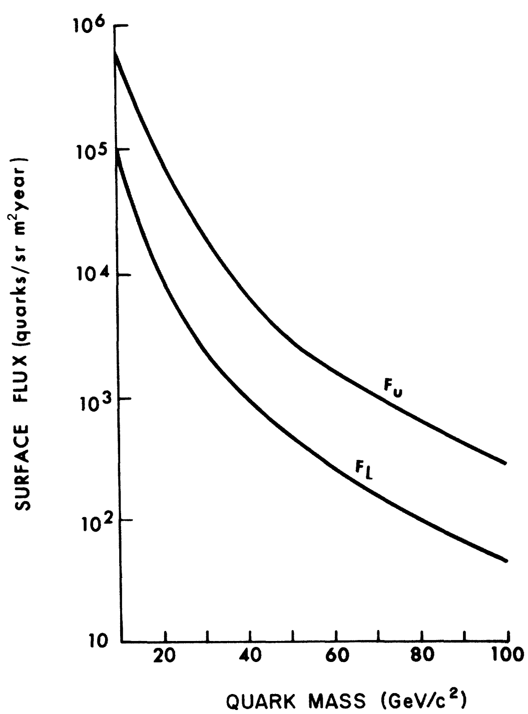

FIG. 1. Estimated upper and lower limits of quark fluxes reaching the surface of the earth, as a function of quark mass.

estimated magnitude of the disintegration cross section, but their *momenta* will not vary.

Considering only quarks produced by diffraction disintegration in the first collision of cosmic-ray protons with nuclei in the atmosphere and taking account of the approximate threshold behavior of the diffraction-disintegration cross section, the qualitative features of the momentum spectrum of the produced quarks are shown in Fig. 2, where $P_{\rm th} \simeq E_{\rm th}/3$ is the momentum of quarks produced by diffraction disintegration of incident cosmic-ray protons at the threshold energy $E_{\rm th}$ and

$$F = \frac{9\sigma_A}{\sigma_{NN}} \int_{P_{\rm th}}^{\infty} [2.3(3P)^{-2.67}] \left(\frac{P}{3P_{\rm th}} - \frac{1}{3}\right)^{5/2} dP$$

is the total integrated flux of quarks produced by diffraction disintegration. Figure 2 will be slightly modified by corrections arising from production of quarks in the second and subsequent collisions between cosmic-ray protons with energy above $2E_{\rm th}$ and atmospheric nuclei. Essentially, the curve will rise slightly higher between $2P_{\rm th}$ and about $8P_{\rm th}$ [see Eq. (7)] and the value of F may be 10% or 20% higher.

E. Momentum spectrum of quarks at the earth's surface

Since the detailed characteristics of quark interactions are unknown, we must make certain assumptions to discuss their momentum spectrum at the surface of the earth and experimental methods for detecting quarks. These are as follows:

(a) The average inelasticity K_Q for quark-nucleon collisions is given by[1,5]

$$K_Q = \left(\frac{m}{M}\right) K_N$$

and the average inelasticity in nucleon-nucleon collisions K_N is 0.5.

(b) At high energy, the additivity assumption holds, so the quark-nucleon total cross section σ_{QN} is given by

$$\sigma_{QN} = \tfrac{1}{3}\sigma_{NN},$$

where σ_{NN} is the nucleon-nucleon total cross section.

The additivity assumption leads to conclusions which seem to be approximately true experimentally at accelerator energies, and should almost certainly be true at very high energy where the quarks are quasifree. The lowest-energy quarks we consider have momentum $\sim\frac{3}{2}M^2/m$, which should be well within the energy range where quarks are quasifree and the additivity assumption should be justified. The mean free path for nucleons in air is about 90 g/cm^2, implying a mean free path of 270 g/cm^2 for quarks. Since the thickness of the atmosphere at sea level is about 1000 g/cm^2, quarks produced in the first collision at the top of the atmosphere will undergo about three interactions before reaching sea level. If the average fraction of the quark's energy lost in each quark interaction in the atmosphere is K_Q, the average energy retained by a quark after N interactions, E_R^N, is $E_R^N \simeq (1-K_Q)^N E_I$, where E_I is the initial energy of the quark. This means that quarks of mass 10 GeV/c^2 retain an average of 86% of their initial energy after passing through the atmosphere and quarks of mass 100 GeV/c^2 retain an average of 99% of their initial energy. Consequently, the momentum spectrum shown in Fig. 2 with the various momenta multiplied by $(1-K_Q)^3$ will describe the majority of quarks observed at the earth's surface.

A *very* few slow quarks could result from backward scattering (in the QQ c.m. frame) of a quark produced by diffraction disintegration of a cosmic-ray proton and a target quark bound in a nucleon contained in an atmospheric nucleus. In the extreme case, backward scattering at a scattering angle of 180° in the QQ c.m. frame could lead to a

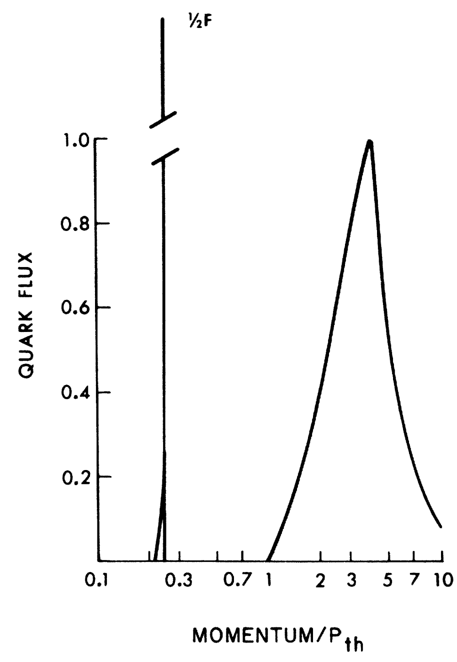

FIG. 2. Estimated laboratory momentum spectrum of quarks produced by diffraction disintegration of cosmic-ray protons. Momentum is measured in units of $P_{\rm th}$, the momentum of quarks produced by diffraction disintegration of protons at threshold. The spike at $0.25P_{\rm th}$ is due to diffraction disintegration of target nucleons, producing an almost monochromatic spectrum in the lab system. The areas under each curve equal $\frac{1}{2}$ the total quark flux.

quark at rest in the lab and "spallation" of the struck nucleon (and possibly the nucleus in which it is contained). This is clear from a symmetry argument. In any case, the number of such events should be very small and they will be neglected in what follows.

III. QUARKS IN COSMIC-RAY SHOWERS

If quarks are produced in a cosmic-ray shower, they will lag behind the shower front because of their large mass. The time delay Δt at a distance S below the point of production of a particle moving with velocity v as compared to particles produced at the same point and moving essentially with the velocity of light is

$$\Delta t = S\left(\frac{1}{V} - \frac{1}{c}\right).$$

If the "slow-moving" particle is a quark of mass M and energy E, we have a time delay for the quark of

$$\Delta t = S\left[\frac{1}{c}\left(1 - \frac{M^2}{E^2}\right)^{-1/2} - \frac{1}{c}\right] \simeq \frac{SM^2}{2E^2c} \tag{8}$$

since all quarks we consider have $E \gg M$. The longest time delay for quarks produced in cosmic-ray nucleon diffraction disintegration will occur for the products of disintegration of the target nucleon, which have $E = 1.5M^2/m$. This time delay is

$$\Delta t_{\max} = \frac{S}{4.5c}\left(\frac{m}{M}\right)^2 \tag{9}$$

or $740(m/M)^2$ nanoseconds per kilometer of travel from the point of production. If quarks have a mass of 10 GeV/c^2, these target-nucleon disintegration products will lag about 7 nsec behind the shower front after traveling 1 km beyond the point of production. If the quark mass is 100 GeV/c^2, the target disintegration products will lag by only 0.07 nsec after traveling 1 km.

Tonwar *et al.*[6] have reported an experiment studying the time structure of hadrons in extensive air showers. They observe particles with time delays of the order of 20–40 nsec associated with air showers of energy greater than 2×10^{14} eV. These particles deposit about 20–30 GeV in the bottom half of a 750-g/cm^2 iron calorimeter and their flux is estimated as 10^{-9} sec^{-1} sr^{-1}. These delayed particles might be interpreted as quarks produced by diffraction disintegration in cosmic-ray interactions some 10–20 km above the detector. For example, a quark of mass 20 GeV/c^2 produced by diffraction disintegration of a target nucleon 15 km above the detector would, by Eq. (9), have a time delay of about 28 nsec. The additivity assumption implies that the interaction mean free path of quarks in iron is about 360 g/cm^2, so on the average a quark would only undergo one interaction in the bottom half of the calorimeter employed by Tonwar *et al.* If the average inelasticity for a quark of mass M is $K_Q = 0.5(m/M)$, quarks with energy $1.5M^2/m$ produced by diffraction disintegration of target nucleons in cosmic-ray interactions would deposit an energy of about $0.75M$ (15 GeV for a quark with mass 20 GeV/c^2) in the bottom half of the calorimeter used by the Tonwar group.

From Fig. 1, the total flux of quarks expected from target-nucleon diffraction disintegration is between 10^{-7} and 10^{-8} cm^{-2} sec^{-1} sr^{-1} if the quark mass is 20 GeV/c^2. This is considerably above the flux of 10^{-9} cm^{-2} sec^{-1} sr^{-1} estimated by Tonwar *et al.* However, the results of the Tonwar group are only for the flux associated with air showers with energy above 2×10^{14} eV, which is well above the 7.2×10^{12}-eV threshold for production of 20-GeV/c^2 quarks by diffraction disintegration. The lower limit on the flux of 20-GeV/c^2 quarks which could result from target-nucleon diffraction disintegration in cosmic-ray events with primary energies above 2×10^{14} eV is $(\frac{3}{8})(1.4)(2\times10^5)^{-1.67}$ cm^{-2} sec^{-1} sr^{-1} or about 7×10^{-10} cm^{-2} sec^{-1} sr^{-1}, in reasonable agreement with the results of Tonwar *et al.* Consequently, if the findings of the Tonwar group are verified by subsequent experiments, they might be looked on as evidence for the existence of quarks produced by diffraction disintegration of nucleons in cosmic-ray events.

IV. OTHER INDICATIONS OF THE EXISTENCE OF QUARKS

A. Breaks in the primary cosmic-ray energy spectrum

We have previously shown[7] that the production of particles with low inelasticity in high-energy collisions could lead to an underestimate of the energy of a primary proton as measured in a calorimeter, and that this would lead to an *apparent* steepening of the cosmic-ray proton spectrum. Since the energy of the particles producing extensive air showers is estimated on the basis of the energy deposited in the shower, it is clear that the production of particles of low inelasticity (e.g., quarks) could lead to an underestimate of the energy of the primary proton and thus produce an apparent break in the cosmic-ray spectrum.

In a model by Naranan[8] in which the cosmic-ray lifetime is limited by collisions, an increase in the nucleon-nucleon cross section and the average inelasticity in nucleon-nucleon collisions is shown to lead to a *real* break in the cosmic-ray spectrum.

The nucleon-nucleon total cross section should rise by about $\frac{5}{40}$ (or 13%) above the threshold for diffraction disintegration. Also, the average inelasticity in nucleon-nucleon collisions (i.e., the average energy transferred to secondaries) should rise when diffraction disintegration becomes possible. This can be seen as follows. Well above the threshold for diffraction disintegration, approximately $\frac{5}{40}$ or $\frac{1}{8}$ of all incident cosmic-ray protons will lose *all* their energy to secondaries by diffraction disintegration into quarks. The remaining $\frac{7}{8}$ of the cosmic-ray protons will lose, on the average, half of their energy to secondaries. Consequently, the average energy lost to secondaries in a single collision by a group of cosmic-ray protons with energy E is

$$\frac{1}{8}E + \frac{7}{8}\frac{E}{2} = \frac{9}{16}E.$$

So, the average inelasticity for protons well above the threshold for diffraction disintegration should be about 0.56, an 11% increase over the value of 0.5 assumed for lower-energy collisions.

Naranan shows that such a change in the parameters of the nucleon-nucleon interaction could lead to a break in the primary proton spectrum believed to occur at 10^{15} eV. If this postulated break in the spectrum were to be ascribed to the onset of diffraction disintegration of nucleons into quarks, this would require a quark mass in the vicinity of 240 GeV/c^2.

B. Change in the cutoff energy in the cosmic-ray spectrum

If primary cosmic-ray particles are largely protons, the cosmic-ray number spectrum as a function of energy should fall off sharply at around 10^{20} eV. This is a result of the interaction of cosmic-ray protons with the 3°K thermal radiation which seem to pervade the cosmos, possibly as a remnant of radiation from a "big bang" occurring at the birth of the universe. The cutoff arises from pion photoproduction in the scattering of high-energy cosmic-ray protons and 3°K photons. This process can occur when

$$[(\vec{p}^2 + m^2)^{1/2} + |\vec{p}_\nu|]^2 - (\vec{p} + \vec{p}_\nu)^2 = (m + m_\pi)^2,$$

where $\vec{p}$ is the proton 3-momentum, $\vec{p}_\nu$ is the photon 3-momentum, m is the proton mass, and m_π is the pion mass. Since $p \gg m$, the above expression yields on the average

$$p = \frac{m m_\pi}{p_\nu} \sim 10^{20} \text{ eV} \qquad (10)$$

as the photoproduction threshold. If massive charged particles (e.g., quarks) exist, they should be accelerated by the same mechanisms responsible for producing high-energy protons. The energy spectrum of these massive particles should also be cut off by pion photoproduction. If the proton mass is replaced by the mass M of the heavy particle in Eq. (10), the particle spectrum will be cut off at $\sim(M/m)\times 10^{20}$ eV or 10^{21} eV if the heavy particles have mass 10 GeV/c^2 and 10^{22} eV if the heavy particles have mass 100 GeV/c^2.

If it is experimentally verified that the cosmic-ray particle flux is *not* cut off at 10^{20} eV, this might be evidence for the existence of massive particles, although they need not be quarks. Lack of cutoff could also be due to some form of local production of cosmic rays. Unfortunately, energy measurements at these very high energies are difficult and usually involve dangerous extrapolations from the known characteristics of low-energy interactions.

C. Problems in experimental detection of quarks

Conceptually, the simplest quark detection experiment involves a bending magnet, detectors for track matching, and a calorimeter. If the magnet had a field strength such that any singly charged particle with energy greater than 100 GeV would pass through without deflection and then impinge on a calorimeter with a thickness of 6 to 8 proton interaction lengths, the apparatus should, in principle, be able to detect quarks. Any particle which went straight through the magnet and deposited substantially less than 100 GeV in the calorimeter would have to be a quark (muons deposit virtually no energy in a calorimeter). In practice, the experimenter will have to deal with the twin problems of very low quark fluxes and track matching in very-high-energy showers.

V. CONCLUSION

The utility of the quark concept suggests the reality of quarks, and there may be some indications of their existence in the changes in the properties of hadronic interactions at extremely high energies. Assuming that

(1) quarks exist as components of protons,

(2) diffraction disintegration of cosmic-ray protons into their constituent quarks can take place at very high energies, and

(3) the proton-nucleon total cross section approaches a constant at very high energies and the ratio of the diffraction disintegration cross section to the total cross section is about $\frac{1}{8}$,

we can calculate the threshold for quark production, the quark flux, the momentum spectrum, and the time delays of quarks produced in diffraction-disintegration processes as a function of quark mass. If we further assume that

(1) the average inelasticity for quarks is $0.5(m/M)$, and

(2) the additivity assumption holds, so that quark interaction lengths are approximately three times the corresponding proton interaction lengths,

then we can estimate the momentum spectrum of quarks at the surface of the earth and discuss the expected behavior of quarks in detectors.

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