so taking $\bar{s}=2$ GeV^2 we have from (19)

$$a_{\pi\pi}\approx(0.5+\tfrac{1}{3}\ln 40)\ \text{GeV}^{-2} = 1.7\ \text{GeV}^{-2}, \tag{20}$$

not far from the expected 2 GeV^{-2}.

It thus appears that if the strip approximation succeeds in explaining the masses and widths of the ρ and f^0 mesons, it will correctly predict both the high-energy $\pi\pi$ total cross section and the width of the diffraction peak.[15]

An additional result not immediately subject to experimental test is the effect of the ρ trajectory on the high-energy $\pi\pi$ amplitude. Using the same approximations as above, one merely adds to formula (16) a factor

$$\begin{bmatrix}\frac{1}{3}\\ \frac{1}{3}\\ \frac{1}{3}\end{bmatrix}+\begin{bmatrix}1\\ \frac{1}{2}\\ -\frac{1}{2}\end{bmatrix}\tfrac{1}{2}(2s/\bar{s})^{\alpha_\rho(t)-\alpha_P(t)}, \tag{21}$$

where the column vectors have elements corresponding to

$$I=\begin{bmatrix}0\\1\\2\end{bmatrix}.$$

Notice that if $\alpha_P-\alpha_\rho\lesssim 0.5$ the influence of the ρ will persist to rather high energies.

[15] Note that even to get the correct sign for $\sigma_{\pi\pi}$ and $a_{\pi\pi}$ from a dynamical calculation of the Regge parameters is a nontrivial achievement.

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Search for Charge $\frac{1}{3}e$ Particles in Cosmic Rays*

A. W. SUNYAR, A. Z. SCHWARZSCHILD, AND P. I. CONNORS†
Brookhaven National Laboratory, Upton, New York

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A search was conducted for particles of charge $\frac{1}{3}e$ (quarks) in cosmic rays at sea level. No such particles were found. The experiment yields an upper limit for the frequency of high-energy quarks of 1 per 2×10^5 relativistic μ mesons. This limit is related to a limit on the quark production cross section as a function of possible quark mass. A short discussion is given of macroscopic experiments which might have detected quarks in matter.

I. INTRODUCTION

RECENT speculation[1] by Gell-Mann concerning the possible existence of fractionally charged particles (quarks) has led to several experiments[2,3] designed to reveal their presence. The negative result of the experiments of Leipuner *et al.* and Bingham *et al.*, performed with high-energy proton beams, resulted in a lower limit of $\sim$2 GeV/c^2 for the mass of the charge $\frac{1}{3}e$ quark. The production of quark pairs in p-p collisions at 28 GeV is kinematically impossible for quarks with $m_Q>2.7$ GeV/c^2. Such a limitation on the mass does not exist for quarks produced by cosmic-ray proton-nucleon interactions in the atmosphere, although the cosmic proton flux is of course much smaller than is available at the Brookhaven alternating gradient synchrotron (AGS). We have performed an experiment designed to detect the possible presence of relativistic particles of charge $\frac{1}{3}e$ in the cosmic radiation at sea level. The distinctive character by which we attempt to identify particles of lower than unit charge is their small specific ionization at relativistic velocities.

II. EXPERIMENTAL EQUIPMENT AND RESULTS

The experimental apparatus consisted of the plastic scintillation counter telescope shown in Fig. 1, and associated coincidence circuitry, together with a dual-beam oscilloscope on which the linearly amplified signals from six of the counters (2, 4, 5, 6, 7, 8) were displayed and photographed.

Events satisfying coincidence requirements [1 $\bar{3}$ 4 8] (see Fig. 1) measured the number of minimum ionizing muons traversing the counter telescope. Photographs of μ-meson traces taken with these coincidence requirements served to provide pulse-height calibrations for minimum ionization for each of the detectors. In order to reduce the number of photographs to be scanned in searching for the charge $\frac{1}{3}e$ quarks, energy selection was

* Research carried out under the auspices of the U. S. Atomic Energy Commission.
† Graduate student, Pennsylvania State University, University Park, Pennsylvania.
[1] M. Gell-Mann, Phys. Letters 8, 214 (1964).
[2] L. B. Leipuner, W. T. Chu, R. C. Larsen, and R. K. Adair, Phys. Rev. Letters 12, 423 (1964); H. H. Bingham *et al.*, Phys. Letters 9, 201 (1964).
[3] D. R. O. Morrison, Phys. Letters 9, 199 (1964); and P. A. Piroué and A. J. S. Smith, Post-deadline paper, American Physical Society meeting, Washington, April 1964 (unpublished). [3a] [*Note added in proof.* After submission of this paper, two Letters have appeared on this subject. The references are: V. Hagopian *et al.*, Phys. Rev. Letters 13, 280 (1964); W. Blum *et al.*, Phys. Rev. Letters 13, 353(A) (1964).]

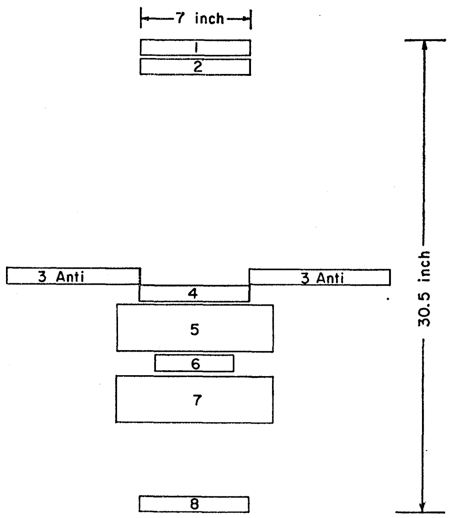

FIG. 1. Scale drawing of counter telescope arrangement. All counters except the anti are cylindrical plastic scintillators viewed by multipliers through Lucite light pipes. The anticounter is a 24-in.×36-in. rectangle with a 7-in.-diam hole in the center.

imposed on the signals from counters 1 and 4. The largest accepted energy loss in counters 1 and 4 was limited to about $\frac{1}{5}$ the energy loss of a minimum-ionizing muon in these counters.

The counter 6 serves a particular purpose. It is the smallest diameter counter in the telescope. It is particularly difficult for a charged particle to traverse counter 6 without passing through the full 3-in. thickness of counters 5 and 7. In addition, we have found that $\frac{5}{6}$ of the μ mesons which traverse the counters 1, 2, 4, 5, 7, 8 also pass through 6. We expect therefore that any particle traversing the telescope without scattering has a $\frac{5}{6}$ probability for traversing counter 6.

Data were accumulated continuously for about one month. During this time, 3.3×10^5 minimum-ionizing particles satisfied the coincidence requirements [1 4 8]. About $\frac{1}{5}$ of these events also trigger the anticoincidence counter 3. During this time, $\sim$500 events satisfied the pulse-height requirements on counters 1 and 4 described above, and photographs were taken of the pulses associated with these events. The large majority of these photographs show large (close to minimum ionization) pulses in at least one counter, and frequently pulses are missing in those counters not required in the triggering conditions. Nine events were observed in which the signals from counters 2, 4, 5, 7, 8 all corresponded to less than $\frac{1}{3}$ minimum, and no signal appeared in counter 6. If these events are all associated with particles of subunit charge, we should expect to observe $\sim$45 events in which counter 6 is also triggered and exhibits a small signal. In fact, only one event in which all six displayed counters exhibit pulses less than $\frac{1}{3}$ minimum was found. In this one event, the pulse height (in units of the mean minimum-ionizing signals for μ mesons) in the counters 2, 4, 5, 6, 7, 8 have amplitudes 0.09, 0.09, 0.22, 0.06, 0.22, 0.10, respectively.[4]

In establishing a limit on the quark production cross section, we will refer the observed events to the number of μ mesons traversing all counters including 6, and not accompanied by an antisignal. The total number of such events was $(3.3\times\frac{5}{6}\times\frac{4}{5})\times10^5\approx2\times10^5$. Therefore, for this sample there appears only one possible candidate. Although the pulses in four of the counters are quite consistent with a charge $\frac{1}{3}$ particle, those in the thick counters 5 and 7 are twice the amplitude expected. We estimate that the probability that this event is due to a single quark is less than (4×10^{-4}). It is conceivable that this event is due to a quark pair, one member of which traverses only the edges of the large diameter counters 5 and 7. (A quark traversing counter 3 would probably not produce an effective antisignal.) It seems very strange that a double-quark event could have been observed when no single-quark events were recorded, since the most probable quark production region is far above our counter telescope. Accordingly, we assert that the ratio of quarks to μ mesons at sea level is less than 1 in 2×10^5.

III. DISCUSSION

Although we have no theory for the mechanism of quark production in the atmosphere, we assume, for purposes of calculation, a very simple model for their production and attenuation in the atmosphere. We make the following assumptions:

(1) Quarks are produced in pairs with a cross section σ_Q by the reaction $p+N\rightarrow p+N+2Q$, where σ_Q is independent of proton energy above threshold.

(2) Quarks have an intrinsic lifetime[2] long compared with their passage through the atmosphere.

(3) All quarks produced in the atmosphere are close to minimum ionization at the point where they are produced. [The kinematics of the reaction listed under (1) requires that at threshold a quark with $m_Q>m_p$ will have $\beta^2>0.75$ in the laboratory frame. We assume that the angular distribution in the production will not seriously modify this situation above threshold.]

(4) Once produced, quarks are removed from the region of minimum ionization with an attenuation coefficient μ_Q.

In calculating the quark production, we take[5] as the

[4] The large size of the scintillators required that rather large Lucite light pipes be used in collection of light to the photomultipliers. These pipes were arranged in a fan-type arrangement, so that vertical lines traversed no more than two light pipes. In the absence of the anticoincidence requirement, we observed approximately 3 events per day in which all six pulses were small. The origin of these pulses was extended particle showers in which all six light pipes emit Čerenkov radiation, and no particle traverses any scintillator. Since the anticoincidence efficiency is not 100%, it is probable that some of the nine events discussed above are associated with light pipe pulses.

[5] Bruno Rossi, *High Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952), Chap. 1.

number of primary cosmic ray protons of kinetic energy greater than E_p (GeV),

$$N(E_p)=2.1(E_p+5.3)^{-1.75}\ \text{protons/cm}^2\ \text{sec sr},$$

and we assume that this $N(E_p)$ is altered as a function of altitude by a proton absorption cross section of 200 mb/atom of air. In addition, the number of minimum-ionizing μ mesons at sea level is about 0.01/cm^2 sec sr. Using $1/(2.0\times10^5)$ as an upper limit for the number of quarks per μ meson, we find

$$\sigma_Q\leq10^{-8}\{2[1+m_Q/m_p]^2+3.3\}^{1.75} \times(\mu_p-\mu_Q)e^{\mu_pX_0}(e^{(\mu_p-\mu_Q)X_0}-1)^{-1},$$

where X_0 is the height of the atmosphere in the appropriate units (atoms/cm^2), and σ_Q is the quark production cross section per air atom.

Figure 2 gives a plot of this upper limit for the production cross section as a function of m_Q/m_p and μ_Q. It has been assumed that the production cross section from a free proton is $\sim\frac{1}{6}$ of that from an average air atom.

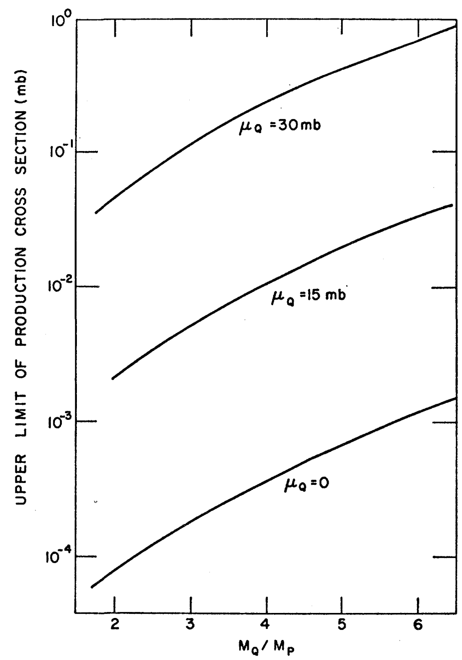

FIG. 2. Upper limit for quark production cross sections in p-N collisions. μ_Q is the cross section for quarks on nucleons for reduction of their kinetic energy to values small compared to their rest mass (appreciably greater than minimum-ionizing).

IV. EARLY MACROSCOPIC EXPERIMENTS CONCERNED WITH THE UNIT OF ELECTRIC CHARGE

It is often stated that evidence for the existence of quarks might have been found in experiments which determine the charge of macroscopic bodies. It is presumed that a quark of low energy becomes bound in an atom which then forever carries a nonunit charge. We assume that quarks are produced from cosmic rays and then come to rest within the uppermost 1 kg/cm^2 of matter on the earth's surface. Further, we assume that the flux has been constant and equal to 5×10^{-5} of the present μ flux[6] for the age of the earth (5×10^9 years). The density of quarks in this surface layer would then be 2×10^8 quarks/g of material. This density is undoubtedly grossly overestimated since no account has been taken of mixing of material in the earth's surface. A conservative estimate of the mixing reduces the density to 2×10^6 quarks/g, corresponding to even distribution over a 1000-ft depth. This limit corresponds to ~1 quark per 10^{16} atoms of matter.

A typical drop of the Millikan oil drop experiment has a radius of $\sim2\times10^{-4}$ cm and a mass of $\sim3\times10^{-11}$ g. Thus one might expect as an upper limit a frequency of nonintegrally charged drops of one per 16 000 drops. It seems unlikely that this would have been observed.

The experiment of Hillas and Cranshaw[7] concerning a comparison of the electron, proton, and neutron charge by detecting the charge on a large volume of de-ionized gas might possibly have detected quarks. Unfortunately, the procedure for removing the effects of ions would probably have resulted also in the removal of atoms containing quarks, thus making their experiment insensitive in this respect.

Experiments designed to detect quarks in matter must insure that chemical procedures in processing the material do not remove the object of the search. For example, the chemical purification of oil for the Millikan experiment will very likely remove an atom containing a quark, should it exist. Distillation processes for gas purification may also be selective against such atoms.

V. CONCLUSIONS

No evidence has been found for the existence of charge $\frac{1}{3}$ particles of relativistic velocity in the cosmic rays at sea level. The limit set for quark production in the atmosphere by this experiment is appreciably less than may be inferred from the Millikan oil drop experiment. A limit on the production cross section in high-energy proton collisions can only be given in terms of the unknown quark mass and the unknown rate of slowing down of quarks in the atmosphere. The limits are presented in graphical form in Fig. 2. It seems unlikely, should they exist, that heavy quarks slow down as rapidly as fast protons in the atmosphere. However, should this be the case, an experiment at high altitudes would be capable of obtaining a lower limit on the possible production cross section.

[6] This number is arrived at from our data. Our limit of 5×10^{-6} quarks per muon refers only to relativistic quarks at sea level. We estimate that the limit on the number of slow quarks (energies reduced by scattering in the atmosphere) may be 10 times greater.

[7] A. M. Hillas and T. E. Cranshaw, Nature **184**, 893 (1959).