Cosmic-Ray Search for Fractionally Charged Particles*

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A mountain-altitude search has been made in the cosmic-ray spectra for the hypothetical, fractionally charged particles known as quarks. These particles of charge $\frac{1}{3}e$ and $\frac{2}{3}e$ have been theorized as the fundamental particles underlying one possible interpretation of the $SU(3)$ classification schemes. A six-element, liquid-scintillator telescope, with the two central elements independent of the triggering requirements, was used in this search. The data were recorded in the form of differentially delayed pulses from the six photomultipliers. Using 90% confidence levels we have found upper limits to the vertical intensities of $\frac{1}{3}e$ and $\frac{2}{3}e$ quarks at 760 g/cm² atmospheric depth to be $I_Q(\frac{1}{3})\leq 8.7\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1} and $I_Q(\frac{2}{3})\leq 1.8\times10^{-8}$ cm^{-2} sec^{-1} sr^{-1}, respectively. The upper limits to the production cross sections have been estimated as a function of the masses of these hypothetical particles and assumed values for attenuation mean free paths. If one assumes that the quark-production cross sections are of the order of 0.01 mb and that the quark-removal cross sections are less than 15 mb/nucleon, then $M_Q(\frac{1}{3})\geq 9$ BeV/c^2 and $M_Q(\frac{2}{3})\geq 7$ BeV/c^2 are the lower limits obtained in this experiment.

INTRODUCTION

THE relative success in the use of unitary symmetry schemes as a method of particle classification in the field of high-energy physics has led to speculation that fractionally charged particles might exist. Gell-Mann[1] and Zweig[2] observed that the $SU(3)$ groupings of 8 and 10 could be simply explained if the known particles are composed of a fundamental triplet which they called quarks and aces, respectively. It was necessary to assign fractional charges and fractional baryon numbers to the members of the fundamental triplet: an isotopic spin doublet with $Z=\frac{2}{3}e$, $-\frac{1}{3}e$ and a singlet with $Z=-\frac{1}{3}e$, all having baryon number $\frac{1}{3}$. Since these quarks have been postulated to explain the structure of the strongly interacting particles, presumably they themselves would be strongly interacting in production and scattering processes.

Several searches at accelerators using bubble chamber[3] and counter[4] techniques have placed a lower limit of approximately 2 BeV/c^2 on the quark mass, since none were found. Sea level[5] and mountain altitude[6] cosmic-ray experiments have extended the search to possible production of charge-$\frac{1}{3}e$ quarks at energies above 30 BeV. In the present work an improvement on the limit for the production of quarks of charge $\frac{1}{3}e$ and an extension of the cosmic-ray search to quarks of charge $\frac{2}{3}e$ is reported.

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[3] V. Hagopian, W. Selove, R. Ehrlich, E. Leboy, R. Lanza, D. Rahm, and M. Webster, Phys. Rev. Letters 13, 280 (1964); D. R. O. Morrison, Phys. Letters 9, 199 (1964); W. Blum *et al.*, Phys. Rev. Letters 13, 353a (1964).
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1. APPARATUS

Figure 1 shows the arrangement of the six element, liquid scintillator telescope used in this experiment. Each of the scintillators was approximately 18×18×2.5 in.³, and was viewed by a 5-in. photomultiplier tube. The area-solid angle acceptance was 237 cm² sr. The 18×18 in.² dimension was selected, as it affords a fairly large area which may still be viewed with uniform light collection efficiency by one 5-in. photomultiplier tube. The total vertical dimension was reduced by introducing mirrors to fold the optical path, greatly improving the solid-angle acceptance of the equipment.

It was possible to operate with two of the photomultiplier tubes' signals independent of the triggering signal described below by increasing the number of scintillator units to six; the previously reported University of Arizona experiment[6] had five units. The last dynode signals of the six photomultiplier tubes were differentially delayed in multiples of about 250 nsec so that the pulses would appear at separate positions when connected to the vertical display of an oscilloscope. Signals from the anodes of PM tubes 1, 2, 5, and 6 became inputs to a 4-fold coincidence circuit and to a 4-input mixer (OR) circuit, followed by a discriminator, into the anticoincidence input. The resolving time of the

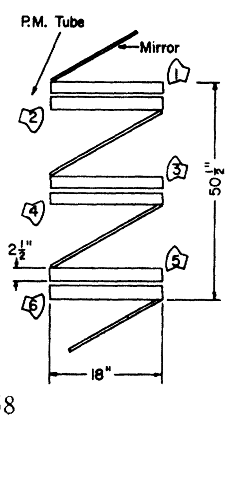

FIG. 1. Arrangement of scintillators.

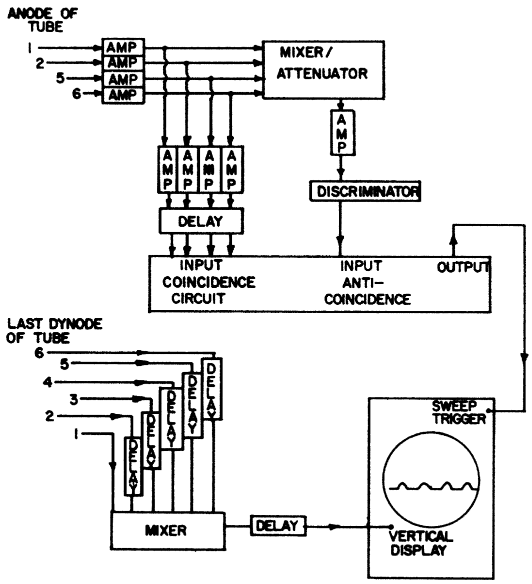

FIG. 2. Block diagram of electronic apparatus.

coincidence circuit was about 100 nsec. The anticoincidence was activated by a pulse corresponding to $dE/dx \geq 0.7$ in units of $(dE/dx)_{\min}$ by means of the anticoincidence discriminator. A four-fold coincidence-anticoincidence requirement was found necessary so that the triggering rate would be low enough (≈ 4 events/min) to make camera cycling and the quantity of raw data reasonable. With a three-fold coincidence-anticoincidence high trigger rates are caused by cosmic-ray showers and fluctuations in the pulse-height response to charge $1e$ particles. A block diagram illustrating the electronics is shown in Fig. 2. The oscilloscope and the recording camera were triggered by this circuit whenever counters 1, 2, 5, and 6 simultaneously received signals which correspond to $0.03 < dE/dx < 0.7$, again in units of $(dE/dx)_{\min}$. Scintillator units 3 and 4 were not connected to the triggering circuit and, hence, have pulse-height distributions which are unaffected by possible triggering biases.

The experiment was carried out on a nearby mountain range at an elevation of 7800 ft; this reduces the atmospheric depth to about 760 g/cm². The apparatus was housed so that approximately 0.5 g/cm² of material was overhead. A vertical path through all of the material of the apparatus would traverse approximately 48 g/cm², mostly due to the toluene of the liquid scintillators. The data were collected during a sensitive time of about 1100 h.

2. DATA ANALYSIS

The pulses from the six photomultiplier tubes were photographed as displayed on an oscilloscope. The 35-mm film was then scanned and measured on a digitized measuring projector. The system was calibrated at intervals throughout the running period by the use of two sets of masks which allowed only 1/9 or 4/9 of the incident light to strike the photocathode of each photomultiplier. These masks consisted of a large number of apertures distributed uniformly over the area that corresponds to the photocathodes. The uniformity assures that the pulse-height factor will not be altered due to variations in photocathode efficiency. The two sets of masks reduced the scintillator light by factors of 1/9 and 4/9 and narrowed the widths of the pulse-size distributions by the same factors. The most probable energy loss distributions have been calculated by the method of Symon[7] for the cases of charge $1e$, $\frac{2}{3}e$, and $\frac{1}{3}e$ traversing one of our scintillators; these are shown in Fig. 3(a). These distributions are displaced by 7.9, 3.5, and 0.8 MeV, respectively, which are the most probable energy losses for the three charges. In Fig. 3(b) we have displayed the results of altering the charge-$1e$ distribution; the coordinates of points on the curve were reduced by factors 1/9 and 4/9 for the abscissas and expanded by factors 9 and 9/4 for the ordinates. The resulting curves are centered at 3.52 and 0.88 MeV for the $\frac{2}{3}e$ and $\frac{1}{3}e$ cases. The corresponding distributions are quite alike. Since the calibration pulses are produced by attenuating the light striking the phototubes, the effects of photon counting statistics, electron multiplier fluctuations, and system noise should be identical for calibration pulses and true quark pulses. Hence, the use of the previously described photomultiplier masks with the charge-$1e$ flux of cosmic rays (obtained by disabling

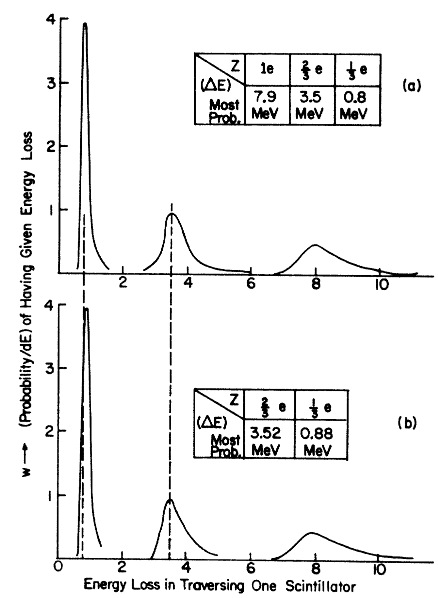

FIG. 3. Most probable energy loss distributions. (a) Calculated distributions which would be caused by relativistic particles of charge $\frac{1}{3}e$, $\frac{2}{3}e$, and $1e$. (b) Calculated distributions produced by charge $1e$ particles with masks admitting 1/9, 4/9 and all of the light to the photomultiplier tube.

[7] B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952), pp. 29–35.

the anticoincidence) closely simulates the passage of charge-$\frac{1}{3}e$ and $\frac{2}{3}e$ particles through the scintillator.

The $\frac{2}{3}e$ calibration distribution was used to set an upper limit pulse height for traces suitable for measurement such that all quark events would have been accepted. Other criteria used to eliminate traces during the scanning were the following: (a) no overlapping traces could be used; (b) each pulse from positions 1, 2, 5, and 6 had to be nonzero and within ± 40 nsec with respect to their mean positions on the trace; (c) the pulses from positions 3 and 4 had to be within ± 40 nsec of their mean positions if they were nonzero; (d) every candidate for measurement must have had no extra pulses. If a trace satisfied all of the conditions, it was measured, and the data were automatically recorded on punched cards.

Computer programs were used to reduce the data. First, the calibration data were analyzed by a pulse-height distribution program. This allowed the assignment of a set of nested limits on pulses 1, 2, 5, and 6, which were determined by subtracting equal percentages of the events from each end of the distributions. Pulse-height distributions of independent units 3 and 4 were obtained with 1, 2, 5, and 6 within the assigned limits. Narrowing the limits on 1, 2, 5, and 6 tends to preferentially eliminate background events, with the assumption that the background events have a much broader distribution than the hypothetical quark events. From these data displays it can be determined whether or not further data purification by narrower limits on 1, 2, 5, and 6 will result in larger signal-to-noise ratios for pulses 3 and 4. A pulse-height distribution was then made on the signals from one of the independent units while the other independent unit's limits were narrowed, and vice versa. Figure 4 shows the results of applying this purification program to the calibration data, $\frac{1}{3}e$, as seen by counter 3. Figure 5 shows the pulse-height distribution observed by counter 3 during the charge-$\frac{1}{3}e$ analysis. The selection criteria on pulses 1, 2, 4, 5, and 6 would include: (a) 91%, (b) 49%, and (c) 25% of all true quark events. Figure 6 is a similar set of distributions for the charge-$\frac{2}{3}e$ analysis.

Limits on the data in counters 3 and 4 from the region

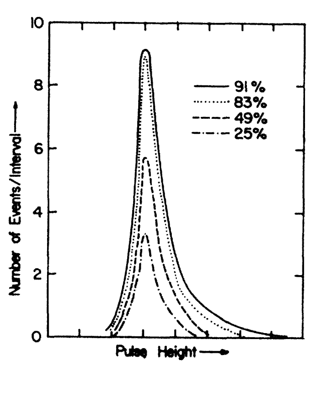

Fig. 4. Simulated charge-$\frac{1}{3}e$ pulse-height distributions. Curves show the pulse-height distributions in counter 3 corresponding to limits in counters 1, 2, 5, and 6 such that the indicated percentage of $\frac{1}{3}e$ quarks would be accepted.

where quark-like pulses would be expected were then set, and pulse-height distributions were compiled on the pulses associated with the events within these limits. The shapes of these distributions are indications as to whether or not the events in the quark pulse-height region are actially due to background events.

The background subtraction was made by making use of the 83% distribution, which has a large number of events. Because this distribution is nearly all background, the proportionality constant C between the number N_i of background events within the quark-like pulse region and the number N_0 of events outside of the interval is determined from this distribution. Then assuming that the shape of the background distribution remains the same, we can use this constant for the more

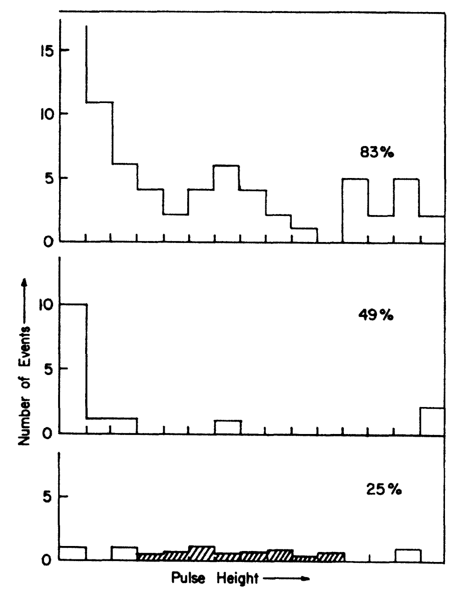

Fig. 5. Pulse-height distributions, charge $\frac{1}{3}e$. The distribution is shown of pulses from counter number 3 with the remaining five counters' limits set to allow the indicated percentage of true quark pulses to remain. The shaded area (in the bottom graph) represents 50 hypothetical quarks ($Z=\frac{1}{3}e$) as they would have been seen in the 25% distribution.

highly purified distributions. In this way we can say that the mean number $\bar{N}_Q$ of quarks is given by

$$\bar{N}_Q = K(\bar{N}_i - C\bar{N}_0)\,, \qquad (1)$$

where K is a constant that depends on the fraction of true quarks expected to fall within the given interval and the fraction of events that survive the selection criteria of the five other counters.

The quark-intensity limits in this paper are reported with a 90% upper confidence limit. This means that $\bar{N}_Q$ has been chosen such that the observed numbers fall at the boundary to the lower 10% tail of the distribution expected with mean $\bar{N}_Q$. The parameters $\bar{N}_i$ and $\bar{N}_0$ have been chosen to maximize $\bar{N}_Q$ subject to this condition. This, or course, tends to raise the upper limit on the quark intensities.

3. RESULTS

A. $Z=\frac{1}{3}e$. The 90% confidence limit based upon the observed events combined with background corrections lead to the upper limits on the number of $\frac{1}{3}e$ quarks traversing our apparatus as shown in Table I. In this $\frac{1}{3}e$ analysis the number of events remaining in the 25% data becomes so small that the signal-to-noise ratio becomes worse than for the 49% data. The two values for $\bar{N}_Q$ from the 49% data shown in Table I were therefore used. Since these two results are not statistically independent, an average was taken as $(\bar{N}_Q)_{90\%}$ as seen by counters 3 and 4. These data yield an upper limit to the vertical intensity of $\frac{1}{3}e$ quarks at 7800-ft altitude, $I_Q(\frac{1}{3})$, of 8.7×10^{-9} cm^{-2} sec^{-1} sr^{-1} using the 90% confidence levels. For those events that remain in the highly purified distributions of counters 3 and 4, the distribution of associated 1, 2, 5, and 6 pulses is consistent with the distribution expected for background events.

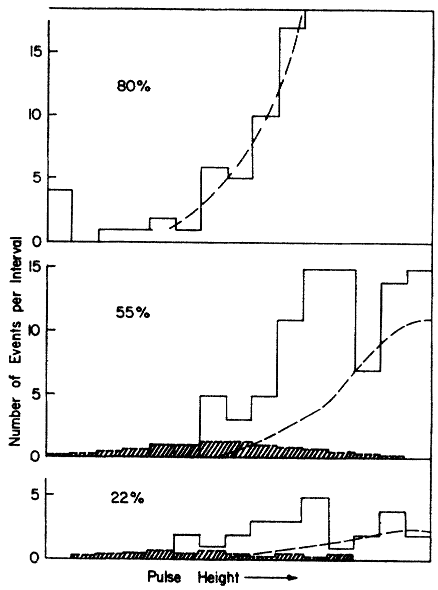

FIG. 6. Pulse-height distributions, charge $\frac{2}{3}e$. Distribution of pulses from counter number 3 with the remaining five counters' limits set to allow the indicated percentage of true quark pulses to remain. The shaded areas represent 50 hypothetical quarks ($Z=\frac{2}{3}e$) as they would have been seen.

B. $Z=\frac{2}{3}e$. Table II shows the results for the charge $\frac{2}{3}e$; again we have used a 90% confidence level. The background in this case is due to the tail of the distribution of charge $1e$ particles. Due to the fact that some of the events above the $\frac{2}{3}e$ region deflect off-screen, the background estimate for the $\frac{2}{3}e$ region is more uncertain than for the $\frac{1}{3}e$ case, above. The backgrounds which were used in the calculations are indicated by the smooth curves in Fig. 6. The 22% purified case yields an average, from counters 3 and 4, of $(\bar{N}_Q)_{90\%}=17$. This corresponds to a vertical intensity of charge-$\frac{2}{3}e$ quarks at 7800-ft altitude, $I_Q(\frac{2}{3})$, that is less than 1.8×10^{-8} cm^{-2} sec^{-1} sr^{-1}. If one assumes that *all* of the events in the interval that corresponds to $\frac{2}{3}e$-quark calibration are signal events (i.e., no background at all) the result is $I_Q\leq3.1\times10^{-8}$ cm^{-2} sec^{-1} sr^{-1}. The associated events (defined in Sec. 3.A for the $\frac{1}{3}e$ case) were again distributed as expected for background events.

TABLE I. Upper limit on the number of $\frac{1}{3}e$ quarks, $N_Q(\frac{1}{3})$, using a 90% confidence level on the observed events.

Fraction of quarks which would be within limits:	49%	25%
Counter 3	11.9	14.3
Counter 4	4.4	12.5

C. *Cross Sections*. Upper limits to the production cross sections for hypothetical charge $\frac{1}{3}e$ and $\frac{2}{3}e$ can be estimated with certain assumptions: The quarks are long-lived, if they exist. Quarks are produced in pairs with a constant cross section per nucleon σ_Q for energies above threshold in $NN\rightarrow NNQ\bar{Q}$ with an average of one quark of charge $\frac{1}{3}e$ or $\frac{2}{3}e$ per reaction. The cosmic-ray primary-proton total-energy integral spectrum for 10 BeV$<E<10^4$ BeV is given by[8]

$$N(E)=0.88E^{-1.5}\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}(E\text{ in BeV})\,. \quad (2)$$

The attenuation mean free path $1/\mu_P$ of protons in air is 120 g/cm^2 and the removal of quarks from the relativistic energy region of the spectrum (where the detection scheme is sensitive) can be approximated by an attenuation mean free path $1/\mu_Q$. The attenuation of protons and the buildup of quark intensity can be described by a simple one-dimensional diffusion equation in which each air nucleus is taken equivalent to 6 free nucleons. The resulting dependence of the quark-production cross section σ_Q on the observed vertical intensity $I_Q(Z)$ at atmospheric depth x is

$$\sigma_Q=(4.1)10^3 I_Q(Z)(\mu_P-\mu_Q)[2(1+M_Q/M_P)^2-1]^{3/2}\times e^{\mu_Q x}[1-e^{-(\mu_P+\mu_Q)x}]^{-1}. \quad (3)$$

The 90% upper confidence levels on σ_Q given by

TABLE II. Upper limit on the number of $\frac{2}{3}e$ quarks, $N_Q(\frac{2}{3})$, using a 90% confidence level on the observed events.

Fraction of quarks which would be within limits:	55%	22%
Counter 3	24	13
Counter 4	45	21

[8] This primary proton spectrum was fitted to the following results: F. B. McDonald and W. R. Webber, Phys. Rev. **115**, 194 (1959) for 5 and 18 BeV; D. Lal, Proc. Indian Acad. Sci. **A38**, 93 (1953) for 1.5×10^3 BeV; M. F. Kaplon, B. Peters, H. L. Reynolds, and D. M. Ritson, Phys. Rev. **85**, 295 (1952) for 5×10^3 BeV; and J. Outhie, C. M. Fisher, P. H. Fowler, A. Kaddoura, D. H. Perkins, K. Pinkau, and W. Walter, Phil. Mag. **6**, 89 (1961) for (6 to 40)$\times10^3$ BeV.

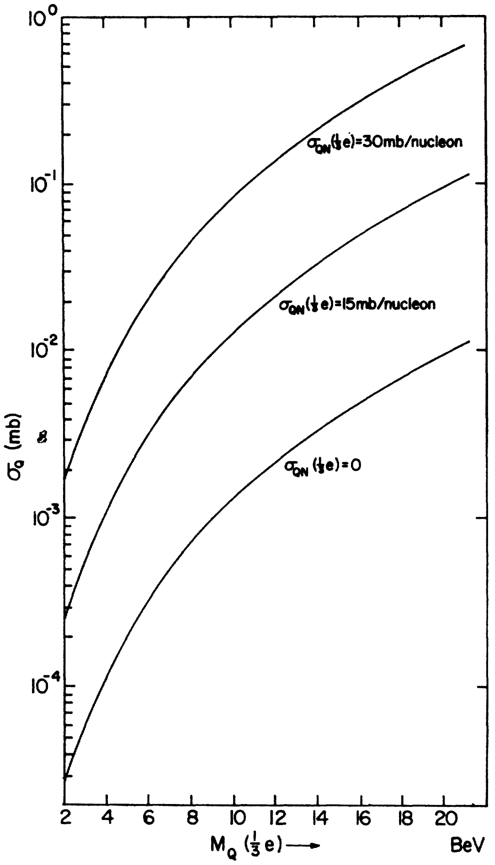

FIG. 7. Upper limit on the charge-$\frac{1}{3}e$ quark-production cross section per nucleon, σ_Q, versus the assumed quark mass $M_Q(\frac{1}{3})$ for several values of the effective quark-removal cross section, σ_{QN}.

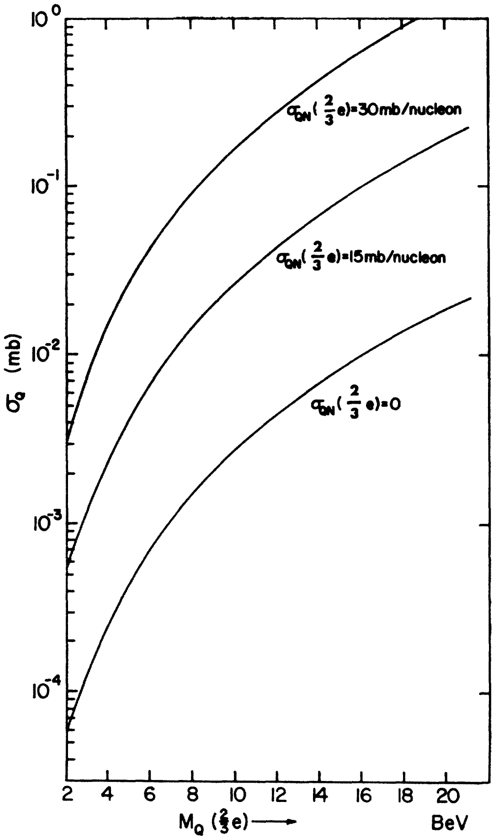

FIG. 8. Upper limit on the charge-$\frac{2}{3}e$ quark-production cross section per nucleon, σ_Q, versus the assumed quark mass $M_Q(\frac{2}{3})$ for several values of the effective quark-removal cross section, σ_{QN}.

Eq. (3) are plotted in Figs. 7 and 8 for the $\frac{1}{3}e$ and $\frac{2}{3}e$ cases, respectively; σ_Q is displayed as a function of the assumed quark mass $[M_Q(\frac{1}{3})]$ for several choices of the quark-nucleon-removal cross section σ_{QN}.

4. CONCLUSIONS

If quarks exist and are strongly interacting, then their production cross section might be $\sim$0.01 mb by analogy to the production of strange particles and antinucleons. From the accelerator experiments it was determined that the hypothetical quark would be a particle whose mass ≥ 2 BeV/c^2, and since a fractional charge cannot be carried away in a collision with an electron or a nucleon, it is probably a fair assumption that the effective cross section for quark removal from the relativistic region is less than 15 mb per nucleon. With these assumptions we have the following lower limits on the masses of the $\frac{1}{3}e$ and $\frac{2}{3}e$ long-lived quarks, if they exist:

$$M_Q(\tfrac{1}{3}) \geq 9 \text{ BeV}/c^2 \quad \text{and} \quad M_Q(\tfrac{2}{3}) \geq 7 \text{ BeV}/c^2.$$

The apparatus was sensitive for over 1100 h as compared with about 240 h in the previous experiment; the area-solid angle acceptance, however, was reduced by about 30% in this experiment. Even with the increased statistics and the additional independent counter we have not increased $M_Q(\frac{1}{3})$ very much (from 7 to 9 BeV/c^2 with the same assumptions). However, data from the new arrangement did yield a new and significant result for the $\frac{2}{3}e$-quark intensity. In order to obtain an order of magnitude improvement on the results of this experiment it would not suffice to perform the obvious improvements to increase the size of scintillators and to extend the running time; the problem is to increase the signal-to-noise ratio, and this will demand much more selective triggering requirements. This is especially true for a $\frac{2}{3}e$ search, since the charge-1e distribution is so large that its tail infringes on the $\frac{2}{3}e$-distribution's interval.

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