Search for Charge $\frac{1}{3}e$ and $\frac{2}{3}e$ Quarks in Cosmic Radiation near Sea Level*

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A large-area (3.35 m^2) scintillation-counter telescope consisting of six scintillation counters and four wide-gap spark chambers was arranged to detect single particles with charge $\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$ which might be present in the cosmic radiation near sea level. Upper limits to the vertical intensities of such particles are 9.8×10^{-11} cm^{-2} sec^{-1} sr^{-1} for charge $\pm\frac{1}{3}e$ and 1.6×10^{-10} cm^{-2} sec^{-1} sr^{-1} for charge $\pm\frac{2}{3}e$ at a 90% confidence level.

I. INTRODUCTION

SINCE 1964 a number of experimenters[1–21] have searched for energetic fractionally charged particles in the cosmic radiation. These experiments arose out of theoretical speculations[22,23] as to the physical existence of a triplet of particles corresponding to a fundamental representation of the symmetry group $SU(3)$. In the simplest version of the theory, such particles, called quarks, should have charges $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$ in units of electron charge. Gell-Mann[22] and deSwart[24] also have suggested the possibility of a low-mass diquark combination with charge $\frac{4}{3}$. To date no definitive evidence for the existence of quarks or quark compounds has been obtained.

II. APPARATUS

The present experiment was designed to be a "second generation" cosmic-ray search for fractionally charged quarks. The fractional charges were detected by their characteristic ionization energy loss dE/dx in scintillation counters. For example, a minimum-ionizing charge $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$ quark should produce, respectively, a dE/dx about 1/9 or 4/9 that of a minimum-ionizing particle of unit charge. In a scintillator array, however, there will be background events due to instrument noise, γ rays, soft showers, or fluctuations in dE/dx of the abundant particles of unit charge. In developing the apparatus, therefore, an effort was made to maximize the signal-to-noise ratio. Since very energetic cosmic-ray collisions occur rather infrequently, the sensitive area and solid angle of the detector were also made large.

The basic detector consisted of six liquid scintillation counters, four wide-gap spark chambers, a shower detector, and a range chamber as shown schematically in Fig. 1. Each scintillation counter consisted of a $72\times72\times6$-(in.)^3 UVT Plexiglas tank filled to a depth of 5 in. with a mineral-oil–based scintillator solution manufactured by Pilot Chemicals, Inc., Watertown, Mass.[25] The scintillation light trapped by total internal reflection was detected by six EMI 9618B 5-in. photomultiplier tubes with "Super S-11" cathodes, three on each of two opposite ends of each tank. Each of the tubes was optically coupled[26] to the scintillator through an intermediate volume of mineral oil acting as a light guide in order to keep variations in pulse height with location of the track in the scintillator to less than 10%. The six anode and six last dynode signals from the photomultiplier tubes on each counter were passively mixed to provide two outputs from each counter. The resolution of each counter was about 33% full width at half-maximum on particles of unit charge (see Fig. 3). This value is consistent with the resolution of 20% calculated from Symon-Landau statistics when appro-

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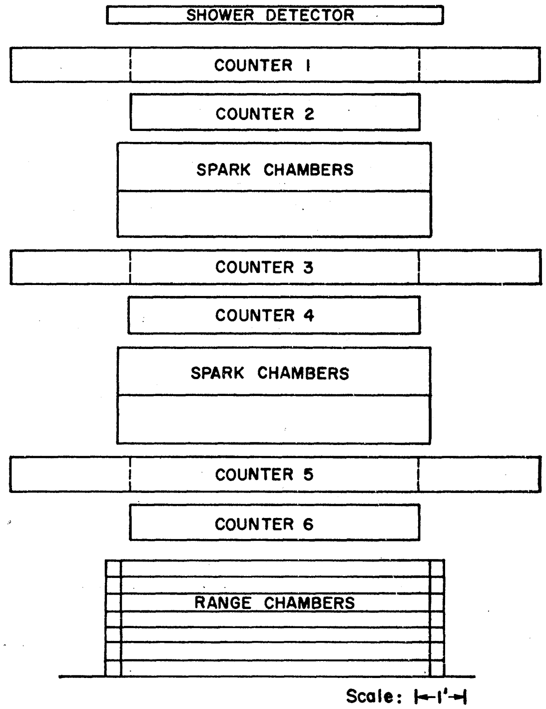

FIG. 1. Experimental arrangement to search for fractionally charged particles.

priately combined with variations of track length and the 10% variation in light-collection efficiency. The counter light guides were alternated such that no single particle could produce Čerenkov light in six guides simultaneously.

The spark chambers were used to ensure that each event of interest was caused by a single charged particle passing through the array. The spark-chamber gaps were $78\times78\times12$-(in.)[3] Plexiglas boxes filled with about 90% helium and 10% argon by volume. Each pair of gaps was driven by an eight-stage Marx generator, charged to 26 kV per stage, for a nominal output voltage of 208 kV with an output capacitance of approximately 1560 pF. The efficiency of the spark chambers was better than 95% for particles of unit charge which make angles less than 30° with the vertical. The gaps were photographed from a distance of 100 ft with mirrors which provided a stereo view of approximately 20°.

The response of the spark chambers to $\pm\frac{1}{3}$ charge quarks was studied by poisoning the He-Ar gas mixture with a small concentration of SF_6 and delaying the trigger pulse a known time interval. The electrons produced along the path of a normal charge-1 particle were removed by attachment to the SF_6 molecules. The frequency of thermal-electron attachment to a 1-Torr concentration of SF_6 is in the range 5.9×10^9 sec^{-1} [27] to 1.1×10^{10} sec^{-1}.[28] Using the lower or worst case value, a 9.3×10^{-5}-Torr concentration of SF_6 produces an attachment rate of 5.5×10^5 sec^{-1}. When this amount of SF_6 is added to the spark-chamber gas, it is calculated that only $\frac{1}{9}$ of the initial ionization electrons would remain after a 4-μsec delay. With the normal gas mixture, a 4-μsec delay produced no noticeable change in the spark-chamber tracks produced by particles of unit charge. With the addition of the SF_6 at 4 μsec, the brightness of the sparks was reduced and the discharges followed somewhat more tortuous paths. No appreciable loss of efficiency could be detected on these simulated $\frac{1}{3}$-quark tracks, however.

A shower detector was inserted in an effort to reduce the number of event triggers corresponding to soft showers or several particles passing through the apparatus. It consisted of 32 Plexiglas cylinders, 2 in. in diameter and 72 in. long, each filled with liquid scintillator and viewed at one end by an RCA 6655A photomultiplier. The 32 signals were mixed and arranged to trigger a threshold discriminator whenever two or more of the scintillator outputs were above a present level. The efficiency of this detector was inadequate to appreciably reduce the triggering rate, however, and it was not used for most of the data run.

The range chamber was provided for use in later experiments to search for charge $\pm\frac{4}{3}$ quark compounds to ensure that all particles of interest are of a sufficient energy to be minimum ionizing. It consisted of six

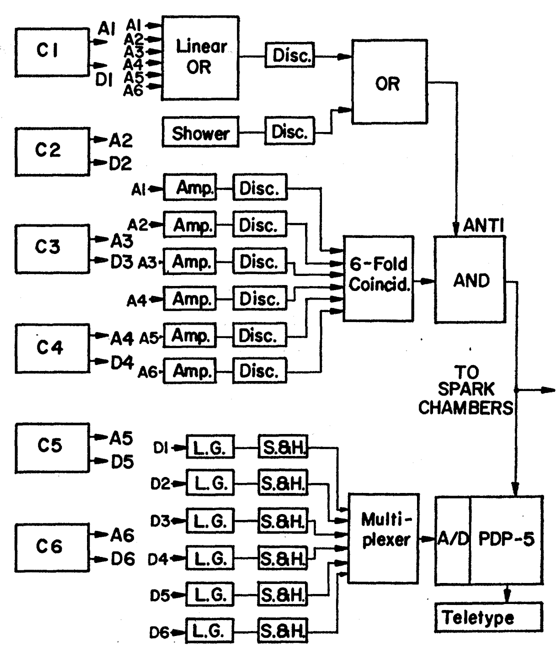

FIG. 2. Block diagram of electronic apparatus. Disc. represents a discriminator; Amp., an amplifier; L. G., a linear gate and pulse stretcher; and S. & H., a sample-and-hold circuit.

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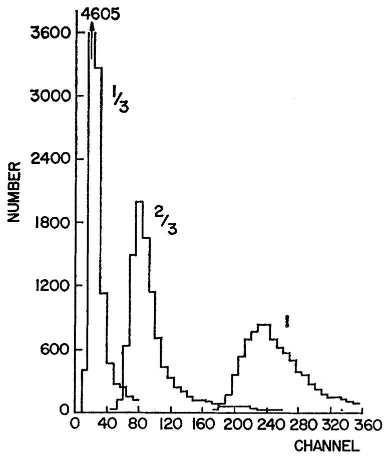

FIG. 3. Simulated $\frac{1}{3}$- and $\frac{2}{3}$-quark pulse-height distributions and the normal charge-1 distribution.

$78\times78\times2$-(in.)^3 spark chambers spaced between 6 in. of steel plates.

The total material in the array, not counting the range chamber, was approximately 115 g/cm^2. The area and solid angle of the telescope were such that about 100 cosmic-ray particles per second were sampled.

Figure 2 shows a block diagram of the electronic apparatus. Anode pulses were used for fast logic and pulse-height discrimination and the dynode signals were used for pulse-height analysis. An event trigger was generated if the peaks of all six counter pulses were in the range $0.06I_0<I<0.8I_0$, where I_0 represents the most probable signal due to a minimum-ionizing particle of unit charge, and if no veto from the shower detector was received. The logic settings were calibrated periodically by inserting light attenuators in front of each photomultiplier tube so as to cause the abundant singly charged particles to simulate the passage of particles with charge $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$. The light attenuators consisted of black Bakelite screens with holes spaced uniformly to allow only 1/9 or 4/9 the scintillation light to reach the tube photocathodes. Figure 3 shows simulated $\frac{1}{3}$- and $\frac{2}{3}$-quark pulse-height distributions together with the unattenuated distribution for particles of unit charge obtained from one of the counters.

With the $0.06I_0<I<0.8I_0$ logic settings, approximately 95% of the simulated charge-$\frac{1}{3}$ events and 85% of the charge-$\frac{2}{3}$ events were accepted. The resolving time of the six-fold coincidence circuit was about 37 nsec. After each sixfold coincidence, including those caused by singly charged particles, the electronics were gated off for 200 μsec to ensure that the spark chambers did not break down on residual tracks. This gate was installed for the last 60% of the data run. After each quarklike event trigger, the electronics were gated off for 2 sec to allow time for the Marx generators to recharge.

When a quarklike event trigger was generated, each anode signal was integrated and fed by way of a linear gate and pulse stretcher to a sample-and-hold circuit. These stored signals were then multiplexed to an analog-to-digital converter and sent to a PDP-5 computer operating on-line. For each event satisfying the selection criteria discussed below, the six pulse heights were immediately typed out together with the average pulse height P_a, rms deviation D_r, and the ratio of these quantities. Also, the pulse heights for each of the six counters, together with their average, were stored in seven histograms in the core memory of the PDP-5. The computer was programmed to permit the printout of these histograms on command. Events with a value of the ratio D_r/P_a greater than 40% were not printed and were not stored in the histogram plots. For each event, the six counter pulses were also differentially delayed and photographed on an oscilloscope as a check on the computer system and as a further check on good candidates for quark events.

For each quarklike event trigger, the spark chambers were photographed together with a set of binary coding lights providing the day, month, film roll, and event numbers as generated by the computer interface. The identical pattern of code lights was conveyed to the oscilloscope camera through plastic fiber optics light guides in order to avoid any identification ambiguities between the computer, spark chamber, and oscilloscope records.

A complete calibration of the entire apparatus was conducted before and after every 100 h of operation. Pulse-height distributions were obtained for each of the 36 5-in. photomultiplier tubes and the bias voltages were adjusted so that all tube outputs were the same to within 5%. The light attenuators simulating both the $\frac{1}{3}$- and $\frac{2}{3}$-charge quarks were inserted and the logic settings checked. The simulated events were also recorded on the PDP-5 and oscilloscope systems to determine the pulse height and timing characteristics of good quark events. Figure 4 shows typical distribu-

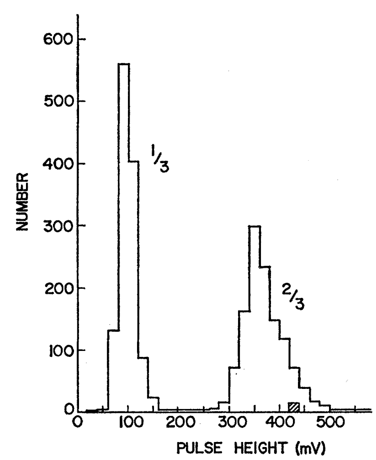

FIG. 4. Distributions of average values of simulated $\frac{1}{3}$- and $\frac{2}{3}$-quark events. Shaded event shows the location of the $\frac{2}{3}$-quarklike event.

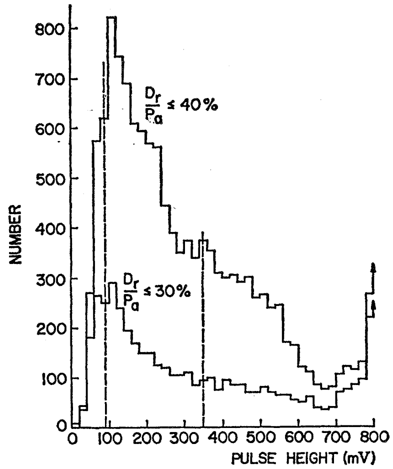

FIG. 5. Distributions of average pulse heights obtained for all event triggers with D_r/P_a less than 30% and 40%. The dashed lines show the positions of the peaks of the simulated $\frac{1}{3}$ and the $\frac{2}{3}$ distributions shown in Fig. 4.

tions of average pulse heights obtained for simulated $\frac{1}{3}$- and $\frac{2}{3}$-quark events.

III. RESULTS

The experiment has been operated for a total of about 1160 h at an altitude of 750 m. During this run, about 190 000 event triggers were generated which, because of the 2-sec Marx generator charging time, reduced the effective running time to 1050 h. The distributions of average pulse heights for all event triggers which had averages less than 0.8 that of a minimum-ionizing singly charged particle and D_r/P_a ratios less than 30% and 40% are shown in Fig. 5.

The spark-chamber records were analyzed for all events with D_r/P_a less than 30%. Since in Fig. 5 there are about 12 000 event triggers with D_r/P_a ratios less than 40% and only 3600 events with D_r/P_a ratios less than 30% in the pulse-height region less than 600 mV, it is clear that the 30% selection criterion greatly reduced the number of background-event triggers. Figure 6 shows the fraction of simulated quark events with D_r/P_a ratios less than a given percentage, X. As can be seen from Fig. 6, the event selection criterion of $D_r/P_a < 30\%$ accepted about 70% of the $\frac{1}{3}$ and about 80% of the $\frac{2}{3}$ simulated quark events.

In analyzing the spark-chamber photographs, events were accepted if they produced a single spark in at least one gap in each pair of spark chambers such that the sparks in the top and bottom pairs were aligned and located between fiducial lights showing the edges of the scintillators. All events with more than one track in any gap were rejected. A total of 12 events passed the specified spark-chamber criteria. Eleven of these events were rejected, however, after a reconstruction of the particle trajectories, based on the stereophotographs, showed they passed through only the front or rear edges of the spark chambers and missed the scintillators.

The pulse heights for the one remaining event, which fell in the $\frac{2}{3}$-quark pulse-height region, as shown in Fig. 4, are reproduced in Table I. Unfortunately, this event was obtained before the addition of the 200-μsec gate and, therefore, could have been caused by a shower of γ rays or some other source of the background events coming shortly after the passage of a normal singly charged particle. In this case, the spark-chamber tracks could have been produced along the residual ionization left by the passage of such a particle, rather than by a quark. A geometrical reconstruction of the trajectory of this event, however, showed that it did pass through a corner of counter 6, which correlates with the low signal from that counter. The oscilloscope record for this event was consistent with the computer output and confirmed that the general pulse shapes and timing characteristics were similar to those of a simulated quark event. No events were obtained in the $\frac{1}{3}$-quark pulse-height region.

These observations can be best expressed quantitatively in terms of upper limits on the expected number of quark events which would be statistically compatible. For the $\frac{1}{3}$-quark pulse region, where no event was observed, we take the 90% confidence upper limit[29] to be 2.30 events; that is, if 2.30 were the expected number of events, the statistical probability of observing zero events in our experiment would be $\exp(-2.30) = 0.10$. For the $\frac{2}{3}$-quark pulse region, where one possible event was observed, we take the 90% confidence upper limit to be 3.89; that is, if 3.89 were the expected number of events, the statistical probability of observing one or less events would be $(1+3.89)\exp(-3.89) = 0.10$.

In order to convert these event limits to upper limits on the vertical flux I_q of quarks at sea level for comparison with the results of others, it is necessary to make some assumptions about the angular distribution of quark intensity and the absorption of quarks in the atmosphere in order to compute the effective geometrical factor (area–solid-angle product) and altitude correction factor for our apparatus. In general, the number of particles per unit time detected by a cosmic-ray telescope is given by[30]

$$R = \int_\Omega \int_A I |\cos\theta| \, d\Omega dA \,,$$

TABLE I. Pulse heights for the event satisfying the spark-chamber and oscilloscope criteria. The mV scale is the same as shown in Figs. 4 and 5.

Date	Event	Counter signals (mV) 1	2	3	4	5	6	P_a	D_r/P_a (%)
7/5/68	5/360	406	436	510	443	417	342	426	12

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[30] D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton University Press, Princeton, N. J., 1949), pp. 330–333.

where I is the number of particles per unit time, area, and solid angle with energies sufficient to penetrate the detector; $d\Omega$ is the solid angle subtended by an area element on the top counter as seen by the area element dA on the bottom counter; and θ is the angle between the normal to the area element dA and the direction of $d\Omega$. For plane counters arranged parallel to each other in an array, this equation becomes

$$R=\int_{A_1}\int_{A_2} I r_{12}^{-2}\cos^2\theta dA_1 dA_2\,,$$

where A_1 and A_2 are the areas of the top and bottom counters, r_{12} is the distance between dA_1 and dA_2, and θ is the angle between r_{12} and the normal to the counters.

If it is assumed that the intensity $I(\theta,x)$ of quarks at atmospheric depth x, arriving with a zenith angle θ, is described by a one-dimensional diffusion equation for the absorption of the high-energy nucleon component and the generation and absorption of a quark component, then the quark intensity is given by

$$I(\theta,x)=\sigma_q N_A I_p(\mu_p-\mu_q)^{-1}\times[\exp(-\mu_q x\sec\theta)-\exp(-\mu_p x\sec\theta)]\,,$$

where σ_q is the average quark production cross section per nucleon in air, N_A is Avogadro's number, I_p is the primary cosmic-ray intensity of protons with sufficient energy to produce quarks, $\mu_p\cong 1/(120\text{ g/cm}^2)$ is the atmospheric absorption coefficient of nucleons having sufficient energy to produce quarks, and μ_q is the atmospheric absorption coefficient of quarks having relativistic energies such that their fractional charge can be detected by the dE/dx method. For most possible choices of μ_q, the inequality $|\mu_p-\mu_q|x\sec\theta\gg 1$ will be satisfied, since $\mu_p x\approx 8$. This condition implies that the expression in brackets will be dominated by the exponential term having the smaller μ. If we let μ be the smaller of μ_p or μ_q, then

$$I(\theta,x)\cong\sigma_q N_A I_p(|\mu_p-\mu_q|)^{-1}\exp(-\mu x\sec\theta)\,.$$

To the same approximation, the vertical quark intensity at sea level, I_q, is

$$I_q\equiv I(0,x_0)\cong\sigma_q N_A I_p(|\mu_p-\mu_q|)^{-1}\exp(-\mu x_0)\,,$$

where $x_0=1033$ g/cm^2 is the atmospheric depth at sea level. The quark intensity at other depths and directions can then be related to the vertical intensity:

$$I(\theta,x)\cong I_q\exp(\mu x_0)\exp(-\mu x\sec\theta)\,.$$

The quark counting rate $R_q(x)$ in a detector at atmospheric depth x is given by

$$R_q(x)=I_q\left[\exp(\mu x_0)\int_{A_1}\int_{A_2}\exp(-\mu x\sec\theta)\times r_{12}^{-2}\cos^2\theta dA_1 dA_2\right].$$

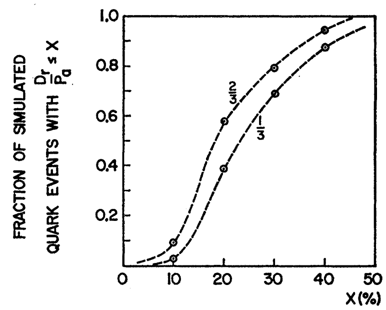

FIG. 6. Fraction of simulated quark events with D_r/P_a ratios less than X percent. Statistical error bars are smaller than the open circles.

The expression in brackets may be regarded as the *effective* geometrical factor for the apparatus which is weighted by absorption in the atmosphere and normalized such that I_q is the vertical intensity at sea level.

If the quark mass is assumed much larger than the nucleon mass, then it seems likely that $\mu_p>\mu_q=\mu\cong 0$, since the fractional charge could not be neutralized and only a small fraction of the quark kinetic energy would be lost in each nuclear collision.[31] Assuming $\mu=0$, the geometrical factor for this experiment was 0.95 m^2 sr. If the scarcity of quarks is attributed to some reason other than a high mass, then the quark might have a mass less than the nucleon mass. In this case, quarks might be brought to nonrelativistic energies where our experiment would not detect their fractional charge after only a few nuclear collisions. If $\mu_q>\mu_p\cong 1/(120$ g/cm$^2)$, then the effective geometric factor for this experiment at 750 m above sea level is 1.5 m^2 sr. We have presented the basis of our area–solid-angle calculation because, for most of the recent cosmic-ray quark searches, we are unable to reproduce geometry factors as high as the published values.

Using a geometric factor of 0.95 m^2 sr corresponding to negligible atmospheric quark absorption ($\mu_q=0$), we find the upper limits to the vertical sea-level quark intensities to be $I_q<9.8\times10^{-11}$ cm^{-2} sec^{-1} sr^{-1} for $\frac{1}{3}$ quarks (0 events) and $I_q<1.6\times10^{-10}$ cm^{-2} sec^{-1} sr^{-1} for $\frac{2}{3}$ quarks (1 event) at a 90% confidence level. If we assume that relativistic quarks are strongly absorbed in the atmosphere ($\mu_q>\mu_p\cong 1/(120$ g/cm$^2)$), the above limits should be decreased by a factor of $\frac{2}{3}$. These results are consistent with the published values of Fukushima *et al.*[21] who obtained 5.0×10^{-11} cm^{-2} sec^{-1} sr^{-1} for $\frac{1}{3}$ quarks, and of Ashton *et al.*[19] who obtained 8.0×10^{-11} cm^{-2} sec^{-1} sr^{-1} for $\frac{2}{3}$ quarks at sea level. The above flux limits neglect the effect of quarks interacting in the telescope itself. If the quark interaction mean free path is about 80 g/cm^2, interactions in the apparatus would cause many quarks not to be recognized and increase the above flux limits by about a factor of 4.

[31] R. K. Adair and N. J. Price, Phys. Rev. **142**, 844 (1966).

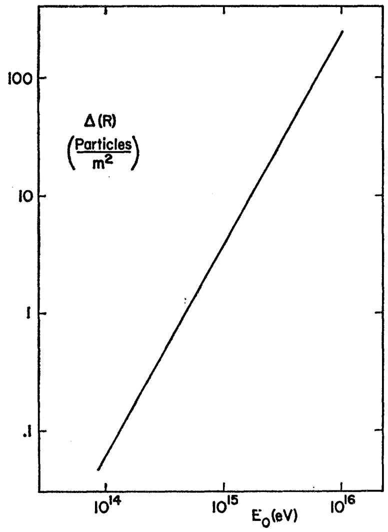

FIG. 7. Density of air-shower particles at R as a function of incident proton energy.

IV. DISCUSSION

The quarklike event discussed above is not inconsistent with the background of this experiment, and, therefore, no conclusive evidence for the existence of quarks has been obtained.

The primary weakness of this type of a search is that any quark accompanied by another particle in passing through the detector is rejected. Since very-high-energy cosmic-ray collisions usually produce extensive showers of photons and electrons in the atmosphere, it is of interest to estimate the likelihood that a quark which passes through the detector will be accompanied by an air-shower particle.

In order to make such an estimate, it is assumed that quarks are produced in energetic proton-nucleon collisions, and that their angular distribution in the center-of-mass system is symmetric in the forward and backward directions but not necessarily isotropic. The lab angle of a cone containing on the average half of the quarks is then given approximately by

$$\theta_{1/2}=\tan^{-1}[(P_t/M_q)(2M_p/E_0)^{1/2}].$$

M_p and M_q are the rest masses of the proton and quark, respectively, E_0 is the incident proton energy, P_t is the quark transverse momentum in the center-of-mass system, and all quantities are in energy units. It is further assumed (a) that the collision occurs after the proton traverses one nuclear mean free path (about 80 g/cm^2 of atmosphere,[32] which corresponds to an altitude of about 16 km above Tucson), (b) that the quark rest mass is about 10 GeV/c^2, and (c) that the quark transverse momentum is about 0.5 GeV/c.[33] These assumptions permit the minimum linear displacement R of half of the quarks from the core of the air shower to be estimated as a function of incident proton energy. Further assuming that about half of the incident proton energy goes into secondary particle production[32] and that about 10 secondaries are produced,[34] of which three are π^0 mesons, a primary proton of energy E_0 could be expected to produce about six photons from π^0 decays, each with an average energy of the order of $E_0/40$. If these photons initiate an electromagnetic cascade such that the lateral structure of the shower is similar to that which would be produced by a single photon with energy $3E_0/20$, then the lateral density distribution of shower electrons and photons can be calculated[35] as a function of distance from the shower core and E_0. Figure 7 shows the density of particles produced at the distance R from the shower core as a function of incident proton energy.

As can be seen from Fig. 7, a 2×10^{14}-eV primary proton produces a particle density at the distance R of about 0.2 particles/m^2. Therefore, the detector is largely insensitive to any heavy quarks which are produced in cosmic-ray collisions with energies greater than this value. It should be noted, however, that since the intensity of primary protons with energies greater than 2×10^{14} eV is about 2×10^{-8} cm^{-2} sec^{-1} sr^{-1},[36] an experimental run much longer than 1000 h would be required with the area–solid-angle product of the present apparatus in order to reliably detect quarks produced by collisions greater than this energy, even if the quark production efficiency were as high as 1%.

If quarks are light particles with greatly inhibited production cross sections, the effect of atmospheric attenuation could be significant. Currently, a mountain-altitude (2740 m) laboratory is being instrumented for further searches for $\pm\frac{1}{3}$, $\pm\frac{2}{3}$, or $\pm\frac{4}{3}$ charged particles.

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