SEARCH FOR QUARKS IN COSMIC RAYS*

R. C. Lamb, R. A. Lundy, T. B. Novey, and D. D. Yovanovitch
Argonne National Laboratory, Argonne, Illinois

(Received 7 October 1966)

A search for fractionally charged particles (quarks) in cosmic rays has been conducted at the Argonne National Laboratory (1000 g/cm^2 of atmosphere). The technique used is similar to that employed in previous cosmic-ray searches.[1] Measurements are made of the ionization of particles traversing a counter telescope. The telescope has an acceptance of 0.4 m^2 sr and has been operated for 1750 h. From this experiment we find upper limits for particles with either a $\frac{1}{3}$ or $\frac{2}{3}$ charge lower than previously published values.[1,2]

Figure 1 is a sketch of the counter telescope. Counters 1 through 6 are scintillation counters. Counters 1 and 2 are $1\frac{1}{2}$ in. thick, 36 in. ×36 in. plastic scintillators viewed from above by four 5-in. photomultipliers. Counters 3-6 are liquid scintillators 4 in. thick, 46 in. ×46 in. Each liquid scintillator is viewed around its perimeter by eight 5-in. photomultipliers. The individual resolution of the six scintillators for minimum-ionizing particles ranges from 26 to 40% full width at half-maximum.[3] Tests of the resolution of the scintillators with 9/10 of the light masked out[4] (approximately simulating charge $\frac{1}{3}$ particles) show no appreciable change of the resolution. Counters P_1 and P_2 are proportional counters constructed from modules. A module is a thin-walled aluminum box 4 in. ×4 in. ×60 in. with a 7-mil center wire. P_1 and P_2 consist of six modules each. The gas filling is 90% argon-10% methane, flowed continuously through both counters. The proportional counters have a uniform response to gamma rays to better than 3% over 90% of their area. Their linearity has been checked with gamma rays of various energies and found to be ±5% in the region of interest. The resolution of both P_1 and P_2 to minimum-ionizing particles is 56%. A charge one particle passing through P_1 or P_2 forms about 1000 ion pairs in the gas; therefore the resolution of the proportional counters is presumed to be independent of ionization over the range of interest.

The acceptance of the telescope is 0.84 m^2 ×0.48 sr. The total thickness of material in the telescope is 60 g/cm^2. Immediately above the apparatus is a roof 20 g/cm^2 thick. It is possible that a quark traversing the 80 g/cm^2 of material may produce one or more charged particles. We are not sensitive to such events.

The pulse heights of the eight counters (1 through 6, P_1 and P_2) are displayed on a dual-beam oscilloscope and photographed on 35-mm film. The oscilloscope is triggered by a fast logic system which requires that a pulse between 0.035 and 0.75 minimum is coincident in each of the six scintillation counters. The pulse heights expected from $\frac{1}{3}$ and $\frac{2}{3}$ charged particles are 0.11 and 0.44, respectively. P_1 and P_2 are not part of the triggering logic.

The gain of the system is calibrated periodically by accepting minimum ionizing particles as triggers. Variations in the gain are less than ±5% for periods of time the order of a week.

The oscilloscope photographs for both calibration runs and data runs are measured on a precision digitized measuring device. A single particle traversing the telescope will produce pulses of similar heights in the seven traversed counters. This correlation in pulse

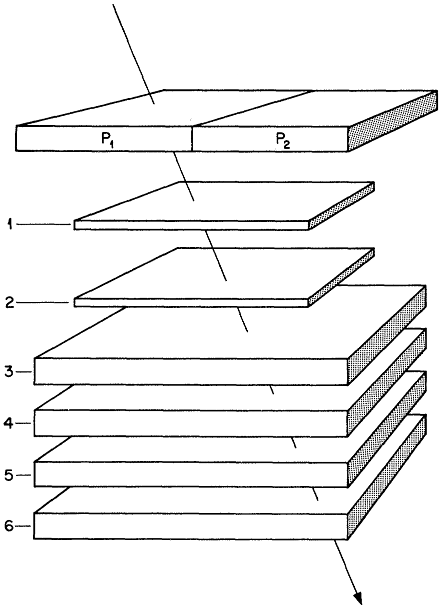

FIG. 1. Sketch of the counter telescope employed in this experiment. Counters 1 through 6 are scintillators; counters P_1 and P_2 are proportional counters. Dimensions of all counters are given in the text. The arrow drawn indicates a cosmic-ray trajectory. The drawing is to scale.

heights is not expected to be present for background events. We test for the correlation by computing for each oscilloscope photograph the following numbers:

$$C=\sum_{i=1}^{6}\left(\frac{m-h_i}{S_i m}\right)^2, \quad D=C+\left(\frac{m-h_7}{S_7 m}\right)^2,$$

where the h_i are the individual normalized pulse heights of the seven counters, m is the weighted average of the seven pulse heights, and the S_i are the percentage half-widths at half-maximum of the counters. From our tests of the resolution of the counters with 9/10 of the light masked out, we know that the S_i are independent of h_i over the ionization range of interest. The correlation in pulse heights in the six scintillators is measured by C; D tests the correlation in pulse heights for all seven counters. By selecting events with low C and D values we obtain a purified sample of events, rejecting strongly the uncorrelated background while retaining with good efficiency any signal.

Figure 2 shows the result of applying the criteria $C < 6$ and $D < 9$ to calibration runs with minimum-ionizing particles; the distribution of average energy losses gives the resolution function of our apparatus, 20% full width at half-maximum. With these selection criteria (35 ± 2)% of the cosmic-ray minimum-ionizing particles are accepted.[5] The peak of the resolution function occurs at 1.05 minimum rather than 1.00 because, in normalizing the individual counter pulse heights, we have used the most probable energy loss rather than the average.

By applying these same selection criteria to our data, we obtain the events shown in Fig. 3(a). We interpret the peak around 0.65 minimum as the low-energy tail for charge-one particles cut off by the triggering logic requirement that all scintillator pulses be less

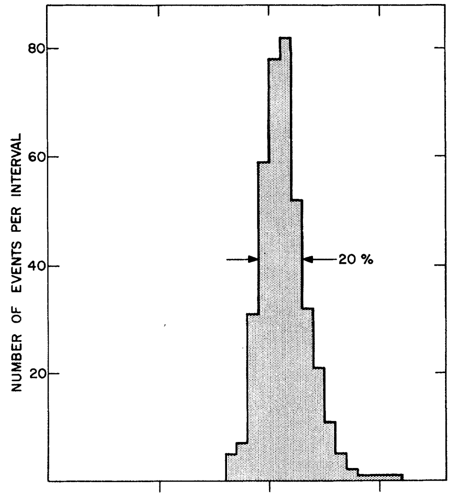

FIG. 2. The resolution function of the telescope obtained with minimum-ionizing particles. Selection criteria testing the correlation in pulse heights of the individual counters have been applied which select (35 ± 2)% of all triggers. This same resolution function is applicable to charge $\frac{1}{3}$ and $\frac{2}{3}$ particles.

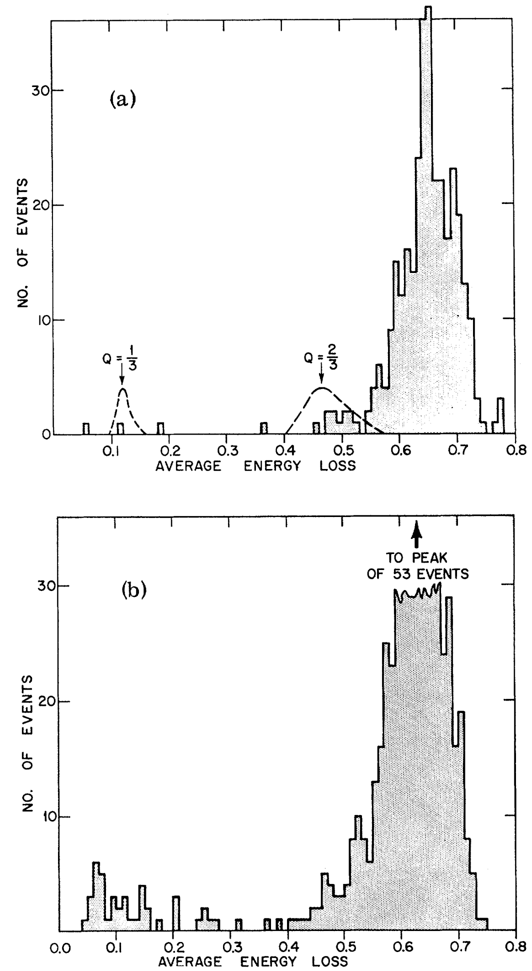

FIG. 3. Data events which satisfy the correlation tests. (a) Shows the events remaining when the correlation in pulse height in all seven counters is tested. The dotted curves are the resolution functions appropriate to charge $\frac{1}{3}$ and $\frac{2}{3}$; there is no evidence for particles of either charge. (b) Shows the events remaining when the correlation of the six scintillation counters is tested.

Table I. Upper limits on $\frac{1}{3}$ and $\frac{2}{3}$ quark flux as determined from data of Fig. 3(a). The limits are given for two different assumptions, A and B, which are explained in the text.

Quark charge	Possible events seen in data	Upper limit with 90% confidence	Flux ($\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$) A	B
$\frac{1}{3}$	$\leq$ 1 event	$\leq$ 4 events	$\leq 0.45\times10^{-9}$	$\leq 1.2\times10^{-9}$
$\frac{2}{3}$	$\leq$10 events	$\leq$14 events	$\leq 1.6\times10^{-9}$	$\leq 4.2\times10^{-9}$

than 0.75 minimum. In this figure the resolution function appropriate to charge $\frac{1}{3}$ and $\frac{2}{3}$ is shown by dotted lines. In the $\frac{1}{3}$ charge region there is at most one event. In the $\frac{2}{3}$ charge region there are at most ten events, all of which may be ascribed to the low-energy tail of the charge-one distribution. To establish an upper limit we have chosen to regard all ten events as possible $\frac{2}{3}$-charge quarks. Figure 3(b) shows the events with $C < 6$ and no selection on D. The only requirement on the proportional counters was that a measurable pulse be present in one of them. These six-counter data have obviously poorer sensitivity, and illustrate the general shape of the background.

Using the numbers from the seven-counter data [Fig. 3(a)], we have calculated the upper limits on the relativistic quark flux, with two different assumptions: (A) The quark does not interact in or immediately above our apparatus to produce charged particles, or (B) the quark may interact in or near our apparatus with an interaction length of 80 g/cm^2. Table I summarizes our results.

We wish to thank Don Hodges for the automatic measurement of our calibration data using the Argonne CHLOE System.[6] We are indebted to Aspasia Georgoulakis for the writing and execution of the computer programs used in the data reduction. We wish to thank the many Argonne National Laboratory technicians and film scanners who helped in the preparation and execution of this experiment.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] A. W. Sunyar, A. J. Schwarzchild, and P. I. Connors, Phys. Rev. 136, B1157 (1964); T. Bowen, D. A. DeLise, R. M. Kalbach, and L. B. Mortara, Phys. Rev. Letters 13, 728 (1964); D. A. DeLise and T. Bowen, Phys. Rev. 140, 458 (1965); H. Kasha, L. B. Leipuner, and R. K. Adair, Phys. Rev. 150, 1140 (1960). We interpret the rates presented in this last article in terms of upper limits on the quark flux.

[2] The limit for $\frac{2}{3}$ charge presented in this paper is somewhat higher than the most recent work of the Brookhaven National Laboratory-Yale group: H. Kasha, L. B. Leipuner, T. P. Wangler, J. Alspector, and R. K. Adair, private communication.

[3] Our source of minimum ionizing particles is the cosmic-ray flux which at this elevation is composed of approximately 90% muons, all of which are essentially minimum ionizing.

[4] The technique of masking out light to simulate quarks was first employed by L. B. Leipuner et al., Phys. Rev. Letters 12, 423 (1964) and by T. Bowen et al., Phys. Rev. Letters 13, 728 (1964).

[5] No correction has been made for the fact that ~10% of the cosmic flux are electromagnetic showers and therefore would presumably not fit the hypothesis of a single charged particle traversing the telescope.

[6] D. Hodges, Argonne National Laboratory Applied Mathematics Division Technical Memorandum No. 61, 1963 (unpublished).