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Search for Relativistic Charge-$\frac{2}{3}e$ Quarks in the Cosmic Radiation*

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A multilayer liquid scintillation detector telescope of aperture 0.51 m^2 sr combined with a flash-tube track detector has been used to search for relativistic charge-$\frac{2}{3}e$ quarks in the cosmic radiation. The results set an upper limit on the vertical intensity of such particles of 2.2×10^{-6} sec^{-1} m^{-2} sr^{-1} at a 90% confidence level.

I. INTRODUCTION

Because of the appealingly simple manner in which the quark model describes the structure of baryons and mesons[1-3] there have been many experiments performed to search for the fractionally charged fundamental particles which form the basis for this model. Results of these searches at accelerators[4,5] have been negative to date, indicating that either these particles do not exist as separate entities or, that their masses are so great that their production threshold lies above the beam energies now available. Many searches have also been carried out for quarks produced in the cosmic radiation,[6-21] where one may study interactions of extremely high-energy protons with atmospheric matter, but unfortunately the rate of such interactions decreases rapidly with increasing energy and most of these have also yielded null results. One unique experiment observing particles in cores of extensive air showers has reported observation of several $\frac{2}{3}e$-charge particles,[10] but there have been several objections raised to the interpretation of these measurements.[22-25]

The experiment we report was motivated by a somewhat preliminary account of observations of Ashton *et al.*[7] of cosmic-ray events which appeared to be interpretable only as particles of fractional charge traversing a cosmic-ray telescope with a flux about equal to the upper limits placed by several null experiments reported at the same time. At the time it seemed desirable to check such an important observation and moreover while the experiment was in progress the desirability of further experiments of this type was suggested by the comments of Adair and Kasha[22] that the positive results of Cairns *et al.*[10] using cloud-chamber detectors indicated that such particles should also be observable with scintillation counter telescopes. During the period in which we made such a check, the final report by Ashton *et al.*[8] as well as a number of somewhat similar experiments[9,11,12,18,20] were published, all of which conclude that no quarks have been observed. Nevertheless in checking the observations of Ashton *et al.* we have introduced a number of refinements in our apparatus and procedures which make our null result one which we feel can be stated with a high degree of confidence even though we are not able to place a better limit on flux than other experiments have concluded.

A brief tabulation of the improvements which we incorporated into our array will be presented here. Thick liquid scintillation detectors of high energy resolution are used in place of the thin plastic scintillators used by most previous groups.[26] The length/width ratio of these detectors is somewhat greater than two, which enhances the probability of observing a quark unaccompanied by other particles. No light guides, in which Čerenkov signals may be generated, are used. The ratio of signal amplitudes from the two ends of the scintillation detectors is also recorded. This permits a rough determination of the particle path which can be compared with the data from the flash-tube track detector. A check of the consistency of these redundant methods proves to be a powerful way to distinguish authentic single-particle events from small-shower background events. Logic circuits have been added to record the time in microseconds between each event and the last previous traversal of the scintillation telescope by a muon, up to 2000 μsec. A circuit has also been added to indicate the passage of a particle through the array during the 8-μsec interval between the traversal of a triggering particle and the application of the high-voltage pulse to the flash-tube array. A pulse-height analyzer is used to continuously monitor the muon flux passing through the array so that changes in gains of amplifiers or photomultipliers can be readily noted. In addition, to reduce the measurements to a relative basis, the full data recording array is used to record the signal from a muon every 10 minutes (later every 15 minutes) so that there is a continuous record of the appearance of relativistic charge-e particles traversing the array.

II. APPARATUS

The experimental arrangement is shown in Fig. 1. The five layers of scintillation detectors are connected so that a trigger signal is generated whenever simultaneous signals are observed in all five detectors with pulse heights in the range $0.3E_0$ to $0.8E_0$, where E_0 is the pulse height corresponding to the peak of the muon pulse-height distribution. Twenty layers of flash tubes are arranged in sandwich fashion above and below and between the scintillators to determine particle trajectories.

A. Liquid Scintillation Detector Telescope

The individual scintillation detectors are tanks made of ultraviolet transmitting acrylic plastic filled with mineral oil based liquid scintillator, making a slab with a sensitive region 135 cm long ×57 cm wide×12 cm deep. There are no structural members inside the sensitive region and the bottoms of the tanks show negligible curvature. Light collection is by total internal reflection at the boundary of the plastic tank and the air. The tanks are wrapped in bright aluminum foil which is not in optical contact with the plastic to conserve some of the light which strikes the tank boundary beyond the critical angle, and the assembly is wrapped with light gauge black polyethylene sheet to make a light tight housing. At each end of each detector there is a group of three 5-in.

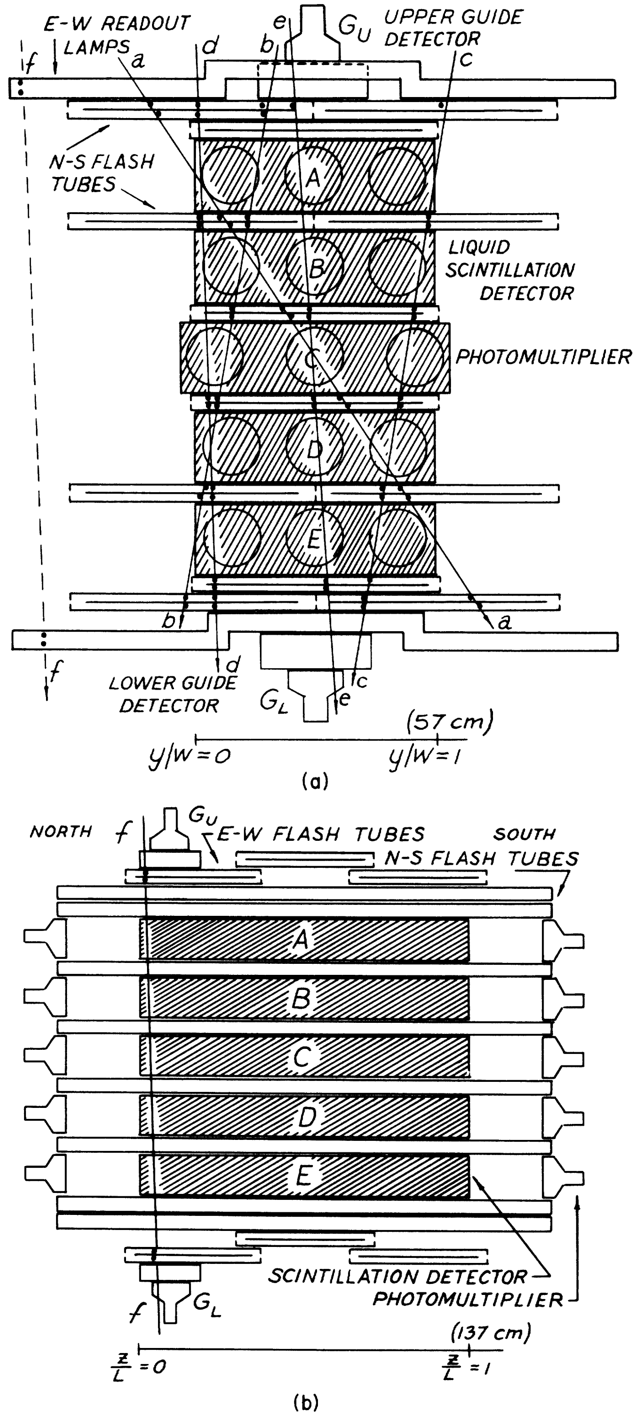

FIG. 1. (a) Experimental arrangement, front view. (b) Experimental arrangement, side view.

diameter photomultipliers placed with a 30 cm separation between photocathode and the edge of the scintillating region in order to assure reasonable uniformity of response for particles passing through different regions of the tank.

The "response function" for a representative detector, that is the relation between particle path location and signal amplitude ratio, is given in Fig. 2(a). It will be noted that there is about a factor of 2.7 variation in signal amplitude ratio for particles traversing the extreme ends of the detector. Figure 2(b) shows that the composite signal obtained by summing the pulses from the two ends of the detector varies only by ±5%. It is readily seen that from a knowledge of the location of a particle path it is possible to determine from Fig. 2(b) the energy deposited in a detector without uncertainty due to variations in the light collection efficiency. In this experiment the particle path location is of course given by the flash-tube data, and it can also be determined in a redundant manner from the ratio of signal amplitudes from the two ends of the detector, using Fig. 2(a).

B. Conversi-Gozzini Flash-Tube Track Detector

The choice of flash tubes as a particle detector was based on a number of considerations. These tubes, invented by Conversi and Gozzini,[27] are the forerunner of the present day spark chamber invented by Fukui and Miyamoto,[28] and have lower efficiency and poorer spatial resolution than spark chambers. They are simple electrode-less glass tubes filled with pure neon gas at a pressure of 0.6 atm. If a charged particle traverses the tube and a strong electric field is immediately applied by means of external electrodes, a visible discharge occurs and spreads the length of the tube. The flash is ordinarily recorded photographically through a window at the end of the tube. They have been developed by Wolfendale and his colleagues at Durham University in collaboration with Robertshaw at International Research and Development Corporation at Newcastle to the point where they represent an elegant device that is relatively simple and inexpensive, quite rugged, and capable of being operated in a useful way with relatively long delay times (up to 30 μsec) between particle traversal and application of the high-voltage pulse. Since this experiment has as a secondary objective the accumulation of experience with hardware being used with an array of 50 000 such flash tubes in a deep undergound experiment,[29] and since it was formulated to a degree as an experiment to check the measurements of Ashton *et al.*[7] in which flash tubes were used, it was decided to use an array of about 1000 flash tubes arranged as indicated in Fig. 1.

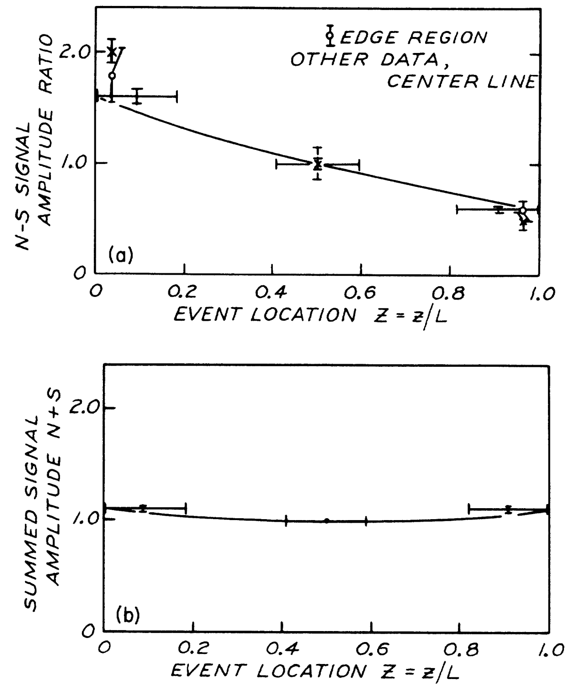

FIG. 2. (a) Scintillation detector response function. (b) Summed signal amplitude vs event location for scintillation detector.

The electrode structures used in the large scale experiment noted above could not be stacked in an ideal fashion for the present experiment, but a configuration was devised giving 20 layers of flash tubes for most particles traversing the telescope and at least 12 layers in the worst case. Two layers above the telescope and two layers below are oriented in the east-west direction while the remaining 16 layers are in the north-south direction. Flashes from the north-south tubes are recorded directly by a camera, which also records the flashes from the east-west flash tubes indirectly using a system of photoelectric cells, memory circuits, multiconductor cables, and incandescent readout lamps developed for the 50 000 flash-tube array mentioned above.

It was hoped that the fact that the sensitive area of the flash-tube array extends beyond the aperture of the scintillation detector telescope would help to understand the detailed nature of the very numerous background events classed as weak showers by Ashton *et al.* To a large extent this expectation has been fulfilled, though it must be acknowledged that the small number of east-west flash-tube layers and the fact that there are non-overlapping areas for the two sets of flash tubes leads to some problems in interpretation of the data.

The measured "layer efficiency" for relativistic cosmic-ray muons, i.e., the probability of producing a flash in a close-packed single layer of flash tubes under conditions of normal incidence, is 82% in the present experiment, omitting corrections for slight departure from normal incidence. There is a geometrical upper limit of about 86% for layer efficiency set by the finite thickness of the glass wall of the flash tubes. Particles incident obliquely are detected with higher efficiency. From analysis of the mechanism of the flash-tube discharge the estimated uncorrected layer efficiency for particles of charge $\frac{2}{3}e$ is 75%.

Since the "seeds" of a flash-tube discharge produced by a charged particle disappear rather slowly by processes of diffusion and recombination in the neon gas, there is a possibility of observing tracks resembling those expected for lightly ionizing particles produced by particles unrelated to the triggering event which traversed the array at an earlier time. The "muon history circuit" described in Sec. IIC has been devised to guard against spurious events of this character.

C. Circuits for Data Recording and Monitoring

A block diagram of the linear and logic electronic circuits used in the measurements is shown in Fig. 3. A dual-beam oscilloscope with linear gate circuits is used with a number of delay lines to display sequentially the pulses from 10 fast amplifiers connected to the north and south ends of the five scintillation detectors during the 2 μsec following the occurrence of a coincidence trigger. Summed signals from each scintillation detector are fed to discriminators and a coincidence circuit which delivers an output trigger whenever all five detector signals are in the range $0.3E_0 \leq E \leq 0.8E_0$, the resolving time being 0.2 μsec. After a delay of 8 μsec the flash-tube electrodes are pulsed. Separate cameras record the pulses displayed on the oscilloscope and the two stereoscopic views of the flash-tube array.

Every 10 or 15 minutes a single muon calibration event triggered by a relaxed discriminator requirement $E \geq 0.3E_0$ is recorded by the telescope, with an identifying marker on the camera frame to designate it as a muon event. The flash-tube high-voltage pulse is inhibited to minimize dead-time effects. There is also continuous recording of the summed muon signals from four of the five scintillation detectors on a pulse-height analyzer, gated by fivefold coincidences of signals with $E \geq 0.3E_0$. An automatic advance to the next

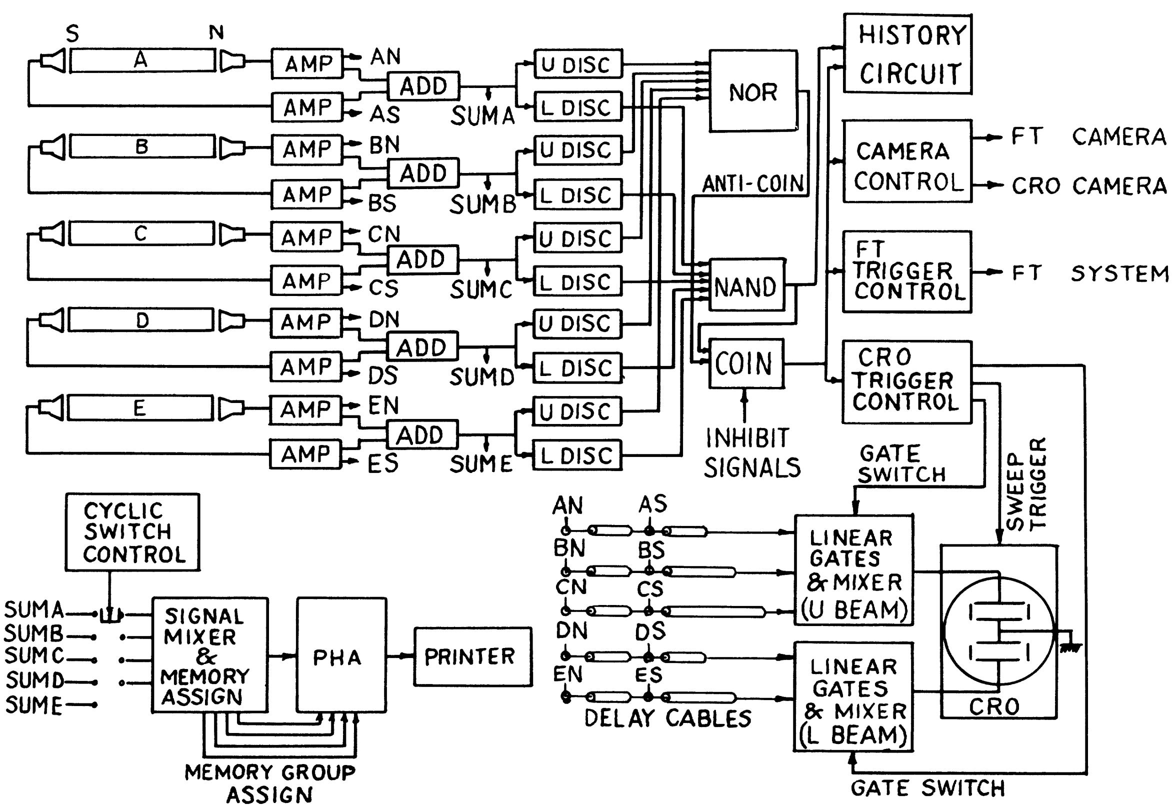

FIG. 3. Block diagram.

detector to be monitored occurs at 40-minute intervals, with a printout of the accumulated spectra every five hours.

On each photograph of the flash-tube array appears information on the elapsed time since the last traversal of the telescope by a muon. This information is recorded in the form of a three decimal digit display number giving this time interval in units of 2 μsec. An overflow lamp indicates events in which this time interval exceeds 2000 μsec. For almost all events this lamp is on, indicating that flash-tube patterns cannot be attributed to passage of a recent unrelated particle through the telescope. Another lamp identifies cases where a particle traversed the telescope during the 8-μsec interval between the triggering signal and the high-voltage pulse to the flash-tube electrodes. No potential quark signals are found to be accompanied by signals from this lamp circuit.

Systematic balancing of the photomultipliers has been carried out at the beginning and midpoint of the three-months measurement interval, with remedial balancing of single detectors as drifts are detected in monitoring data.

III. ANALYSIS OF RESULTS

Table I summarizes the results of approximately three months of continuous running of the array. Despite the rather restrictive requirement placed by the discriminators and coincidence circuit it is observed that triggers occur at a rate of 0.83 per hour. Thus from the data provided by the scintillation detector telescope alone we observe 963 events which have the signature expected for quarks. However the track detector results make it clear that most of these are not associated with single particles traversing the array as indicated in following sections.

A. Shower Events (QSh)

Of the 963 events which triggered the logic system (Q events), over 70% are found to be small showers. These are not showers in the usual sense, because if any scintillation detector is penetrated by even two electrons the event is surely rejected by the logic circuits. The energy deposited in the scintillation detectors usually seems to enter from the sides judging from the flash-tube photographs and from the fact that a shower detector placed over the top of a similar array used by Krider, Bowen, and Kalbach[9] did not appreciably reduce the trigger rate. In our experiment the majority of the showers are recognized by a few tracks observed in the flash-tube array that overhangs the sides of the telescope aperture. The "track reconstructions" from the scintillation detector data for these events have quite random patterns. In addition a histogram of the mean energy deposition for these showers shown in Fig. 4 indicates that the chance injection of signal energy from these events may occur anywhere in the window and thus bears no relation to the ionization of penetrating particles of single or frac-

TABLE I. Experimental results.

Total effective running time		1157.97 hours
Potential quark events (Q)	963	
Shower events (QSh)	685	
Events with no track in aperture (QNT)	118	
Events with a single track in aperture (QT)	160	
Events rejected as edge events	30	
Events rejected for low efficiency	3	
Events rejected for inconsistency of flash-tube and scintillator data	12	
Events with a clear single track which survive screening process	115	
Noise triggers [recognized by oscilloscope waveforms (N)]	91	
Muon calibration events (C)	7428	
Single-particle events	92%	
Shower events	8%	
$ABCDE$ coincidence rate $E \geq 0.3E_0$	26.1 sec^{-1}	
$ABCDE$ coincidence rate $0.3E_0 \leq E \leq 0.8E_0$ (i.e., Q trigger rate)	0.83 h^{-1}	
C trigger rate	$4 \sim 6$ h^{-1}	
Guide detector coincidence rate $G_U ABCDEG_L$ $E \geq 0.3E_0$	0.08 sec^{-1}	

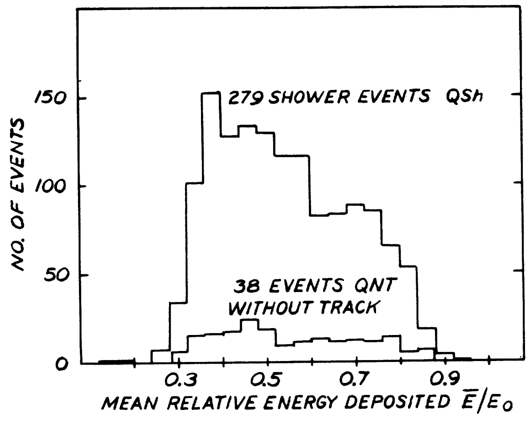

FIG. 4. Spectrum of energy deposited for shower and no-track events. E_0 is the most probable energy loss for a relativistic muon.

tional charge.

It is of course acknowledged that an experiment such as this is not capable of recording the passage of quarks accompanied by shower particles passing through the scintillation detectors, although the use of somewhat long and narrow scintillators is possibly more favorable for seeing quarks in showers than a square geometry.

B. Events with No Track in Aperture (*QNT*)

About 12% of the Q events show no track in the telescope aperture, though sometimes there is a single track in the overhanging flash-tube array. It is believed that these events are probably also showers of a size so small that the characteristic track structure cannot be recognized. The same random patterns are observed in the scintillation detector "track reconstructions," in addition to which the histogram of the mean energy deposition for these events shown in Fig. 4 is also seen to be similar to that for the shower events.

C. Events with a Single Track in Aperture (*QT*)

About 17% of the Q events (160) are observed to have a track accompanying the coincidence signal. A track is recognized as a line of at least three or four flashes in the main north-south flash-tube array, with at least one flash in the top and one in the bottom array of east-west flash tubes. A more stringent requirement on apparent efficiency discussed in Sec. III C 1 b results in a loss of 2% of the tracks in the north-south array, while the criterion cited above for the east-west array causes about 12% of potential quarks to be lost.

Since more than 10^8 muons traverse the array in the running time it is important to consider carefully the ways in which this large background can simulate a quark signal. From the asymmetrical shape of the Landau distribution it is calculated that a muon passing vertically through these scintillation detectors deposits an average energy of 1.15 E_0, where E_0 is the most probable energy deposited by a relativistic muon. Averaging over acceptance angles, the average energy deposited by muons traversing the telescope is about $1.25E_0$. Therefore, although the Landau distribution is inherently broad, the probability that a muon will deposit less than $0.8E_0$ in *each* of the five detectors is very small. This, of course, is the reason for using a multilayer scintillation detector telescope.

A number of control experiments have been performed during the three month run interval. The principal ones are runs in which the discriminator requirement is relaxed from $0.3E_0 < E < 0.8E_0$ to $E > 0.3E_0$ to record muon events complete with flash-tube patterns for comparison purposes. These runs complement the continuous recording of calibration events (C events) for which the high-voltage pulse to the flash tubes is inhibited. Runs are also recorded with relaxed discriminator or coincidence requirements for single detectors or pairs of detectors to further study the system's performance.

From geometrical considerations, a muon track like *aa* in Fig. 1(a) might be expected to be recorded with especially high probability, since two of the detectors, A and E, would give small signals because of the short particle path, leaving only three layers in which simultaneous small signals must occur by fluctuations. However such tracks have not been recorded because the increased path length in B, C, and D offsets the effective loss of two layers of the telescope. Virtually all of the triggers are caused by tracks such as *bb*, *cc*, and *dd*, that is by near-vertical tracks giving short paths in all scintillators and often especially short paths in either the top detector A or the bottom detector E. The partial aperture of the telescope for tracks like *bb* and *cc* which clip a corner of one of the detectors is not very large, but with the relatively thick scintillators used in this array an appreciable number of such events are recorded. It should be noted that although theoretically geometrical corner clipping can occur only in detectors A and E, the top and bottom layers, it can occur in B, C, and D if the alignment of the array is not perfect. This matter will be discussed further in Sec. III C 1 a and in the Appendix.

Tracks like *dd* are favored over tracks like *ee* for another reason. The six photomultipliers on each scintillator are "balanced" by adjusting their high voltages so that the peak of the cosmic-ray spectrum obtained with each photomultiplier operating singly falls in the same channel of the pulse-height analyzer. This method of "balancing" gives slightly smaller detector sum signals for events near the edges of the scintillating liquid. Thus, as indicated in Fig. 5, most of the particles which trigger the array when it is operating in the normal quark search mode are traveling in almost vertical trajectories and passing through the detectors with y/W near zero or unity (though not in the region of the rejected "extreme edge events" to be described in Sec. III C 1 a) and with z/L near 0.5. The pronounced asymmetry has been traced to small (~4%) systematic east-west differences in scintillator liquid depth. In Fig. 6 is shown the very different distribution observed when the array is operating in the mode intended to display muon events.

1. Events Rejected as Spurious

Of the 160 events classed as QT events, 45 have been rejected for spurious characteristics which are apparent from a study of the whole body of data from the quark search and muon runs.

a. Extreme edge events. Thirty of the QT events fall into a class having a distinctive signature indicating a particle which has passed so very near to the edge of all of the detectors that the scintillation detector signals are systematically small due to a combination of geometrical corner clipping and possible loss of some energy to the detector wall without production of the normal scintillation light. More quantitatively these are events which have passed so near to the edges of all of the detectors that the quantity $\frac{1}{5}\sum|y_k/W|$ or $\frac{1}{5}\sum|1-y_k/W|$ has a value < 0.05. These events fall into a very readily identified group, the actual mean distance from the edge being usually ~0.01. The correction in the telescope aperture for these events whose projected zenith angle is very near to zero is only about $\frac{1}{2}$%. Geometrical corner clipping is most common in detectors A and E but, as noted in the Appendix, slight misalignment of the detectors can give rise to some corner clipping in detectors B, C, and D as well. These extreme edge events produce the δ functionlike structure (indicated by arrows) near $y=0$ and $y=1$ in the histogram of Fig. 7. Again the asymmetry in the

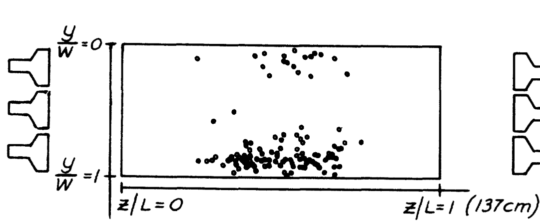

FIG. 5. Locations of potential quark events in a representative detector (B).

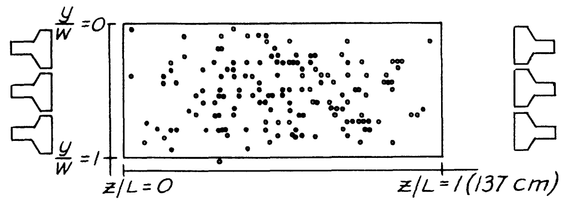

FIG. 6. Locations of muon events in a representative detector (B).

distribution is caused by small (~4%) systematic east-west differences in scintillator liquid depth. For comparison Fig. 8 shows the same kind of histogram found for muon events. The differential aperture function for the telescope accounts for the shape of this histogram.

b. Events rejected for low flash-tube efficiency. Tracks seeming to have very low efficiency may actually be due to chance alignment of a few random flashes or old tracks outside the telescope aperture. From analysis of muon runs and formulas describing flash-tube efficiency as affected by various parameters, it is concluded that events for which flash-tube efficiency is less than 30% should be rejected. In rejecting such events (there are three) it is calculated that about 2% of valid events are thereby lost.

c. Events rejected for inconsistency. Twelve events are rejected for gross inconsistency between the particle track shown by the east-west flash-tube array and the confirmatory data given by the ratios of scintillation detector pulse heights. Such events generally have randomly scattered track locations from scintillation detector data similar to the scattered patterns observed for

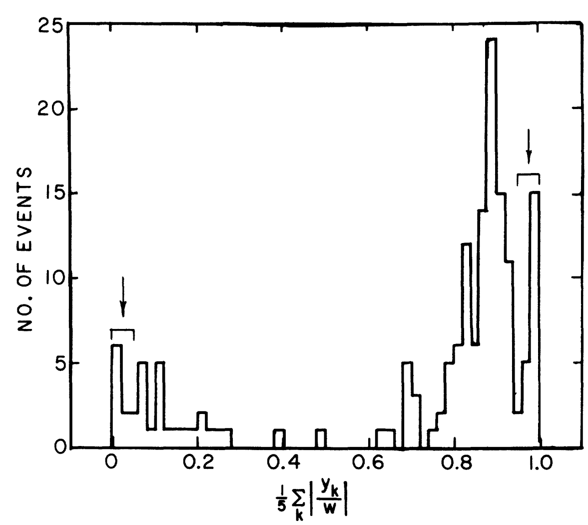

FIG. 7. Histogram of mean y coordinate for 160 potential quark events with single track in aperture.

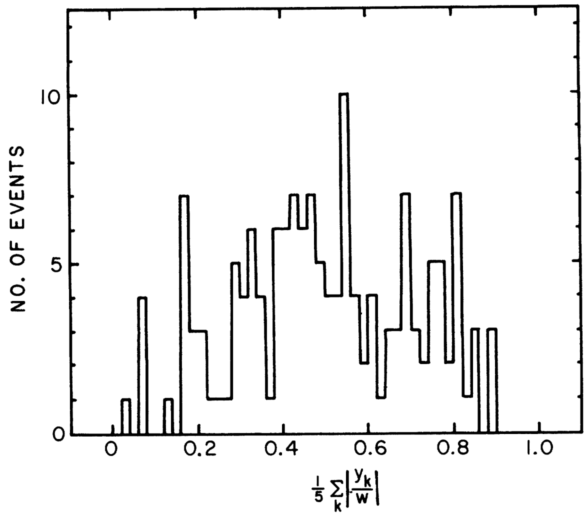

FIG. 8. Histogram of mean y coordinate for 152 muon events.

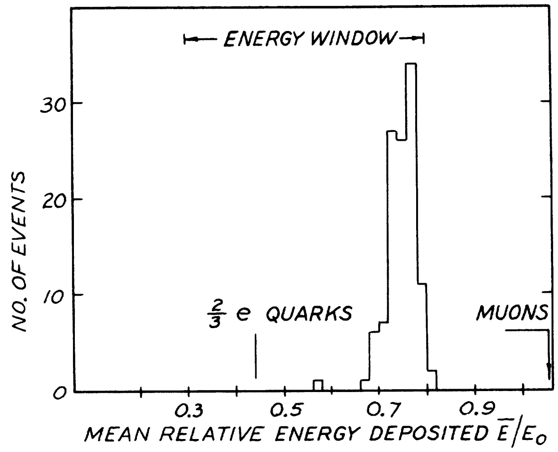

FIG. 9. Spectrum of energy deposited for 115 potential quark events with single tracks in aperture. E_0 is the most probable energy loss for a relativistic muon.

shower events. It is believed that these events are shower events accompanied by flash-tube tracks from unrelated particles outside the telescope aperture. Insistence on consistency between the two redundant determinations of the z coordinates of the tracks is used in our analysis in place of the restriction of other groups of limited scatter in the values of energy deposition in the several layers of scintillation detectors. Quantitatively the consistency requirement is that the fractional rms deviation of the particle trajectory calculated from the scintillator signals from the flash-tube track should be <0.2. This value was somewhat arbitrarily selected after noting from the muon control experiment data that the probability for a bona fide event to fail to satisfy the restriction on consistency is only about 5%.

2. Events Considered Valid

The remaining 115 events have consistent scintillation detector and flash-tube data indicating the passage of a single penetrating charged particle through the array. From the shape of Fig. 9, the histogram of mean energy deposition, it is quite clear that with the exception of one event with $E = 0.57E_0$ the events which have survived the screening process described in Sec. III C 1 represent the low-energy tail of the Landau distribution for relativistic muons, and the low-energy cutoff is sufficiently sharp to make it seem very probable that no events due to muons should give mean energy deposition less than $0.7E_0$. In addition to the characteristic shape of the spectrum for these events at the high-energy end of the window they have a geometrical characteristic which confirms their identification as muons. Their trajectories are quite vertical, passing through the regions where it is expected that the scintillation signals will be slightly smaller than the average for all possible trajectories. (See general discussion of Sec. III C.)

The single event with $E = 0.57E_0$ is well below the cutoff of the muon distribution and somewhat above the most probable value for the $\frac{2}{3}e$ quark distribution ($0.44E_0$), though it could certainly be within the Landau distribution expected for $\frac{2}{3}e$ quarks. It looks like a reasonably bona fide event in every respect, with an unusually large zenith angle (33°) compared to most QT events. This single event must be considered a potential quark event which appears not to be a muon, though in screening 10^8 penetrating particle signals it is difficult to exclude the possibility that some spurious effect might give such a single valid appearing event. For example it could have been a case of a shower event coincident with two unrelated tracks through the nonoverlapping regions of the overhanging flash-tube array. Table II lists pertinent information for this event.

IV. CONCLUSIONS

From careful consideration of the data we believe that no signals characteristic of $\frac{2}{3}e$ charge quarks have been observed, though we must acknowledge that the single event with energy deposition $0.57E_0$ must be considered to be a potential quark signal. Therefore, assuming Poisson statistics for the random arrival of quarks, the mean number of events $\bar{n}$ for which there is 90% probability that more than zero or one events will be observed is determined from the relation

TABLE II. Data on the single potential quark event observed.

Detector	Energy deposition relative to muon peak E/E_0	Event location $Z=z/L$ Flash-tube data	Scintillator data
A	0.79	0.35	0.18
B	0.65	0.28	0.33
C	0.58	0.21	0.11
D	0.73	0.14	0.14
E	0.57G	0.06	0.09

G denotes a signal which is small for geometrical reasons (corner clipping)

Fraction of flash-tube layers discharged:
N-S 9/11, four background flashes
E-W 3/4, three background flashes

$1-(\bar{n}+1)e^{-\bar{n}}=0.90$, which gives $\bar{n}=3.9$. Since we must base our quark flux determination on this single event it seems most reasonable to cite only an upper limit on flux, which, with our effective running time of 1157.97 hours, with aperture 0.51 m^2 sr, becomes, at a 90% confidence level, $<2.2\times10^{-6}$ m^{-2} sec^{-1} sr^{-1}. This flux limit is corrected for the several small losses mentioned in the Sec. III discussion of data screening processes but is not corrected for interactions in the telescope.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge helpful discussions and continuous encouragement from Professor Frederick Reines. Foon Kim helped with some of the early preparations for these measurements. The fast amplifiers used with the array follow a design very kindly supplied by Dr. Henry Gurr. Dr. Erwin Shrader, Bruce Shoffner, and John Lathrop have contributed useful ideas for the photoelectric readout system and high-voltage pulsing circuits.

APPENDIX

Because of the important role played by the thick liquid scintillation detectors used in the quark search telescope, careful attention has been paid to many details of their performance. Since similar detectors have useful applications wherever low-cost detectors of large area are needed, some of the results of measurements of their performance will be presented here.

Figure 10 shows the sea-level cosmic-ray spectrum for a single horizontal detector (C) gated by fivefold cosmic-ray coincidences ABCDE. This spectrum is drawn just as recorded, and

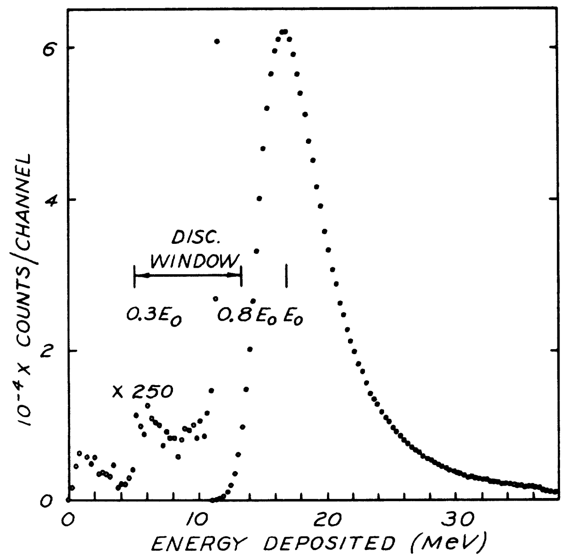

FIG. 10. Penetrating particle monitoring spectrum for detector C. The magnified region shows a small "plateau" caused by "corner clipping." E_0 is the most probable energy loss for a relativistic muon.

therefore is expected to depart from the Landau distribution because of the presence of shower events (about 10%), variation of particle path length with zenith angle, and the small variations of detector signal with event location. Upon correcting the data for these three effects, the ex-

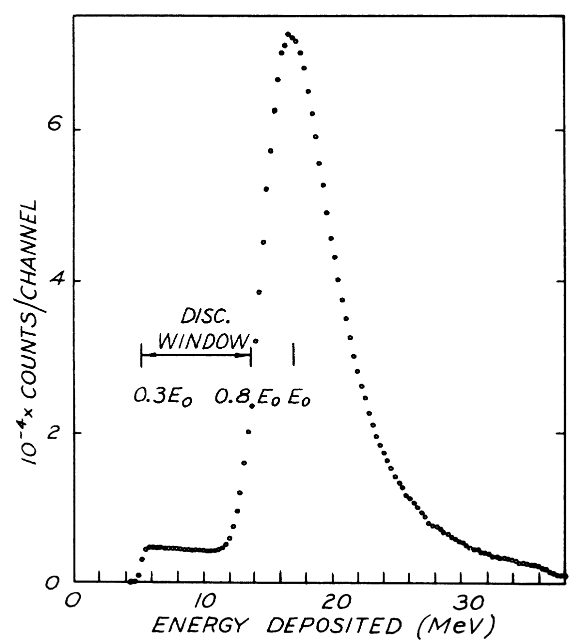

FIG. 11. Penetrating particle monitoring spectrum for detector A. E_0 is the most probable energy loss for a relativistic muon.

perimental peak is still found to exhibit a width in excess of the Landau distribution amounting to 27% instead of the expected 19%.

Since measurements with a pulsed light source show that the mean number of photoelectrons produced by a relativistic muon incident upon the detector is 360, it is not possible to explain the additional width of the experimental peak in this way. The additional width of the experimental peak is possibly due to the approximate nature of the correction made for event location and to the departure from perfect "balance" of the set of six photomultipliers used with each detector.

Figure 11 shows the coincidence gated cosmic-ray spectrum for detector A, the top slab of the array. The "plateau" in the low-energy region represents the pronounced geometrical effect of "corner clipping." The same spectrum is, of course, observed for the bottom detector, E.

For an array with perfect alignment no corner clipping would be expected for detectors B, C, and D. However slight variations in detector size or shape or alignment can produce very small subapertures for which the particle path in B, C, or D is less than the full detector thickness even though the particle traverses all layers, A, B, C, D, and E. Figure 10 also shows the "plateau" of low amplitude observed for detector C. The observation of this small "plateau" for detector C probably indicates slight north-south misalignment, since detector C is wider than the others. A similar small "plateau" is observed for detector B, but not for detector D, presumably because of alignment variations.

The response functions for detectors B, C, D, and E are identical to the accuracy to which they can be measured. That for detector A is noticeably steeper because of a small leak of scintillator oil which partially destroyed the conditions for total internal reflection at the bottom surface of the detector. Two redundant sets of monitoring data permit the run data to be readily corrected for such variations in response function.

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