ing and data analysis, and E. H. Synn and Dr. J. G. Mowat were helpful in the tedious business of track counting and error evaluation. We wish to acknowledge helpful discussions with Dr. F. Selleri and Dr. A. M. Buoncristiani. The cooperation of the Computing Centers of the University of Notre Dame and of the Oak Ridge National Laboratory, at appropriate stages, is appreciated.

APPENDIX (added in proof)

Maximum-likelihood fits to the angular distributions of the final-state pions have been made with an expression of the form

$$\frac{d\sigma}{d\cos\theta_\pi}=\frac{\sigma_{\text{inel}}}{2}1+\sum_{i=1}^{n} C_i(\pi^\pm)P_i(\cos\theta_\pi)\,,$$

where the P_i are the Legendre polynomials. The $C_i(\pi^\pm)$ obtained from the maximum-likelihood fit with $n=4$ are as follows:

$\pi^-\pi^+n$	604 MeV	790 MeV	830 MeV	870 MeV
$C_1(\pi^+)$	-0.35 ± 0.040	-0.36 ± 0.073	-0.058 ± 0.077	-0.045 ± 0.075
$C_2(\pi^+)$	-0.36 ± 0.054	0.12 ± 0.087	0.12 ± 0.094	0.016 ± 0.093
$C_3(\pi^+)$	0.17 ± 0.064	0.55 ± 0.10	0.46 ± 0.11	0.47 ± 0.11
$C_4(\pi^+)$	0.055 ± 0.071	-0.54 ± 0.12	-0.31 ± 0.12	-0.27 ± 0.13
$C_1(\pi^-)$	0.39 ± 0.045	0.72 ± 0.085	0.50 ± 0.11	0.68 ± 0.10
$C_2(\pi^-)$	0.034 ± 0.056	0.34 ± 0.11	0.59 ± 0.12	1.15 ± 0.11
$C_3(\pi^-)$	-0.004 ± 0.066	-0.23 ± 0.13	-0.29 ± 0.15	-0.021 ± 0.14
$C_4(\pi^-)$	-0.19 ± 0.075	-0.12 ± 0.15	-0.25 ± 0.18	0.070 ± 0.16
$\pi^-\pi^0P$				
$C_1(\pi^-)$	0.085 ± 0.056	0.32 ± 0.11	0.71 ± 0.12	0.48 ± 0.12
$C_2(\pi^-)$	0.014 ± 0.071	0.28 ± 0.14	0.54 ± 0.15	0.35 ± 0.15
$C_3(\pi^-)$	0.080 ± 0.085	0.025 ± 0.17	-0.26 ± 0.18	-0.37 ± 0.17
$C_4(\pi^-)$	-0.083 ± 0.096	-0.18 ± 0.19	-0.33 ± 0.21	-0.009 ± 0.20
$C_1(\pi^0)$	0.078 ± 0.058	-0.27 ± 0.13	-0.36 ± 0.14	0.34 ± 0.13
$C_2(\pi^0)$	0.091 ± 0.074	0.60 ± 0.16	0.61 ± 0.17	0.48 ± 0.15
$C_3(\pi^0)$	-0.14 ± 0.084	0.12 ± 0.20	0.19 ± 0.20	-0.11 ± 0.19
$C_4(\pi^0)$	-0.078 ± 0.097	0.17 ± 0.21	0.17 ± 0.22	-0.44 ± 0.22

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Search for Fractionally Charged Particles Produced by Cosmic Rays

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Measurements were made of the flux of particles with charges of one-third and two-thirds the charge of the electron, which reach sea level from the vertical with relativistic velocities. A set of six scintillation counters with an acceptance of 650 cm² sr was directed so that the particles passed through the array. The apparatus was in operation for about 3500 h. Particles with fractional charge were identified through their characteristic energy loss in each of the six counters. The flux of particles with a charge of one-third was determined to be $(2.6_{-1.8}^{+2.1})\times10^{-9}$ cm^{-2} sr^{-1} sec^{-1}. The flux of particles with a charge of two-thirds was determined to be $(2.1_{-1.5}^{+1.8})\times10^{-9}$ cm^{-2} sr^{-1} sec^{-1}. The statistical probability that no anomalously charged particles were detected is about 5%.

I. INTRODUCTION

It has been emphasized by Gell-Mann[1] and Zweig[2] that the existence of a triplet of elementary particles with charges of $\pm e/3$ and $\pm 2e/3$, where e is the charge of the electron, provides an exceptionally simple basis for the SU_3 symmetry character which hadrons are observed to follow. Gell-Mann has called these particles quarks. The success of the Gell-Mann[3]–Okubo[4] mass formula, which treats the large symmetry-breaking action implicitly as a perturbation, further suggests that the symmetric interaction is very strong and hence that the masses of the fundamental triplets are likely to be quite large.

Experiments conducted at the major accelerators appeared to definitely exclude the existence of quarks[5] with masses less than 2 BeV/c^2 and to very much restrict the possibility that strongly interacting particles of this type exist with masses less than about 4 BeV/c^2.[6–10]

Since the primary cosmic-ray flux contains appreciable intensity at nucleon energies beyond that avail-

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able from the accelerators it seemed desirable to explore the existence of heavier quarks by measuring the intensity of fractionally charged particles in the flux of secondaries from the interaction of the primary cosmic rays. It is also possible that the primary flux itself contains a small proportion of quarks. These experiments[11–14] establish that the flux of quarks deep in the atmosphere from all sources with relativistic velocities is less than a few times 10^{-8} cm^{-2} sr^{-1} sec^{-1}.

The systematics of SU_3 together with the symmetry-breaking character of the electromagnetic interaction and the part of the strong interaction which appears to transform as Y, the hypercharge, suggest that the charge-$\frac{2}{3}$ state will be the lightest quark state and therefore stable. This state, together with one of the charge-$\frac{1}{3}$ states, constitutes an isospin doublet where the mass splitting results from electromagnetic effects and is not likely to be much greater than a few MeV. The charge-$\frac{1}{3}$ member of the doublet can decay into the charge-$\frac{2}{3}$ member by ordinary beta decay and the lifetime can be expected to be of the order of seconds: at any rate long compared to the proper time of a few microseconds required for the passage of the particles through the atmosphere to the detectors after production. The other charge-$\frac{1}{3}$ quark will probably have an appreciably larger mass as a result of the strong symmetry-breaking interaction and might decay very quickly into the other members of the triplet through the strong interactions by the emission of K mesons. One should then expect to detect quarks of either charge from production in the atmosphere by nucleon-nucleon collisions. Though only the stable quark will be represented in the primary flux there will probably be enough charge exchange and hypercharge exchange in the passage of these quarks through the atmosphere so that the detected flux is again made up of both charge states. Indeed the intensities can be expected to be roughly the same for charge $\frac{1}{3}$ and for charge $\frac{2}{3}$.

The information concerning the limits of intensity can be related to the cross sections for the production of triplets in nucleon-nucleon collisions, and to the flux of quarks in the primary cosmic rays. Though the results are necessarily dependent to some extent on the assumptions made concerning the detailed character of the production and interaction of triplets, it has been shown[15,16] that if the particles are very massive and if the interaction can be characterized by a momentum transfer which is not larger than a BeV/c the details of the model do not affect the conclusions strongly. The cross-section limits derived from these experimental limits on the secondary flux are typically of the order of $(\hbar/Mc)^2$, where M is the mass of the triplet or quark, for values of M near 10 BeV/c^2. In the absence of any theory of quark dynamics such limits hardly exclude the existence of heavy quarks. In view of the limited extent of the previous negative results and in view of the importance of the hypothesis of such fractionally charged triplets it appeared to us essential to proceed with more extensive investigations.

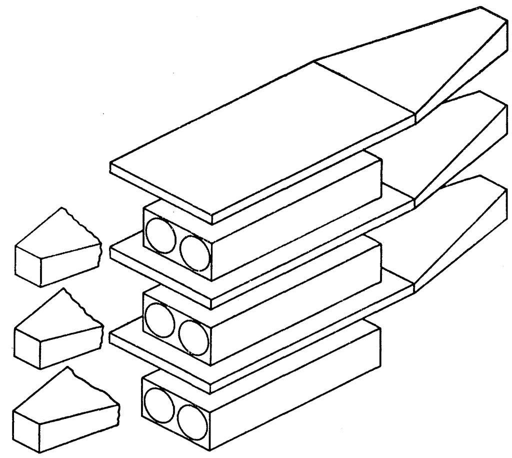

FIG. 1. A schematic view of the counter assembly.

II. EXPERIMENTAL DESIGN AND EQUIPMENT

The detector consisted of six scintillation counters arranged in the configuration illustrated in Fig. 1. The acceptance of the array was determined to be about 650 cm^2 sr. Three of the counters were constructed from plastic scintillator 1 in. thick: The sensitive dimensions of these counters were 16×38 in. Light from the scintillator was transmitted to two 5-in. photomultiplier tubes through light pipes which conserved the cross section of the scintillator and therefore the phase space of the internally reflected photons. The tubes have a photocathode area of 16 sq. in., about matching the cross-section area of the scintillator. The other three counters used a toluene-base scintillation liquid as the active element. These counters were 5.5 in. deep and their sensitive area was 30×11$\frac{1}{2}$ in. The liquid was viewed by four 5-in. photomultiplier tubes through ports in the aluminum containers. Particles which traverse the array pass through about 50 g/cm^2 of material.

The pulses from the two tubes connected to each plastic counter were added, and the pulses from the four tubes connected to each liquid counter were added, after the gains of the tubes were balanced, so that each counter produced one effective pulse. The sensitivity of each counter was measured at various points over the area of the counters by observing the pulse heights upon passing a beam of π mesons from the Brookhaven Cosmotron through the counters. The counters were

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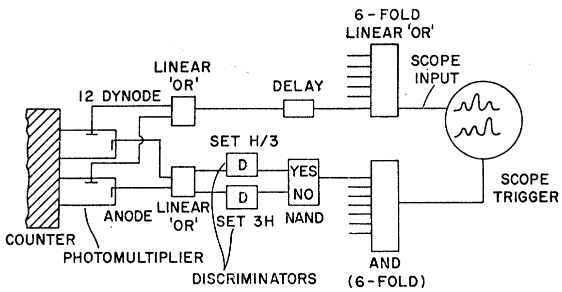

FIG. 2. A block diagram of the electronic logic used in the course of the measurement.

quite uniform in sensitivity; the spread in average pulse height was less than 10% over almost the whole of their sensitive area.

The experimental design was directed to the specific purpose of detecting relativistic particles with the specific charges of $\frac{1}{3}e$ or of $\frac{2}{3}e$, where e is the charge of the electron. Such particles will lose $\frac{1}{9}$ or 4/9 as much energy as a minimum ionizing singly charged particle. Any other particle will lose more energy in passing through matter. In general, then, the quarks were to be detected by virtue of their anomalously small ionization. The basic logic and some of the procedures used in this experiment were similar to that used in a previous experiment of this group[5] concerning a search for quarks produced by the interaction of 30-BeV protons at the Brookhaven Alternating Gradient Synchrotron.

It is convenient to discuss the logical procedure of the experiment in parallel with the discussion of the general logical design. We discuss the procedures used in the investigation of the existence of charge-$\frac{1}{3}$ particles in particular. The procedure used in the search of particles with charge $\frac{2}{3}$ is only slightly different. Figure 2 presents a schematic chart of the essential elements of the data-handling system. Pulses from the anodes of the several photomultiplier tubes which view a particular counter were mixed in a linear "or" circuit. Dual outputs of the "or" circuit then passed through separate discriminators. One discriminator was set to accept pulses greater than $h/3$ and the other was set to accept pulses greater than $3h$, where h is the pulse height expected from the particle under investigation—$\frac{1}{9}$ of normal minimum. The output of the discriminator set at $h/3$ passes to the "yes" input of a "nand" circuit; the output of the discriminator set at $3h$ passes to the "no" input. The set of discriminators and the "nand" circuit acted as a single-channel pulse-height analyzer; a pulse was emitted from the analyzer only upon the input of a pulse smaller than $3h$ and larger than $h/3$. The output of the analyzer circuit, together with the similar outputs from the analyzers associated with the other five counters, was used as an input to a set of circuits which acted as a sixfold "and" circuit. The pulse from this circuit block was then used as an input to the trigger circuit to a dual-beam oscilloscope. In summary, the oscilloscope was triggered upon the simultaneous reception, in each counter, of events which produced pulses which were greater than $h/3$ and smaller than $3h$. The time resolution of this logic was about 5 nsec.

Pulses from the 12th dynode of each photomultiplier associated with the counter were added, again, in a linear "or" circuit. This output of the counter was differentially delayed with respect to similar pulses from the other counters and fed into a linear "or" circuit, which acts as a mixer, together with the pulses from two other counters. These were fed into one of the inputs to the dual-beam oscilloscope. Pulses from the other three counters were treated similarly and fed into the other input to the oscilloscope. In particular, pulses from the three liquid scintillators were displayed on one trace and pulses from the three plastic counters were displayed on the other trace.

The pulses were photographed and then the pulse heights registered on the film were measured by personnel unfamiliar with the purpose of the experiment using measuring engines designed for the analysis of bubble chamber film. The output of the measurements was then processed by appropriate computer programs with a minimum of human intervention.

Typically about 100 pictures were obtained per day. The source of the background which was recorded was somewhat different for the measurement of charge-$\frac{1}{3}$ particles and for the measurement of charge-$\frac{2}{3}$ particles. In the former case the background was the result of soft cosmic-ray showers. A typical event resulted from the deposit of energy in each of the counters by soft photons, or occasionally soft electrons, which resulted from the shower. There appeared to be almost no correlation between the pulse heights recorded in the various counters. The spectrum of pulse heights from this background peaked at low energy. Figure 3 shows

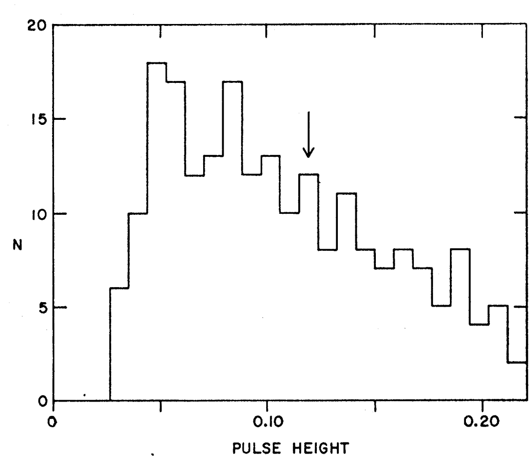

FIG. 3. The pulse-height spectrum resulting from the background in a typical counter. The cutoff at low pulse heights results from the effect of the low level discriminator in the acceptance logic. The pulse heights are normalized to a value of one for a minimum ionizing particle of charge one.

the spectrum of background pulses observed in one of the counters. The spectrum was very much the same in the other counters.

During the part of the experiment devoted to the search for particles with a charge of $\frac{2}{3}$ the discriminators were set at different levels. The discriminators which fed into the "no" input of the "nand" circuits were set at about 0.85 of minimum while the discriminators which fed the "yes" inputs were set at about 0.15 of normal minimum. These settings resulted in somewhat less background in terms of counts per day than was observed in the search for charge-$\frac{1}{3}$ particles. This background was not entirely the result of the effects of soft showers as there was a small component from the passage of relativistic muons through each of the six counters such that abnormally small pulses were produced in each counter. There is a certain statistical probability of this in view of the finite number of photoelectrons produced in the photocathode of the tube by a minimum ionizing particle. Of course there was a very significant correlation between the size of the pulses from the various counters from this source of background.

It must be noted that although the quarks may well propagate close to the cores of extensive air showers, the probability that another shower particle will hit the detector with the quark is small for showers of less than 10^{14} eV.

III. PROCEDURES AND ANALYSIS

A standard procedure was adopted and followed throughout the experiment. It was convenient to divide the measurements into blocks of about one-day duration. Between blocks the anticoincidence part of the logic was disconnected, the oscilloscope amplifier setting was changed, and a set of pictures was taken such that each picture registered 50–70 pulses due to muons passing through the apparatus. The oscilloscope amplifier was adjusted so that the pulse heights from the muons were of the same magnitude as the pulse heights expected from quarks. These muon pulses were used as calibration pulses and served to normalize the pulse heights recorded during the runs which were adjacent in time. The absolute pulse heights presented then represent the ratios of the pulse heights measured during the run to the calibration pulses multiplied by the ratio of the amplifier settings.

The reliability of such a normalization then depended upon the linearity of the oscilloscope amplifiers and upon the linearity of amplification of the photomultiplier structure up to the 12th dynode under the conditions of voltage and current prevailing during the experiment. The linearity of the amplifiers was shown to be adequate through measurements of pulse heights from a pulse generator and a set of attenuators. The linearity of the photomultiplier tubes at the 12th dynode was checked by passing pions and protons of a known momentum and different specific ionization through the counters and measuring the pulse heights obtained. Measurements were also made with the photocathode masked to various degrees. From these measurements it appeared that there were no large nonlinearities though we cannot exclude the possibility of an effect of a few percent upon the average pulse heights determined in the experiment.

Such a saturation effect would reduce the size of the calibration pulses and give an erroneously large value to the normalized pulse height. This would effect the results in two ways; the average pulse heights measured for real events would be too large—any peak would be shifted to larger values; and the correlation between pulse heights in the various counters would generally be decreased, reducing the number of events appearing to be real. This last effect would become important only if the shift due to the nonlinearity was larger than the pulse spread due to the finite resolution of the counter.

In general the data from the runs were examined in detail very soon after the run. The pulse-height spectra from each individual counter was monitored for evidence of any change in character. In particular the average pulse height, the largest pulse height, and the smallest pulse height, were monitored for each counter during any appreciable running period to guarantee that there was no important shift in the levels of the various discriminators. A small portion of the data was discarded as a result of such drifts.

Since the logical criteria established by the electronic design can be fulfilled by background events resulting from soft showers as well as real events initiated by a single fractionally charged particle it is necessary to devise a further method of analysis so as to statistically differentiate between real events and the background.

The passage of a quark through the array will be expected to produce pulses in each of the six counters such that each individual pulse height is nearly equal to $\frac{1}{9}$ or 4/9 of the pulse height from a singly charged relativistic particle. Since the pulse-height resolution of the individual counters is limited by the statistical fluctuations in the number of photoelectrons produced at the cathode of the photomultiplier and also by the Landau effect and effects due to differences in light gathering efficiency over the effective area of the counters, deviations from this average behavior must be expected for any individual event. Although the individual pulse heights in the different counters would not be precisely equal to the canonical pulse height expected from a fractionally charged particle they will be more nearly equal to one another than will the pulses which result from the primary background of pulses which result from the photons and electrons from soft showers. We can then expect to differentiate between real events and background by considering the correlations in the normalized pulse heights in the various counters. There should be a strong and well-defined

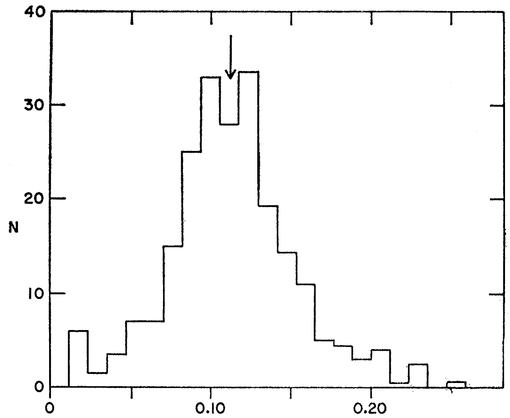

FIG. 4. The pulse-height spectrum of simulated quarks in a typical counter. The low level discriminators are disconnected. The pulse heights are normalized to a value of one for the pulse height of a minimum ionizing particle of charge one.

correlation between the individual pulses if the event results from the passage of a single real particle. If the event results from the background the pulse heights will be distributed more nearly at random throughout the gross pulse-height acceptance region.

We chose to use the quantity C as a measure of correlation:

$$C=\sum_j (h_j-h_{\mathrm{av}})^2/(D_j h_j/h_q)^2,$$

where h_j is the normalized pulse height in counter j, h_{av} is the weighted average of the pulse heights for all of the counters, h_q is the pulse height corresponding to the fractionally charged particle, and the quantity D_j is the standard deviation of the pulse heights from counter j upon the passage of the fractionally charged particle. The summation is over the six counters. Since a beam of fractionally charged particles is not available to establish the values of D_j and of h_q, the character of the pulses from such particles was simulated by pulses from the cosmic-ray muon flux under conditions such that only $\frac{1}{9}$ of the light from the scintillator was passed through to the photocathodes of the photomultipliers. The light was reduced by placing appropriate masks over the faces of the tubes.[17] The pulse-height spectra obtained in that way should adequately represent the pulse-height spectra expected from particles of charge $\frac{1}{3}$.

The pulse-height spectrum from the various counters differed in character. This difference primarily represented different effective resolutions for the various counters. The pulse-height distribution obtained by viewing cosmic-ray events through masks using the electronic logic described previously is shown for a representative counter, (the counter with the 4th best resolution out of 6) in Fig. 4. The distribution is not Gaussian and the value of D_j which was used was taken such that 68% of the pulse heights h fell in the region such that $(h_{\mathrm{av}}-D_j)<h<(h_{\mathrm{av}}+D_j)$. Table I presents the effective resolution of the six counters. Since some of the pulses from the cosmic-ray spectrum result from events other than the passage of single relativistic muons through the array the "true" resolution of the counters may be slightly better than that represented by the figures of Table I. Since the resolution of the various counters differed, the value of h_{av} was obtained by weighting the contributions of the various counters such that their weight was taken to be inversely proportional to D^2.

For real events, in the approximation that the individual pulse-height distributions were Gaussian, one would expect that the distribution of values of C would be that of a χ^2 distribution with 5 deg of freedom. If the pulse heights in the various counters are com-

TABLE I. The pulse-height resolution of the various counters. The plastic scintillation counters are denoted as P, the liquid scintillation counters as L. The resolution is measured in terms of the standard deviation from the average pulse height of a quark with a charge of $\frac{1}{3}$, divided by that average pulse height.

Counter	D/h_q (standard deviation)
$L1$	0.20
$L2$	0.26
$L3$	0.25
$P1$	0.23
$P2$	0.39
$P3$	0.39

[17] Such masks were used by our group in a previous experiment (Ref. 5) and also by Bowen *et al.* (Ref. 12).

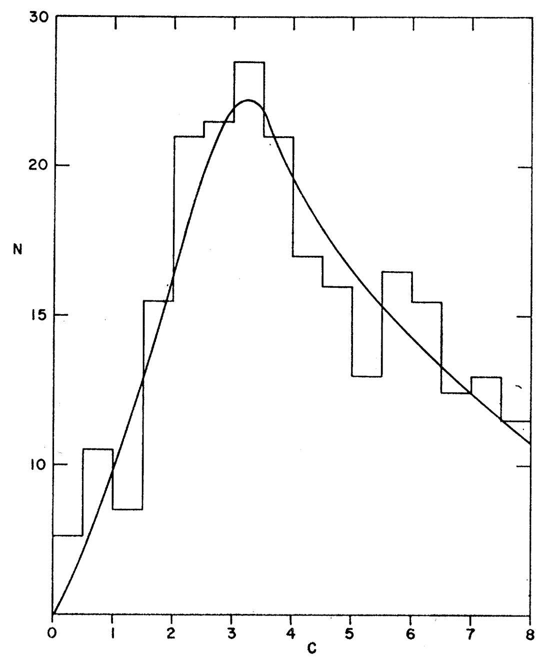

FIG. 5. The histogram represents the distribution of values of the correlation function C for simulated events. The solid curve represents the distribution to be expected if the experimental design is correctly described statistically by a χ^2 distribution with 5 deg of freedom.

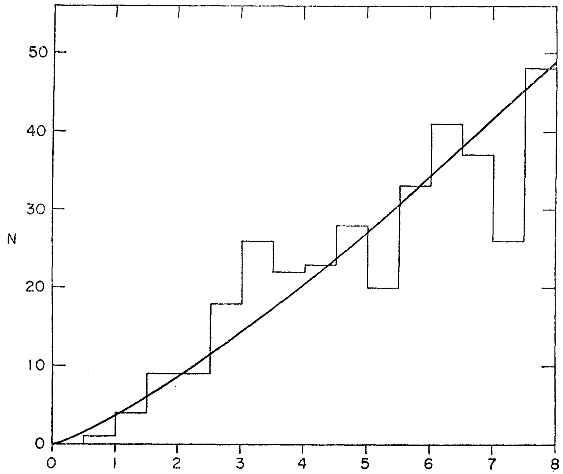

FIG. 6. The histogram represents the distribution of values of the correlation function C for measured events ascribed to the background. The solid curve represents the distribution of values of C to be expected if the individual pulse heights in the counters are completely uncorrelated.

pletely uncorrelated, the distribution of values of C will follow a variation approximately like $dN/dC \approx C^{1.25}$ for small values of C, nearly independent of the individual pulse-height spectra in the various counters. The distribution of values for C for the simulated events is shown in Fig. 5 together with a solid curve representing the distribution expected from a χ^2 distribution with five degrees of freedom. The diagram of Fig. 6 shows the distribution of values of C from nominally background events taken during the regular run together with a solid curve proportional to $C^{1.25}$. In either case the agreement is sufficiently good so as to suggest that no serious errors will be made by using the distribution model as a basis for discussion.

Clearly any criteria designed to accept 100% of the real events would also accept most of the background events. The χ^2 distribution has a very long tail extending to very large values of C. Real events can be selected from the background events only on a statistical basis. We chose to accept events such that the value of C was less than 4.0. We can see from an examination of Figs. 5 and 6 that the signal-to-background ratio will be reduced for larger values of C. With this criterion we can expect to select about 45% of the real events. Of the simulated events 40±4% did fall within this selection restraint.

A secondary part of the analysis was performed by plotting the distribution of average pulse heights for all events such that C was less than the chosen cutoff value of 4.0. If particles with a charge of $\frac{1}{3}$ or $\frac{2}{3}$ contribute to these events we expect to see a peak at pulse heights corresponding to $\frac{1}{9}$ and 4/9 of normal minimum. The width of this peak would be determined by the general resolution of the apparatus acting according to the constraints imposed by the methods of analysis. This is difficult to deduce reliably from a knowledge of the experimental parameters alone but the simulated events provide an ideal operational measure of the effective resolution. This resolution function is shown for simulated charge-$\frac{1}{3}$ particles in Fig. 7. The resolution function for charge-$\frac{2}{3}$ was not measured directly but through an interpolation of the measured resolution functions for muons and for the simulated charge-$\frac{1}{3}$ particles it is evident that the resolution for charge-$\frac{2}{3}$ was slightly better than that for charge-$\frac{1}{3}$ shown in Fig. 4.

The results for the two experimental runs are shown in Fig. 8. The width of the bins is chosen to match the resolution of the apparatus as displayed in Fig. 7. The small peaks shown in each distribution at the value of pulse height anticipated for quarks are, aside from the very limited statistical significance, of the character to be anticipated if real quarks were in fact detected.

The data from the measurements concerned with the detection of charge-$\frac{1}{3}$ particles are divided into two parts in Fig. 8 representing the data collected in the first half of the run and the data from the second half of the run. The excess of events in the channel corresponding to quarks is realized wholly from the first half of the run. While this is not excluded statistically, the result suggested to us that errors might have been made in one of the two portions of the measurement. A careful analysis of the detailed structure of the data shows no such difference between the two runs. Furthermore, while we can conceive of a number of errors which might obscure a real signal we do not know of any erroneous procedure which would simulate a peak in the distribution.

The apparatus was run for about 1000 h with the logic set so as to detect charge-$\frac{2}{3}$ particles and about 2500 h set to detect charge-$\frac{1}{3}$ particles. The measure-

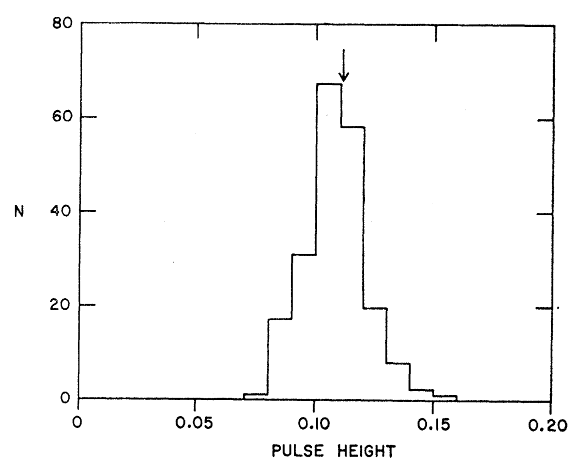

FIG. 7. The histogram represents the measured pulse-height spectrum from simulated quarks. The pulse heights represent the values of h_{av} for all events such that the correlation function $C \leq 4$. This is the same criteria used in the final analysis of the data. The pulse heights are normalized to a value of one for the pulse height resulting from a minimum-ionizing particle of charge one.

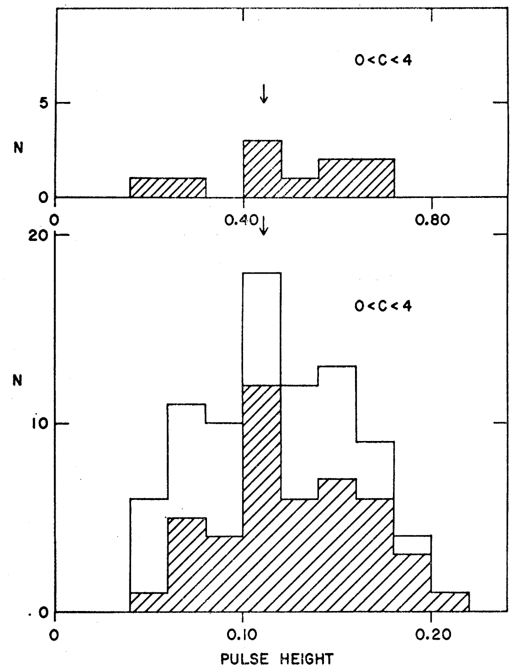

FIG. 8. The histograms represent the pulse-height spectra measured during separate runs for charge-$\frac{1}{3}$ particles and for charge-$\frac{2}{3}$ particles. The pulse heights are normalized to the value of one for minimum-ionizing particles of charge one and therefore represent the square of the value of the charge of the particle which produces the pulse. The arrows show the position where one should expect peaking if quarks were detected. The cross-hatched area in the lower histogram designates the data taken during the first half of the run.

ments were discontinued when it appeared that it would be quite difficult to either definitely establish the reality of the small positive signal which was observed or to demonstrate that the effect was merely a statistical fluctuation. We hope to clarify this using a more sensitive apparatus which is under construction.

IV. CONCLUSIONS

Since there is an appreciable background any analysis of the sensitivity of the experiment to quarks, or of the meaning of any observed indication of the existence of quarks, must depend upon an understanding of the character of the background. In view of the stochastic nature of the soft showers which are primarily responsible for the background it seems likely that the probability of an energy loss E_a in counter a is independent of the energy loss E_b in counter b. Such an assumption is in reasonable accord with the observed distribution of values of C for the background shown in Fig. 5. The solid line in that figure represents the distribution to be expected if the individual pulse heights are indeed uncorrelated with one another.

The distributions accepted by the logic of the counter system are not completely random because of the cutoffs at $h_q/3$ and $3h_q$. As a result of this, events such that h_{av} has a value near either cutoff will have a distribution of values of C which is different than that shown in Fig. 5. Small values of C are favored for such events. This is easily seen by considering an event such that h_{av} is almost exactly equal to $h_q/3$. Since none of the six pulses can be smaller than $h_q/3$ as a result of the character of the electronic logic, every pulse height must be very near to $h_q/3$, the correlation between pulse heights must be very high, and the value of C must be correspondingly small.

Since the background in each individual counter peaks at low values of h, as suggested by the curve of Fig. 3, and since the number of events such that each pulse has a height in a narrow interval near cutoff varies about as I^6, where I is the intensity of a single counter in that channel, small changes in the lower discriminator setting result in very large changes in the background corresponding to pulse heights near the lower cutoff. The discriminator cutoff is not completely sharp and some of the individual pulse heights which contribute to events which have an average pulse height of h' will be appreciably smaller than h'. As a result of these factors a change in the mean lower discriminator bias changes the background radically in channels of h_{av} up to values of about 0.6 h_q. The discriminators were set somewhat lower for a short time at the end of the run designed to measure the flux of quarks with a charge of $\frac{1}{3}$. The background at low values of h was then increased by about an order of magnitude. These data are not included in the final analysis.

We were concerned that our general method of analysis might simulate a peak near h_q: By selecting a set of pulse heights such that h_q was the geometric mean of the cutoffs we might have biased ourselves strongly towards an average pulse height of h_q in a manner obscure to us. To get some insight into the possibility that the method of analysis itself could produce such a peak we constructed a Monte Carlo simulation of a set of events using a random-number generator and proceeded to analyze these events using the same programs

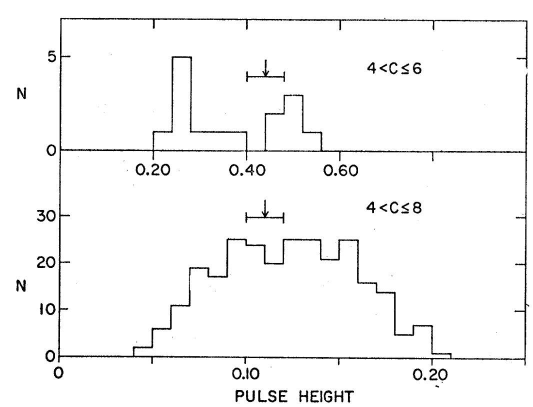

FIG. 9. The top histogram shows the pulse-height spectra of all events measured during the charge-case $\frac{2}{3}$ run such that $4<C\leq 6$. The lower histogram presents the pulse-height spectra of events measured during the charge-$\frac{1}{3}$ run where $4<C\leq 8$. The arrows show the pulse heights corresponding to quarks.

we had used for the real events. No peak was produced. As a further check we plotted the pulse-height distributions for the charge-$\frac{1}{3}$ events such that $8>C>4$, and the distributions for the charge-$\frac{2}{3}$ events such that $6>C>4$. These distributions, shown in Fig. 9, show no peaks at the position of h_q. This is the pattern to be expected if the flux of quarks is as small as suggested by the results of Fig. 8 and strongly suggests that neither experimental techniques nor analysis procedures produce a false peak at $h_{av}=h_q$.

It is possible to derive a value for the flux of quarks from the experimental results in a direct manner by comparing the number of events found in the pulse-height region where one expects to see the quarks with the number of events in adjacent bins where the events should result almost wholly from background. From Fig. 8 we have 18 events in the pulse-height region which ranges from 0.91 h_q to 1.09 h_q compared to an average of 11.15 events in the adjacent four bins. Using the value of 650 cm^2 sr for the acceptance of the detector, the value of 2500 h for the detection time, and the efficiency of 45% deduced from the acceptance criteria which was used, we deduce a flux of $(2.6_{-1.9}^{+2.1})\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1} for charge-$\frac{1}{3}$ quarks. From the measurements of charge-$\frac{2}{3}$ quarks we have three events in the bin in which the quarks are expected to fall and an average of one event in the adjacent four channels. The operating time for this part of the measurement was about 900 h and the flux which is deduced is then $(2.1_{-1.5}^{+1.8})\times10^{-9}$ cm^{-2} sec^{-1} sr for the charge-$\frac{2}{3}$ quarks. Of course neither of these results is inconsistent with zero.

Since the results of the search are nominally positive it is desirable to consider the statistical significance of the results with respect to the question "What is the probability the quarks were detected in the experiment?" Like most experiments this experiment is not so simple that it can easily and precisely be fitted into a standard statistical model. Efforts to conduct a completely formal analysis are then difficult and the meaning of any results is likely to be obscure. Nevertheless it seems worthwhile to compare the results with some very simple models in order to establish a subjective basis for an evaluation of the results. The average number of events in the five bins centered about h_q is 12.8 for the charge-$\frac{1}{3}$ measurement and 1.4 for the charge-$\frac{2}{3}$ measurement. The probability of getting 18 or more events where the average is 12.8 is about equal to 0.08. The probability of getting three or more events where the average is 1.4 is about equal to 0.20. The probability of getting eighteen or more events for the charge-$\frac{1}{3}$ measurements *and* three or more events for the charge-$\frac{2}{3}$ measurements is then about 0.016. In general we believe that if we were to simulate the experiment many times using a random-number generator we would be sufficiently ingenious (or ingenuous?) to find equally strong evidence for quarks in about 5% of the runs.

Positive results of the magnitude reported here do not appear to be in contradiction with any experiments published up to this time nor are they in disagreement with any unpublished work which is familiar to us. Accepting the results either as a positive indication or as a limit to the possible flux it is interesting to associate the reported flux with quark production cross sections and with the prevalence of quarks in the primary cosmic-ray flux. From the results of Adair and Price[15] the observed flux corresponds to a production cross section of 0.6 μb using their production model and a quark mass of 10 BeV/c^2. The cross section which corresponds to the flux varies approximately as $M^{3.4}$, where M is the quark mass. For M equal to 10 BeV/c^2 this cross section[18] is about equal to 0.15 $(\hbar/Mc)^2$. Again using this model to calculate the energy loss of quarks passing through the atmosphere the flux suggested by these measurements would result from a quark-to-nucleon ratio of about 10^{-6} for particles in the primary cosmic-ray flux with a kinetic energy greater than 30 BeV. This number is valid for quark masses greater than 10 BeV/c^2 but will not be very much different for smaller masses down to about 5 BeV/c^2.

It is interesting to note that if such a bombardment of quarks has continued over the age of the earth's crust, taken as about 10^9 years, and if the geologically active depth of the earth's crust is taken as about 300 kg/cm^2, the mean density of quarks would be about 500 per gram. The chemistry of quarks appears to be obscure but it seems likely that there would be considerable differentiation of quarks in geochemical and biochemical processes and mean values given here can only be a guide to a more carefully reasoned estimate.

[18] Statistical models of particle production suggest much smaller cross sections. The relevance of these models to baryon production has not been established. G. Domokos and T. Fulton, Phys. Letters **20**, 546 (1966); V. M. Maximinko, I. N. Sisakjan, E. L. Feinberg, and D. S. Chernavsky, JETP Letters (to be published).