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Search for fractionally charged particles in cosmic rays at large zenith angles

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We have performed a single-particle search for fractional charge in cosmic rays having residual ranges at sea level >250 g/cm^2 concrete and zenith angles between 45° and 90°. The detector is a hodoscope of 24 layers of plastic scintillator, eight layers of multiwire proportional chambers, and two layers of lucite Cherenkov counters. The acceptance of the instrument is 4.0×10^3 cm^{2}sr. An analysis of 3.5×10^6 triggers during a running time of 8×10^5 sec yields no particles with charge $Q=\frac{1}{3}$ or $Q=\frac{2}{3}$ and velocities greater than $\approx 0.1c$. We deduce an upper limit on the flux of fractionally charged particles of 8.5×10^{-10} (cm^{2}sr sec)$^{-1}$ for relativistic $Q=\frac{1}{3}$ and 7.6×10^{-10} (cm^{2}sr sec)$^{-1}$ for $Q=\frac{2}{3}$.

I. INTRODUCTION

Experiments to discover fractionally charged fundamental particles produced in accelerators or in cosmic rays have been attempted without confirmed success since the quark model was first proposed in 1964[1]. Despite this failure, it is important to extend this search where possible, particularly in view of the recently reported experimental evidence for fractionally charged matter.[2]

The present cosmic-ray experiment utilizes an apparatus constructed primarily to search for free quarks in high-energy e^+e^- annihilation at the Positron-Electron Project (PEP) located at the Stanford Linear Accelerator Center (SLAC). The basic function of the detector is simple; it samples ionization energy loss in plastic scintillators and measures particle velocity ($\beta=v/c$) by time of flight. The charge (Q) of the particle is inferred from the Bethe-Bloch formula

$$dE/dx \propto \frac{Q^2}{\beta^2} f(\beta) ,$$

where $f(\beta)$ depends on the material, but is only a slowly varying function of β. Good tracking is achieved with multiwire proportional chambers allowing reliable rejection of backgrounds from soft γ rays that have plagued previous searches for weakly ionizing charged particles in cosmic rays.[3] The detector is highly segmented and has high redundancy having been designed for the intense-background-radiation environment of colliding-beams physics. The acceptance for cosmic rays is large, allowing significant flux limits to be set in a few weeks of running.

In this paper, we present results from a single-particle search for penetrating fractionally charged particles at large zenith angles conducted during August 1980. The total live time was 8×10^5 sec. The apparatus is located at sea level in a PEP-interaction-region tunnel. Thus, in addition to the intervening atmosphere, cosmic-ray particles must penetrate the 250-g/cm^2-thick shielding blocks which surround the detector.

It has been noted[4] that single-particle searches at large zenith angles may be sensitive to quarks produced within high-energy air showers because the intervening atmosphere acts as a filter for the less penetrating particles in the shower. Positive indications for fractionally charged particles in air showers have been previously reported by McCusker,[5] although the method employed has been criticized and the conclusions have been contradicted by results from later experiments. If quarks in cosmic-ray showers can be isolated by their increased penetration or distinct arrival time they would be observable here.

Three fractional-charge candidates with low velocities were reported by Yock[6] in a vertical single-particle search. Such low-velocity particles with fractional charge would have been missed in other cosmic-ray searches without time-of-flight measurement, but they can be observed in our detector. We note, however, that with increased running time and a slightly modified apparatus Yock did not confirm his previous result.[7]

THE DETECTOR

The detector configuration is illustrated in Fig. 1. Three types of charged-particle detection are provided: Long scintillation counters of varying sizes measure ionization energy loss and a subset of these also measures particle velocity, multiwire proportional chambers provide tracking information,and two layers of plastic Cherenkov counters provide a redundant check on particle velocity to supplement counter time-of-flight information. One layer, $S4$, has scintillating light pipes to flag events with a particle that makes small Cherenkov pulses in other light pipes. The sizes and angular orientation of the components are summarized in Table I. Each counter is equipped with two photomultipliers, one at each end.

For e^+e^- annihilation experiments, the detector can be visualized as two identical arms each subtending one face of a cube centered at the interaction region and thus the detector covers a solid angle of $\frac{1}{3}\times 4\pi$ sr. For cosmic-ray detection the acceptance depends on the trigger requirements. We define a hit as a single photomultiplier signal above $\frac{1}{30}$ of that made by a minimum-ionizing, $Q=1$ particle, normally incident on the center of the counter. For our trigger, we require at least one counter with both photomultipliers hit in layer TR1 (see Table I) on either arm in coincidence with at least one counter with both photo multipliers hit in layer TR2 on each arm. This trigger configuration ensures that a cosmic-ray particle travels through many but not necessarily all of the detector layers. This trigger is fully efficient for charge 1 and $\frac{2}{3}$. For charge $\frac{1}{3}$ the efficiency is 0.86 at $\beta=1$ and rises to unity at $\beta=0.6$.

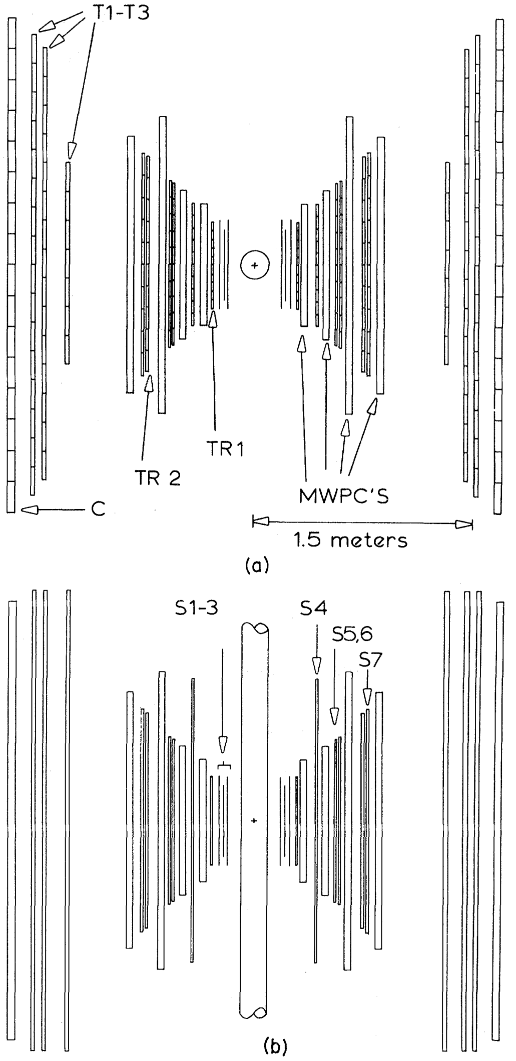

FIG. 1. A diagram of our detector showing elevation (a) and plan (b) views. The scintillator, proportional chamber, and Cherenkov components are indicated. As listed in Table I, the components are labeled from the point of symmetry out through either arm. The detector arms occupy two sides of a cube which is 3 m on a side.

With this trigger and the geometry of the detector as described, our detector covers a range of zenith angles from 45° to 135°. We calculate our admittance, however, just by considering angles above the horizontal, i.e., angles less than 90°. The resulting integration over area × solid angle gives

TABLE I. Description of detector components on each arm.

Layer	Detector type	Distance from center (cm)	Orientation angle[a]	No. of elements	Pulse height	Time of flight	Tracking
S1	Scint.	21	90°	8	Yes	No	No
S2	Scint.	23	0°	8	Yes	No	No
S3	Scint.	24	90°	10	Yes	No	No
TR1	Scint.	30	0°	10	Yes	Yes	No
M1	MWPC	36	80°		No	No	Yes
S4	Scint.	43	0°	10	Yes	No	No
M2	MWPC	49	0°		No	No	Yes
S5	Scint.	56	0°	10	Yes	No	No
S6	Scint.	58	0°	10	Yes	No	No
M3	MWPC	66	110°		No	No	Yes
TR2	Scint.	75	0°	10	Yes	Yes	No
S7	Scint.	77	0°	10	Yes	No	No
M4	MWPC	80	0°		No	No	Yes
T1	Scint.	139	0°	7	Yes	Yes	No
T2	Scint.	146	0°	15	Yes	Yes	No
T3	Scint.	153	0°	16	Yes	Yes	No
C1	Cherenkov	165	0°	16	Yes	No	No

[a] For counters, 0° means the long axis is parallel to the ground. For MWPC's 0° means the wires are parallel to the ground.

an admittance of 4.0×10^3 cm^2. The distribution in zenith angle for a small sample of events is shown in Fig. 2. This distribution is compared with a Monte Carlo calculation which assumes that the cosmic rays arrive according to a cosine-squared distribution in the zenith angle.

Each photomultiplier pulse height is recorded by analog-to-digital converters. In addition, discriminators and time-to-digital converters are connected to the photomultipliers in layers TR1, TR2, T1, T2, and T3 on each arm. The typical scintillation counter yields ~ 150 detected photoelectrons for a minimum-ionizing unit-charged particle. The position dependence of the pulse height of the scintillation counters is compensated by an algorithm which takes the square root of the product of pulse heights for each end. This procedure is exact for purely exponential attenuation of the scintillation light. Measurements indicate that the charge-measurement error introduced by the inaccuracy of this assumption is $<2\%$. Figure 3 shows a typical pulse-height distribution for a single counter. Particles passing through the edges of counters lead to the small pulse heights shown in the figure. A correction for this "edge" effect is made by adding in the energy loss measured in the appropriate adjacent counter. The overall normalization for energy loss is obtained from cosmic-ray muons.

The time-of-flight resolution was also determined with cosmic-ray muons. Counter edge hits were used to measure the response for pulse heights down to $\frac{1}{10}$ of normal. The time of a hit in a particular counter is determined by taking the sum of the times measured in each of the two phototubes. After correcting for pulse-height dependence of time-of-flight, we obtained a single-counter time resolution of 150 psec for a minimum-ionizing $Q=1$ particle.[8] The single-counter time resolution increases to about 0.7 nsec for pulse heights of $\frac{1}{9}$ normal. The position of the hit along the counter can be determined by taking

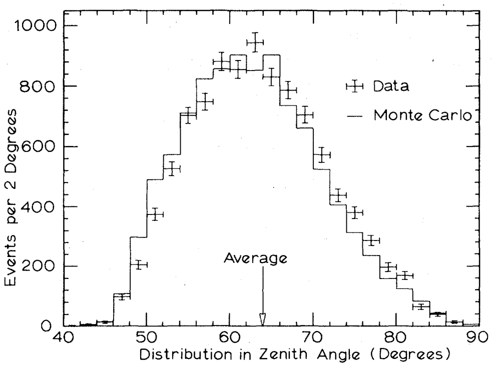

FIG. 2. Distribution of zenith angles for cosmic-ray tracks triggering our apparatus. The Monte Carlo calculation assumes a $\cos^2\theta$ distribution for cosmic rays.

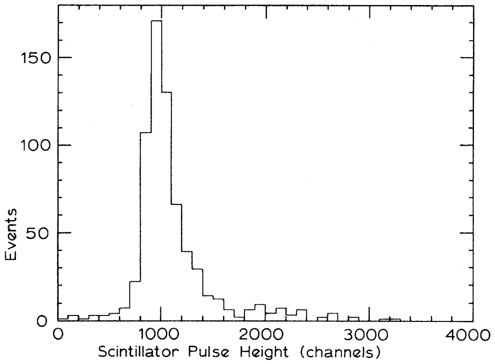

FIG. 3. A typical pulse-height spectrum from one of the counters. The low pulse heights are from particles traversing the counter edge. These edge hits are used as an aid to study the detector behavior for low pulse heights.

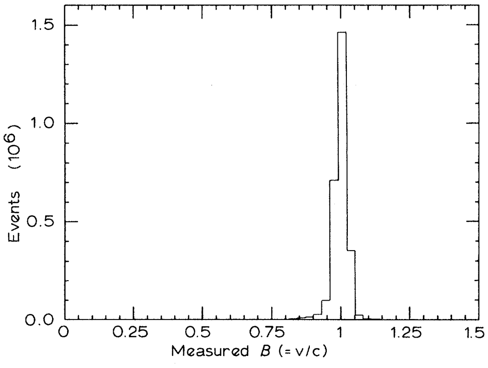

FIG. 4. Histogram of β as measured on cosmic rays during the course of this experiment. The rms resolution is $\pm 1.8\%$.

the difference of each of the two times and correcting for the velocity of scintillation light. The resolution (standard deviation) for this position determination is ± 2.5 cm for a minimum-ionizing $Q=1$ particle. The resolution for particle velocity in the experiment reported here averaged over all tracks is $\Delta\beta/\beta \approx \pm 1.8\%$. The dynamic range of the time-digitizing electronics restricts our velocity measurement to values greater than about 0.1 *c*. Figure 4 is a histogram of the number of tracks vs β.

The lucite Cherenkov counters form the two outermost layers of the detector. Each counter is viewed by a photomultiplier on each end whose pulse height is recorded by an analog-to-digital converter. The threshold β is approximately 0.70. The Cherenkov counters reduce the possibility of misidentifying a $Q=1$ particle with typical ionization, but incorrectly determined velocity as a low-charge particle.[9]

A total of eight layers of multiwire proportional chambers (MWPC's) are present in the detector. The orientation of the MWPC's is listed in Table I. The chambers have a 2 × 1.2 cm gap and are filled with 80% Ar–20% CO_2. Tests with reduced high voltage and comparisons with gas fills of different densities in other chambers indicate the chambers are 98% efficient for minimum-ionizing $Q=\frac{1}{3}$ and >99% efficient for $Q=\frac{2}{3}$ and $Q=1$.[10] Cathode strips are read out by electromagnetic delay lines, but only anode wire-latch information was used in the current experiment. The spatial resolution for tracking is about ± 0.5 cm.

For each trigger the entire detector is read out through CAMAC interfacing into a VAX 11/780 on-line computer and the data is recorded on magnetic tape.[11] The information relevant to the present study is (1) Pulse-height information from the 496 photomultipliers connected in pairs to scintillation counters, (2) timing information from a subset of 232 photomultipliers, (3) Pulse heights from 64 photomultipliers connected in pairs to Cherenkov counters, and (4) latched anode wires from eight MWPC's. The results given here were obtained with an off-line program. The detector was monitored on-line with a sampling of cosmic-ray triggers.

ANALYSIS

Approximately 3.5 × 10^6 triggers were collected on magnetic tape. These were reduced to a small number of fractional-charge candidates using an analysis procedure we will now describe.

First, using a combination of scintillator and MWPC information, we attempted to locate events with only a single track passing through the detector. A track was defined as a line having coordinates in at least five out of eight MWPC's and a fitting χ^2 of less than 10 per degree of freedom. This procedure, which yielded a single track for 85% of the triggers, has essentially a 100% efficiency for minimum-ionizing $Q=\frac{1}{3}$ particles. The remainder of the triggers are mostly complicated events probably due to air showers and interactions in the PEP concrete shielding tunnel.

After a track was found, we proceeded to determine the particle velocity. We first required at least three time-of-flight (TOF) counters to be intercepted along the track. To eliminate bad TOF values from multiple hits, these counters were also required to have a position along the counter as measured by the time difference to be within 3.5 standard deviations of the projected track intersection. We then fit the times to a straight line to determine the velocity which was assumed in general to be constant. If the velocity was low or the χ^2 was bad, times were fit to a parabola allowing the velocity of particles to slow down in the detector. Finally, the velocity measurement was accepted if the χ^2 was less than 5 per degree of freedom. This procedure yielded a value of β on 99% of the tracks.

Next we used the scintillation layers to measure the ionization energy loss (dE/dx) of the track. As mentioned earlier, we added pulse heights of the extrapolated hit counter and the adjacent counters in the same layer. If a track came within 2 counter thicknesses of the top or bottom of the layer, or if it came within 2 cm of the end of the counter, that layer was not included in the dE/dx determination. In addition, we required the summed energy loss in the layer to be at least $\frac{1}{100}$ of minimum ionizing.

If the digitizer for any of the phototubes used registered a saturating value (about four times minimum ionizing), that value was nevertheless included. Candidates arising from the use of this data will be discussed later. Finally, it was required that there be at least six scintillation layers satisfying the above cuts along the track. These stipulations yielded a dE/dx measurement on more than 99% of the tracks. The efficiency for $Q=\frac{1}{3}$ particles is >98% from Monte Carlo studies. dE/dx is then calculated by taking the truncated mean of the 80% of the individual layer measurement, which yielded the smallest variance. Taking the truncated mean reduces the Landau fluctuations in the pulse-height distribution.

Finally, we inferred the charge Q from β and dE/dx. If β could not be determined it was assumed to be 1.0. To a reasonable approximation, we have

$$Q=\beta(dE/dx)^{1/2} .$$

However, for low particle velocities this expression can be in error by up to 15%. To obtain an empirical formula for Q, we simulated the dE/dx of low velocity particles using a Monte Carlo program based on a more exact form of the Bethe-Bloch formula and a Vavilov distribution (instead of Landau). The form of a dE/dx vs β is shown in Fig. 5.

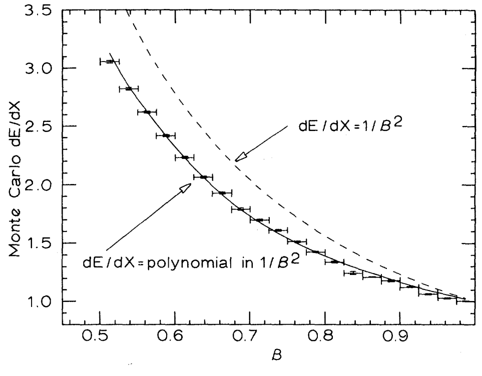

FIG. 5. Result of Monte Carlo determination of the most probable energy loss (dE/dx) as a function of velocity β. The curve through the points is a fitting function used in the analysis. Also shown is a curve of the function $1/\beta^2$.

The observed Q for this experiment is histogrammed in Fig. 6. All events with Q less than 0.8 were retained for the subsequent, more stringent analysis. The charge resolution obtained throughout the entire data taking is about 3.5%. Monte Carlo studies show that the probability of a $Q=\frac{2}{3}$ particle giving a measured charge value greater than 0.8 is less than 5%.

Up to this point, the requirements for a charged-particle track have been extremely loose. This has been done to ensure high efficiency and also to yield a sample of quark-candidate events with which we can study our backgrounds. With the observed resolution in charge, all events with charge less than 0.80 must be caused by a type of background, or by free fractional charge. The 271 events which remain at this point are histo-

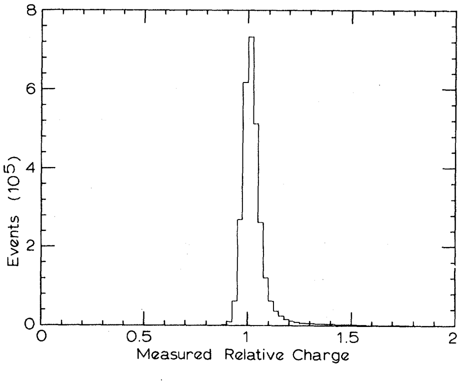

FIG. 6. Histogram of the charge Q as measured with cosmic rays during the course of this experiment. The rms resolution of the peak is ±3.5%.

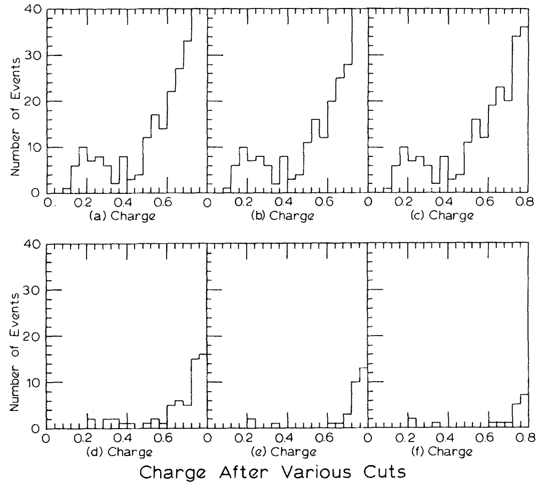

FIG. 7. Charge distribution at various stages of the analysis (see Table II). The 18 events remaining in Fig. 7(f) were scanned by hand and none were found to be evidence for fractional charge (see Table III).

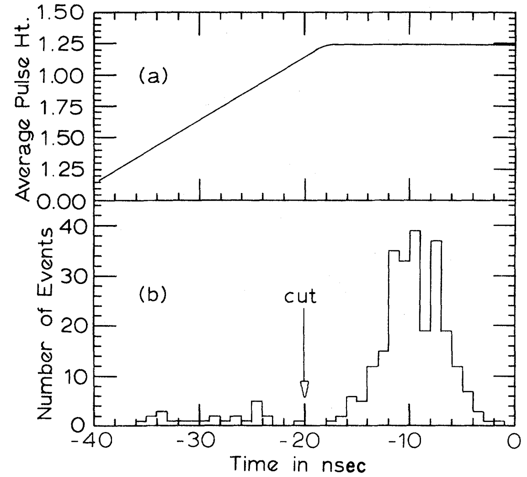

FIG. 8. (a) Average pulse height in the scintillators versus the time the scintillator is hit. The fall-off for low times is due to clipping of the pulse-height digitizers. (b) Number of events versus average time in the detector for the first set of candidates. Events with average time less than −20 nsec are rejected.

grammed versus charge in Fig. 7(a). Each of these events was examined individually. No convincing candidates remained. The events were generally found to be either a result of some easily recognized systematic problem, or they appeared to be a showering event that passed the analysis but could not be interpreted as a single track. In the next section, however, we offer a reduction in the number of candidates using a systematic series of cuts which illuminate the sources of the candidate events.

EXAMINATION OF THE LOW-CHARGE EVENTS

Before proceeding with a software analysis of the candidates, particles with velocities too low to be consistent with a proton were examined. Most were due to backgrounds, but the rest were consistent with deuterons. Some of these appeared to be low-charge candidates, because their velocity was low enough to result in a dE/dx high enough to saturate the analog-to-digital converters (ADC's). None, however, had a low enough velocity to be a $Q=\frac{2}{3}$ particle which saturated the ADC's. So, in the following analysis, saturated ADC values were not used for the dE/dx measurement. The ADC's saturate at approximately four times the pulse height of a $Q=1$, $\beta=1$ particle.

The first systematic background we discuss is due to the gating of the pulse-height digitizers. If a normal cosmic ray passes through the detector but does not generate a trigger, a spurious pulse may cause the trigger to be satisfied some time after the original particle passes through. The signals from these "early cosmic" events arrive before the digitizers are gated and reduced pulse heights are obtained, simulating a low dE/dx measurement.[12] To eliminate this background we require the average time in the event to be greater than −20 nsec. [The time- digitizing electronics were constructed in such a way that normal cosmic-ray events gave average times between −18 and 0 nsec (see Fig. 8).] Even with the time resolution expected for $Q=\frac{1}{3}$, $\beta=1$ particles, this cut is essentially 100% efficient. The charge distribution after this cut is shown in Figure 7(b).

Many of the candidates arise from incorrectly measured values of β. These are generally rejected because of hits in the Cherenkov counters, but a large fraction of the events were traced to hardware malfunctions in a few channels of TOF electronics. After eliminating these channels during the periods of malfunction we arrive at the charge distribution in Fig. 7(c).

Having eliminated candidates due to systematic effects in the detector, we now turn to more specific physical backgrounds. The most serious of these stems from the loose "track" requirements. We required only five independent MWPC wires and allowed rather large errors. Since four wires are necessary just to determine a line in space, an accidental fifth is all that it takes and is not that uncommon. To better define a track we now required that it intercept at least eight scintillators in which both phototubes have a pulse-height hit in them of at least $\frac{1}{30}$ minimum-ionizing $Q=1$. If the track did not satisfy this, the event is removed from the sample. This reduces the number of fractional-charge candidates to 59 and illustrates the need for accurate tracking. The resulting histogram is shown in Fig. 7(d).

Examination of the remaining candidates indicated that there was still a significant number of accidental tracks. This led us to require a greater consistency in both dE/dx and time measurements. A root-mean-square variance in the pulse-height measurements was required to be less than 50% of the dE/dx value. This requirement is seen to be greater than 99% efficient on single-track cosmic rays and Monte Carlo studies indicate that the efficiency for $Q=\frac{1}{3}$ particles is at least 98%. Finally, to eliminate velocity errors, we required the fit for β use at least four TOF counters. If this was not satisfied, the particle velocity was assumed to be 1.0. The charge distributions resulting from these cuts are shown in Figs. 7(e) and 7(f). At this point there are 18 candidates remaining.

The results of the above cuts are summarized in Table II. Our analysis procedure illustrates that, at each stage, there are spurious candidates that might look like a quark in a less elaborate detector. The accumulated probability of rejecting a good event by these cuts is less than 1% for $Q=1$, less than 5% for $Q=\frac{2}{3}$, and less than 2% for $Q=\frac{1}{3}$. Instead of imposing additional cuts, the remaining events were carefully examined by us for evidence of fractionally charged particles. None passed our inspection. The events appeared to fall into the categories outlined in Table III.

RESULTS

With an overall analysis efficiency of 98% for $Q=\frac{1}{3}$ and 95% for $Q=\frac{2}{3}$, a trigger efficiency of 86% for relativistic $Q=\frac{1}{3}$, with a live-time of 8 $\times\ 10^5$ sec, and with an admittance of 4.0 $\times\ 10^3$ cm^2 sr, we obtain for the flux F of fractionally charged particles with $45^\circ \le \theta_{\text{zenith}} \le 90^\circ$

$$F \le \begin{cases} 8.5\times10^{-10}, & Q=\frac{1}{3},\quad 0.6\le\beta\le1.0 \\ 7.3\times10^{-10}, & Q=\frac{1}{3},\quad 0.1\le\beta\le0.6 \\ 7.6\times10^{-10}, & Q=\frac{2}{3},\quad 0.1\le\beta\le1.0 \end{cases}$$

in units of $(\text{cm}^2\text{sr sec})^{-1}$ at 90% C.L.

We compare our results with those of other searches at large zenith angle in Table IV.

An important feature of this experiment is the wide range of velocities we have investigated. Yock (Ref. 6) has reported three candidates for

TABLE II. Summary of candidate cuts.

Level	Cuts imposed	Q histogram Fig.	No. of candidates left	Monte Carlo efficiency (accumulated) $Q=\frac{1}{3}$	$Q=\frac{2}{3}$
0	None (all triggers)		3.5×10^6		
1	Single track in MWPC's		3.0×10^6		
2	Measure dE/dx with at least six layers	6	2.9×10^6	> 99%	> 99%
3	$Q \le 0.80$	7(a)	271	> 99%	> 95%
4	Average time ≥ -20 nsec	7(b)	247	> 99%	> 95%
5	Hardware checks	7(c)	226	> 99%	> 95%
6	No. of hits along track ≥ 8	7(d)	59	> 99%	> 95%
7	$\sigma(dE/dx) \le 0.5\ dE/dx$	7(e)	31	> 98%	> 95%
8	≥ 4 TOF counters for velocity	7(f)	18	> 98%	> 95%
9	Hand scanning		0		

TABLE III. Descriptions of remaining candidates.

Symptom	Number of events	β	Charge
(1) Multiple particles, showers, or interactions in a section of the detector giving incorrect time information and a bad value for β. Recalculation of β gave normal values for charge.	6	0.521 0.541 0.548 0.582 0.579 0.596	0.786 0.712 0.736 0.781 0.735 0.734
(2) Incorrectly determined tracks having large azimuthal angles outside the detector fiducial volume giving too large a value for particle path length in the detector. These arose from the track using an incorrect MWPC coordinate (which can result from hardware errors or spurious hits). Path length recalculated from positional information in scintillators from TOF information gave normal charge.	3		0.759 0.785 0.727
(3) Accidental tracks formed from parts of showers in the detector with no β measurement and several low-pulse-height hits in scintillators. A single-particle track could not be seen in the event and they were therefore rejected.	3		0.783 0.205 0.218
(4) Slowing particles in the detector which stop before accumulating enough TOF data for the existing software to recognize it as a slowing track. The value of β was recalculated from the first portion of the track giving a somewhat hgher value for velocity and a normal charge.	2	0.435 0.321	0.787 0.360
(5) Early particle which did not satisfy the trigger but passed the "early cosmic" cut because of random normal time hits in the TOF counters.	1	0.753	0.778
(6) Slight mistracking because of an error in an MWPC coordinate. Scintillator TOF position indicated that the particle actually passed through scintillator light guides. This is supported by the presence of large pulse height in layer S4.	1	0.988	0.724
(7) Spurious TOF value along track giving an incorrect β. Hits in Cherenkov counters indicated a fast particle. β was recalculated by hand from the remaining TOF data, and a normal charge was found.	1	0.488	0.609
(8) Slight mistracking giving zenith angle just greater than 45°, but scintillator pattern shows that particle path traveled through top and bottom layer edges giving low pulse height.	1	0.953	0.767

TABLE IV. Limits of fractionally charged particles from cosmic-ray searches at large zenith angles

Experiment	Range of zenith angles	$Q=\frac{1}{3}$ Flux (90% C.L.) $[(\mathrm{cm}^2\mathrm{sr\ sec})^{-1}]$	β	$Q=\frac{2}{3}$ Flux (90% C.L.) $[(\mathrm{cm}^2\mathrm{sr\ sec})^{-1}]$	β
Kifune *et al.* (Ref. 3)	$45° \le \theta \le 90°$	$\le 2.3\times10^{-10}$	≈ 1		
Hicks *et al.* (Ref. 13)	$75° \le \theta \le 90°$	$\le 1.7\times10^{-8}$	≈ 1	$\le 1.7\times10^{-8}$	≈ 1
Franzini and Shulman (Ref. 14)[a]	$\theta \approx 84°$			$\le 5.1\times10^{-8}$	$0.5 \le \beta \le 0.9$
This Experiment	$45° \le \theta \le 90°$	$\le 8.5\times10^{-10}$ $\le 7.3\times10^{-10}$	$0.6 \le \beta \le 1.0$ $0.1 \le \beta \le 0.6$	$\le 7.6\times10^{-10}$	$0.1 \le \beta \le 1.0$

[a] This experiment was designed to detect slow massive particles. Though pulse-height information was retained, efficiencies and results for fractional charge were not discussed.

fractional charge, all with low velocity. We can make only a very qualified statement concerning this claim at this time. One important difference between the two experiments is that ours searches at large zenith angles while the previous experiment searched vertically. A second and perhaps more crucial difference is the additional material in the concrete PEP shielding tunnel which may have absorbed particles such as those reported by Yock. Our detector has been modified to alleviate these problems and the results will be presented later.

In conclusion, we would like to point out experiments such as this differ greatly in sensitivity. Without a clear idea of how the free quark might appear in cosmic rays, sophisticated instruments should be applied to this problem whenever the opportunity arises.

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