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A search for relativistic quarks in the cosmic radiation

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Abstract. A scintillation counter telescope of aperture 0·47 m^2 sr and incorporating layers of crossed neon flash tubes has been used to search for relativistic $e/3$ and $2e/3$ quarks in the near-vertical cosmic radiation at sea level. Events were selected where the scintillator pulse heights were as expected for quarks and the corresponding flash tube records were studied.

No events satisfied all the rigorous acceptance criteria and only upper limits can be given for the quark flux. These are, at the 90% confidence limits:

$$< 1{\cdot}15 \times 10^{-10}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1} \text{ for relativistic } e/3 \text{ quarks}$$

and

$$< 8{\cdot}0 \times 10^{-11}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1} \text{ for relativistic } 2e/3 \text{ quarks.}$$

1. Introduction

The experimental results on resonances and new particles obtained using accelerators can be interpreted in terms of three fundamental particles with fractional charge which have been termed quarks. To date there has been no direct evidence for the existence of these particles from accelerator studies although a lower limit to the quark mass of several GeV/c^2 has been set. If quarks exist as separate entities, and if their mass is not too great, they should be detectable amongst the secondaries of high-energy cosmic-ray interactions. The process with the lowest energy threshold for quark production is

$$\text{N}+\text{N} \rightarrow \text{N}+\text{N}+\text{q}+\bar{q}.$$

For $M_q = 10$ GeV/c^2, for example, the threshold energy in the laboratory system is 240 GeV and the flux of primary cosmic-ray nucleons of energy greater than this value is 2×10^5 m^{-2} d^{-1} sr^{-1}. The expected flux of quarks low in the atmosphere depends on their production cross section in nucleon–nucleon collisions, their interaction cross section with air nucleons σ_q and the fraction K_q of their energy retained in a q–N collision. If σ_q is about the same value as for nucleons (or smaller), and if $K_q = (1-M_p/M_q)\, 0{\cdot}5$ as suggested by Cocconi (1965), then all the produced quarks will reach sea level in the vertical direction with relativistic velocities. $K_q = (1-M_p/M_q)0{\cdot}5$ implies the average quark four-momentum transfer in a quark–nucleon collision is the same as that for nucleon–nucleon collisions. The other limiting case of $K_q \rightarrow 0$ has been considered by Ashton (1965), who showed that some heavy quarks would reach sea level even in this case, although the majority would have $\beta < 0{\cdot}5$.

In the experiment to be described here the method adopted has been to use scintillators to enable an accurate estimate of the charge of the penetrating cosmic-ray particles at sea level to be determined and to use visual detectors (neon flash tubes) to indicate the passage of a single particle through the detector.

2. Experimental arrangement

A scale diagram of the apparatus is shown in figure 1. The construction and performance of the large area scintillation counters A, B, C, D, E and F have been described by Ashton *et al.* (1968). To find the most probable pulse height from each scintillation counter produced by relativistic muons traversing the telescope a sixfold coincidence ABCDEF is used to register their passage. The pulse from each counter is displayed sequentially on a

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single oscilloscope and photographed, and a photograph is taken of the flash tubes in both the front and side elevations (figure 1). The resulting pulse height distribution for each counter (called a C distribution) is found to be consistent with the distribution obtained when a similar calibration is made using the selection $G_aG_bG_c$, after the non-uniformity of response of the scintillators over their area is taken into account, together with the increased track length in the phosphor for highly inclined particles.

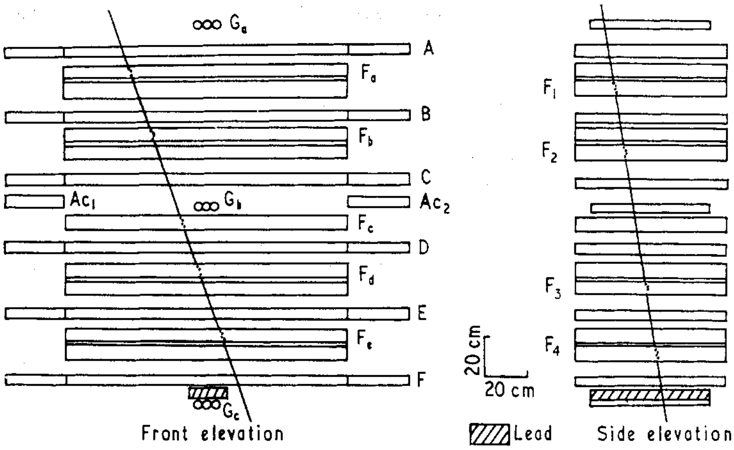

Figure 1. Quark telescope apparatus, A, B, C, D, E, F, Ac_1, Ac_2 are scintillation counters; F_a, F_b, F_c, F_d, F_e, F_1, F_2, F_3, F_4 are flash tube trays; G_a, G_b, G_c are Geiger counters.

As the most probable value of the light output from a scintillator which is traversed by a particle of charge e and velocity β is proportional to z^2e^2/β^2, the most probable pulse heights produced by relativistic $e/3$ and $2e/3$ quarks in a single scintillator are $0{\cdot}11E$ and $0{\cdot}44E$ respectively, where E is the most probable pulse height produced in a given scintillation counter from the C distribution measurement.

To select quarks it is, in principle, only necessary to place two discriminators on each counter, one at a level of about $0{\cdot}85E$ and the other at a level of about $0{\cdot}05E$ and to require a pulse lying in this region from all six scintillation counters. In practice one requires the upper discrimination level to be set rather high so that no $2e/3$ quarks are lost, but if placed too high the rate of muons triggering the selection system becomes large and a compromise has to be reached. With the selection system $0{\cdot}05E$ to $0{\cdot}85E$ on all six counters and using Ac_1 and Ac_2 in anticoincidence (to suppress Čerenkov-light guide pulses) the trigger rate was found to be 30 h^{-1} and inspection of the flash tube film showed that effectively all the trigger events were due to what appeared to be weak electron–photon showers (indicated by only a few random flashes in the visual detector) incident on the apparatus from above and from the side. After this preliminary series of runs, the separation of discriminator levels was accordingly reduced.

Table 1 gives details of the selection systems used and the running times for each.

2.1. *Scintillator line shapes*

The pulse height distribution for a single counter produced by the passage of single relativistic muons through the telescope is shown in figure 2. The shape of this distribution is governed by several factors, notably the Landau distribution of energy loss, fluctuations in the number of photoelectrons produced at the photocathodes, fluctuations in the photoelectron multiplication process and the non-uniformity of the counter. The contributions of these different processes to the full width at half-height of the scintillation line are 18%, 16%, 16% and 25%, respectively. Knowing the average number of photoelectrons produced by a relativistic muon in traversing the scintillator to be 220 and the r.m.s. pulse height to be equal to the average pulse height produced by single electrons leaving the

Table 1. Running times for different selection systems and counting rates of the apparatus

	Run number				
	T1–T70	Q1–Q49		Q50–Q97	
	Type of selection and discriminator levels used				
	$2e/3$	$e/3$	$2e/3$	$e/3$	$2e/3$
Counter A	0·20–0·85E	0·05–0·30E	0·30–0·85E	0·05–0·30E	0·30–0·85E
B	0·20–0·85E	0·05–0·30E	0·30–0·85E	0·05–0·30E	0·30–0·85E
C	None	0·05–0·30E	$\geqslant$ 0·30E	0·05–0·30E	$\geqslant$ 0·30E
D	0·20–0·85E	0·05–0·30E	0·30–0·85E	0·05–0·30E	0·30–0·85E
E	0·20–0·85E	0·05–0·30E	0·30–0·85E	0·05–0·30E	0·30–0·85E
F	0·20–0·85E	0·05–0·30E	0·30–0·85E	0·05–0·30E	0·30–0·85E
ABCDEF rate	1·7 . 10^3 min^{-1}	1·87 . 10^3 min^{-1}	1·65 . 10^3 min^{-1}	1·87 . 10^3 min^{-1}	1·65 . 10^3 min^{-1}
μ-reject rate	2.10^4 min^{-1}	3.10^4 min^{-1}	2.10^4 min^{-1}	3.10^4 min^{-1}	2.10^4 min^{-1}
Anti-rate	4.10^4 min^{-1}	4.10^4 min^{-1}	4.10^4 min^{-1}	4.10^4 min^{-1}	4.10^4 min^{-1}
Total veto rate	6.10^4 min^{-1}	7.10^4 min^{-1}	6.10^4 min^{-1}	7.10^4 min^{-1}	6.10^4 min^{-1}
Trigger rate	2·3 h^{-1}	1·4 h^{-1}	0·75 h^{-1}	1·4 h^{-1}	0·75 h^{-1}
Total running time	1255 h	758 h	720 h	888 h	591 h
Effective running time for relativistic $e/3$ quarks	—	669 h	—	776 h	—
Effective running time for relativistic $2e/3$ quarks	1002 h	—	610 h	—	506 h
Previous particle indicator used	No	No	No	Yes	Yes
Number of quark candidates	13	6	1	4	1
Number of background muons expected	2·4 ±0·9	2·7 ±1·0	0·10 ±0·04	None	None

E is the most probable pulse height produced by a relativistic muon in a scintillation counter when selected by an ABCDEF coincidence. The ABCDEF coincidence rate was measured with the discriminator level on each counter set at the lower level indicated in the table. The μ-reject rate refers to the total rate of pulses from all six counters which are larger than the upper discriminator levels shown in the table. The anti-rate is the total rate of pulses from Ac_1 and Ac_2 (figure 1).

photocathode, the expected scintillation line shapes for relativistic $e/3$ and $2e/3$ quarks have been calculated and are also shown in figure 2. It is seen that with the discriminator windows shown in table 1 relativistic $e/3$ and $2e/3$ quarks are expected to be detected with high efficiency (in what follows it is assumed that the quarks under discussion are relativistic unless stated otherwise).

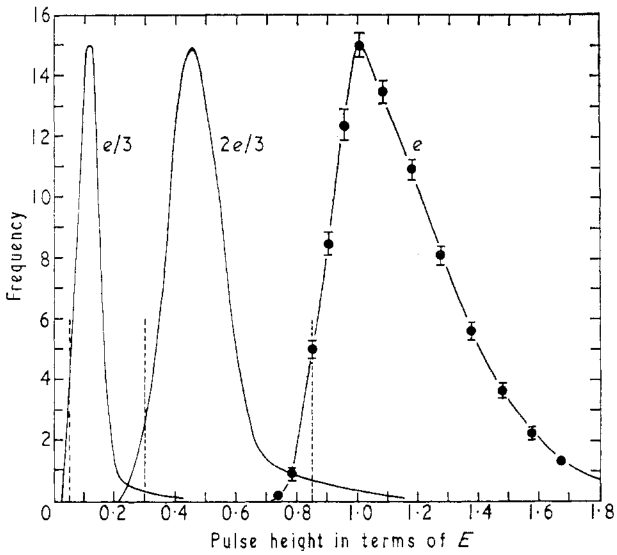

Figure 2. The measured scintillation line shape for muons traversing a scintillation counter in the telescope and the calculated line shapes for relativistic $e/3$ and $2e/3$ quarks. E is the most probable pulse height produced by a relativistic muon. The broken lines indicate the discrimination levels used in the experiment.

2.2. *Neon flash tubes*

The flash tubes used have internal diameter 1·5 cm, wall thickness 1 mm and are filled with neon to a pressure of 600 torr. The average track length of a particle traversing a tube is 1·18 cm and on the average a relativistic muon produces about 22 ion pairs. The corresponding numbers of ion pairs for $2e/3$ and $e/3$ quarks are 10 and 2·5 respectively.

The efficiency of the tubes for detecting quarks can be calculated from a knowledge of these numbers and the variation of layer efficiency with the time delay between particle and pulse, using the theory of flash-tube operation given by Lloyd (1960). The measured efficiency against time delay for relativistic muons is given in figure 3, and in figure 4 the expected efficiency time delay curves for $2e/3$ and $e/3$ quarks are shown. In the experiment a time delay of 5 μs was used and from figure 4 it is seen that the expected layer efficiency is 77% for $2e/3$ and 58% for $e/3$ particles. These efficiencies are high enough for the flash tubes to act as efficient detectors even at the low level of ionization due to an $e/3$ quark.

2.3. *Correlation between scintillator pulse heights*

On the passage of a relativistic muon through the telescope the six scintillator pulse heights are recorded. After dividing each scintillator pulse height by the most probable pulse height produced by a relativistic muon in that counter, the mean of the six pulse heights, $\bar{v}$, and the standard deviation of the mean, α, are calculated. The measured frequency distribution of $\alpha/\bar{v}$ is shown in figure 5 for events in which the pulse heights in all six counters are less than twice the most probable pulse height. The distribution is seen to be peaked at $\alpha/\bar{v} = 7\%$, with virtually no events having $\alpha/\bar{v} > 20\%$.

Using the expected scintillator line shapes shown in figure 2, and accounting for the selection discriminator levels used in the experiment, the expected frequency distribution of $\alpha/\bar{v}$ for quarks has been computed using a Monte Carlo method. These results are also shown in figure 5.

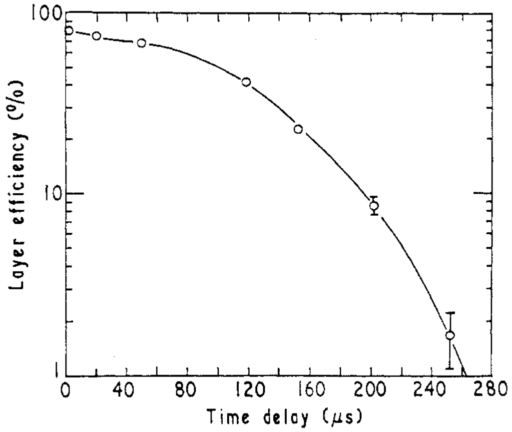

Figure 3. The measured efficiency–time delay curve for the flash tubes to record relativistic muons.

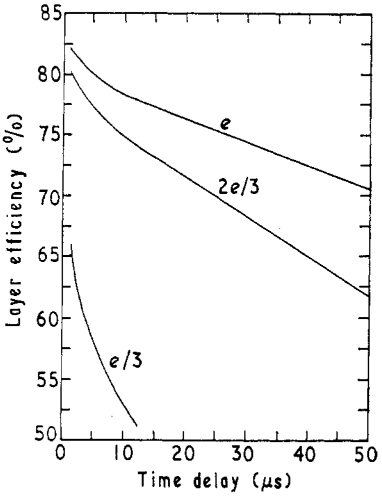

Figure 4. Layer efficiency for relativistic e, $e/3$ and $2e/3$ particles in the flash tubes as a function of the time delay between the passage of the particle and the application of the high-voltage pulse. A time delay of 5 μs was used in the quark search experiment.

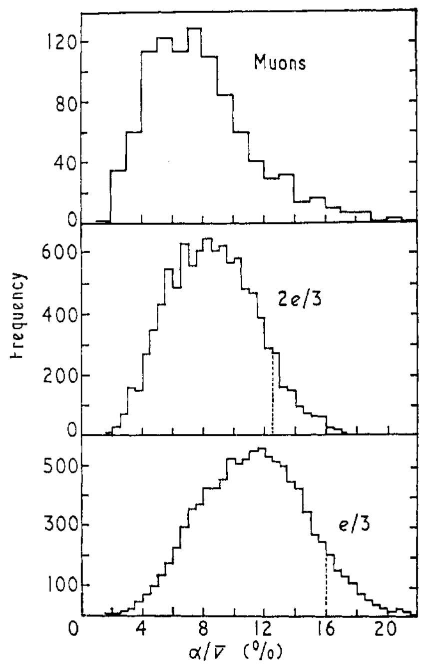

Figure 5. The measured frequency distribution of $\alpha/\bar{v}$ for muons and the expected distributions for relativistic $e/3$ and $2e/3$ quarks. $\bar{v}$ is the mean of the six scintillator pulse heights and α its standard deviation. The 90% limits of the quark distributions are indicated by the broken lines. The muon distribution is for events in which the pulse heights from all six counters are less than twice the most probable pulse height. The abscissae of all the histograms have the same scale. The $2e/3$ and $e/3$ distributions have been found by a Monte Carlo calculation.

Table 2. Details of each quark candidate

Event number	$\bar{v}$ in terms of E	$\alpha/\bar{v}$ (%)	$(N/M)_f$	$(N/M)_s$	Event number	$\bar{v}$ in terms of E	$\alpha/\bar{v}$ (%)	$(N/M)_f$	$(N/M)_s$
T16†	0·34	19·7	0·82	0·58	QL11	0·13	19·9	3·80	2·60
T19	0·51	15·9	0·60	0·33	QL13	0·11	18·1	0·31	0·75
T48†	0·27	16·7	0·63	0·40	QL14	0·06	18·9	0·47	0·33
T49†	0·56	19·0	0·30	0·80	QL26	0·16	11·7‡	0·57	0·84
T51	0·61	18·6	1·00	2·33	QL38	0·18	13·1‡	0·67	1·00
T52(i)	0·49	14·5	0·50	0·37	QL45	0·11	15·0‡	3·00	2·60
T52(ii)	0·33	18·1	0·27	0·37	QU18	0·46	12·5‡	0·38	0·57
T53	0·63	16·8	0·25	0·43					
T55	0·22	12·5‡	0·53	0·31	QL66	0·16	17·2	0·38	0·80
T56†	0·49	19·7	0·50	1·20	QL74	0·14	18·0	1·60	∞
T61(i)†	0·43	13·1	0·58	1·00	QL84	0·17	13·0‡	0·28	0·45
T61(ii)†	0·34	9·8‡	0·31	1·09	QL88	0·14	18·2	0·46	0·82
T61(iii)	0·52	10·3‡	0·41	0·75	QU54	0·63	18·9	2·25	1·00

L refers to the $e/3$ selection and U to the $2e/3$ selection. $\bar{v}$ is the mean of the six scintillator pulse heights and α the standard deviation of the mean. E is the most probable pulse height produced by a relativistic muon in traversing a counter. $(N/M)_f$ and $(N/M)_s$ are the ratio of the number of flashes on the track N to the number of flashes in the background M for the front and side views respectively. The events marked † would not have been selected by the Q run selection electronics. The events marked ‡ have $\alpha/\bar{v}$ values inside the 90% limits which are 12·5% for $e/3$ and 16·0% for $2e/3$, $\beta = 1$ quarks (see figure 5).

3. Selection of quark candidates

The selection criteria comprised two parts: preliminary criteria, which were used to select a sample containing all the possible quark events plus background events which are not too dissimilar, and final criteria, which were designed to enable the abstraction of only genuine quarks.

The preliminary criteria were:

(i) The mean of the six pulse heights should be in the expected region for quarks.

(ii) The ratio, $\alpha/\bar{v}$, of the standard deviation of the mean pulse height to the mean should be less than 20%. This limit was chosen as, even for $e/3$ quarks, there should be a negligible fraction of events with $\alpha/\bar{v} > 20\%$, as shown in figure 5.

(iii) There should be a track in both flash tube views and it should traverse the full counter thickness of both the top and bottom scintillators. The definition of a track, in either flash tube view, was that there should be at least one tube flashed in each of three independent flash tube trays.

The numbers of observed events, which are referred to as 'quark candidates', satisfying these criteria are shown in table 1 and the details of each individual event are given in table 2. Drawings of all the candidates have been given by Simpson (1967). From the data in table 2 it is apparent that not all the quark candidates are genuine as the majority of the events are close to the cut-off values for $\alpha/\bar{v}$ and only 8 have $\alpha/\bar{v}$ values within the 90% limit values for $e/3$ and $2e/3$ quarks.

At this stage it is relevant to ask what fraction of the quark candidates are due to spurious phenomena. One possibility is that a weak shower triggered the telescope giving pulse heights with the correct $\bar{v}$ and $\alpha/\bar{v}$. However, if a muon had traversed the telescope in the 170 μs sensitive time preceding the shower (this is the time delay for which the efficiency drops to such a value as to give on average only 3 flashes along a track) then this track would also be observed, as well as the flashed tubes associated with the weak shower. The number of such events can be estimated from the measured number of random triggers applied to the flash tubes to produce a track and knowing the total number of triggers with $\bar{v}$ in the correct region and with $\alpha/\bar{v} < 20\%$. The expected number of such events is given in the bottom row of table 1. It is seen that the number of quark candidates is in excess of this background in all cases.

In an attempt to record such background muon events directly electronic logic was used in the runs Q50–Q97 to indicate whether a particle had traversed the telescope in the 200 μs preceding a selection trigger. As shown in table 1 some quark candidates were still observed.

A further possibility is that weak showers could both trigger the selection system and also give rise to apparent tracks. In an attempt to distinguish these events the ratio N/M is used as an estimator, where N is the number of flashes lying directly on the 'track' and M is the total number of background flashes in the picture. Measurements with muon triggering show that 95% have $N/M > 2$ in the front view flash tubes and 95% have $N/M > 2$ in the side view. Thus 90% have $N/M > 2$ in both flash tube views. Allowing for the efficiency of the flash tubes for detecting $2e/3$ and $e/3$ quarks it is calculated that 90% of $2e/3$ quarks should have $N/M > 1{\cdot}9$ in both views and 90% of $e/3$ quarks should have $N/M > 1{\cdot}45$ in both views. One of the final criteria is, therefore, that the candidates should lie above these limits. Figure 6 shows an N/M scatter plot for the quark candidates (table 2) and it is seen that only three events are in the allowed region. All of them are $e/3$ candidates and only one, QL45, has an $\alpha/\bar{v}$ value inside the expected 90% limit for this parameter.

The second of the final criteria is that the flash tube photographs should show no evidence of particle accompaniment. If a particle is observed to be accompanied, i.e. if it generates an energetic secondary within the apparatus, it almost certainly corresponds to a pre-event track (e.g. a muon during the sensitive time) because of the small-pulse requirement in the scintillation counters. Unfortunately, event QL45 shows evidence for secondary production near the bottom of the apparatus and it is accordingly rejected. There are thus no remaining events which satisfy all the selection criteria.

Imposition of the various criteria reduces the effective running times shown in table 1 by a factor 0·81, and this has been allowed for in calculating the upper limit to the quark flux. In view of the dependence of ionization on particle velocity the efficiency with which quarks are detected is a function of velocity as well as charge. The limits for $e/3$ and $2e/3$

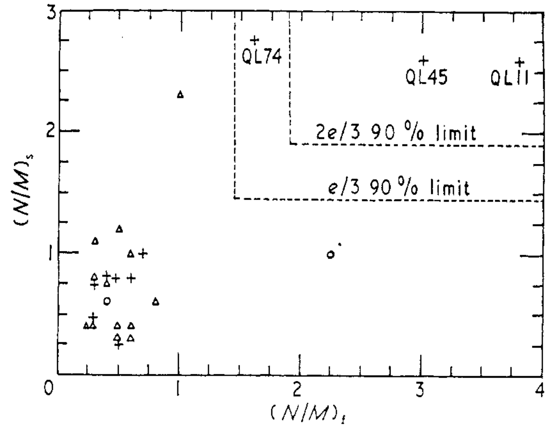

Figure 6. Scatter plot of N/M values for all quark candidates. $(N/M)_f$ and $(N/M)_s$ are the ratio of the total number of flashes N on the track, to the number of flashes M in the background for the front and side views respectively. Only candidates with N/M inside the 90% expectation limits are identified.

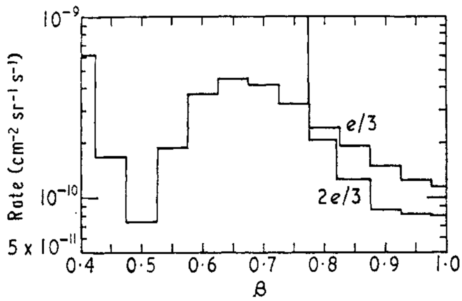

Figure 7. The upper limit for the rate of $e/3$ and $2e/3$ quarks at the 90% confidence level as a function of β. The limits refer to near-vertical particles at sea level and have been calculated assuming that the probability of a quark interacting in the apparatus is negligible.

quarks shown in figure 7 have been derived using the expected scintillation line shapes and the discriminator settings used in this experiment. No correction has been applied for interactions in the telescope; if the interaction cross section is one third of the nucleon–nucleon cross section, as has been suggested, then the limits should be increased by a factor 1·5.

4. Conclusions

The result of the present search is negative and the upper limits at the 90% confidence level for the flux of quarks in the near vertical cosmic radiation at sea level are as shown in figure 7. These limits are somewhat lower than those given by other workers who have carried out similar experiments (see Buhler-Broglin *et al.* (1967) for a summary). To extend the search by this type of experiment to lower flux levels, telescopes of much larger aperture are required; a telescope using layers of 10 m long, 15 cm square proportional counters of the type described by Ashton *et al.* (1968) would be suitable. It should be noted that neither this experiment nor others would have detected a flux of $2e/3$ quarks with $\beta < 0{\cdot}77$.

Acknowledgments

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