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Search for quarks using a flash-tube chamber

F Ashton, D A Cooper, A Parvaresh and A J Saleh
Physics Department, University of Durham, Durham, England

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Abstract. A search for charge $e/3$ quarks has been made in extensive air showers where the local electron density is greater than 40 m^{-2}. The apparatus has been operated for 2570 hours and no definite quark tracks have been detected. The limit on the charge $e/3$ quark flux set by the present work is less than $8{\cdot}0 \times 10^{-11}$ cm^{-2} s^{-1} sr^{-1}.

1. Introduction

Preliminary results using a prototype flash-tube chamber to search for quarks in air showers showed the importance of the use of defining layers of flash tubes at the top and bottom of the chamber to eliminate edge effects that could simulate quarks (Ashton *et al* 1971a) and also the importance of the recovery time of flash tubes which again could generate spurious quarks (Ashton *et al* 1971b). With the above effects well understood the initial chamber volume was doubled in the summer of 1971 and in this paper an analysis of the data obtained up to June 1972 is described (run 4).

2. Experimental arrangement

A scale diagram of the experimental arrangement used is shown in figure 1. As in previous work air showers were selected by a threefold coincidence between the liquid scintillators N, M, S shown in figure 1, the discriminator threshold on each scintillator corresponding to an electron density of greater than 40 m^{-2}. With this selection system the minimum shower energy to produce a trigger is 3×10^{14} eV, the median shower energy is $3{\cdot}5 \times 10^{15}$ eV and the median core distance is 13·5 m.

3. Analysis of the results

3.1. *The basic data*

The procedure in scanning the film has been to measure the sum of the number of flashes $F2+F3$ of all tracks that traverse F2 and F3 (figure 1) and produce at least one flash in the defining layers F1 and F4. A summary of the basic experimental data is shown in table 1, and table 2 shows the frequency distribution of the number of measurable tracks per photograph. All the data were taken with a time delay of 20 μs between the occurrence of the air shower and the application of the high voltage pulse to the chamber.

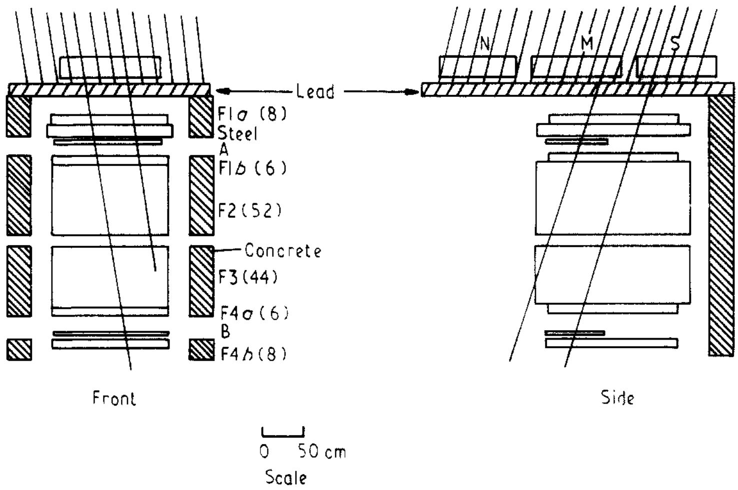

Figure 1. Scale diagram of the flash-tube chamber. F1–F4 refer to blocks of flash tubes, the number in brackets being the number of layers of flash tubes in the various blocks. N,M,S are liquid scintillation counters and A,B are plastic scintillation counters.

Table 1. Basic experimental data

Running time (hr)	Total number of photographs	Total number of measurable photographs	Percentage of photos that give at least one measurable track	Total number of measurable tracks
2570	12057	2753	23	4501

Table 2. The frequency distribution of the number of triggers N having n measurable tracks

Number of measurable tracks per photograph, n	Number of photographs, N	Nn
1	1604	1604
2	758	1516
3	254	762
4	84	336
5	42	210
6	7	42
7	3	21
8	0	0
9	0	0
10	1	10
Total	2753	4501

The frequency distribution of $F2+F3$ for the 4501 measured tracks is shown in figure 2. The expected number of flashes for minimum and plateau ionizing charge e particles and quarks have been determined in the manner described by Ashton *et al* (1971a). It can be seen from figure 2 that the chamber will only resolve $e/3$ quarks and not quarks with charge $2e/3$. Tracks with $F2+F3 > 60$ were only measured in the

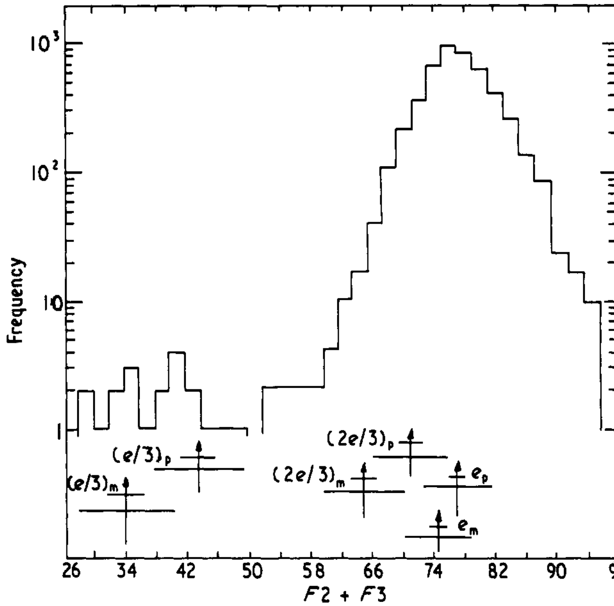

Figure 2. Basic experimental data. Tracks with $F2+F3 > 60$ were only measured in the scanning if they had at least one shower track of length greater than 60 cm in the chamber and were parallel to it to $\pm 5°$. So as not to eliminate quarks all tracks with $F2+F3$ in the range 20–60 were measured irrespective of the angle they made to shower tracks in the picture. The arrows indicate the expected number of flashes for minimum ionizing and plateau ionizing charge e, $2e/3$ and $e/3$ particles. The small bars indicate the uncertainty in the position of the arrow and the large bars the expected standard deviation of the distribution. Total number of measured tracks = 4501. No events were observed with $F2+F3$ in the range 20–26.

scanning if they had at least one shower track of length greater than 60 cm in the chamber and were parallel to it to $\pm 5°$. However, so as not to eliminate quarks, all tracks with $F2+F3$ in the range 20–60 were measured irrespective of the angle they made to shower tracks in the picture. (Quarks are expected to have a value of $F2+F3$ in the range 28–50.)

4. Analysis

The form of the analysis is to select out potential quark events from the distributions and to devise criteria which will enable genuine quarks to be distinguished from various background effects.

The most serious background effect is that due to single muons which were not associated with the shower and which passed through the chamber prior to the triggering event. In particular, tracks with $F2+F3$ in the range 28–50 could be produced by incoherent muons which traversed the chamber in the period 103 μs to 144 μs preceeding the air shower trigger. From the measured efficiency time delay curve for the chamber tracks it can be shown that the distribution of $F2+F3$ for incoherent muon tracks should be flat over the range 28–50 flashes and the expected number of such tracks is 16·0. This figure is to be compared with the observed number of tracks of 20 with $F2+F3$ in the range 28–50 indicating rough agreement, although not ruling out the presence of a few genuine quarks.

To identify possible quarks it is assumed that their tracks should be essentially parallel to shower tracks and a limit of $\pm 5°$ has been imposed. This reduces the 20 tracks with $F2+F3$ in the range 28–50 to 6 and should be compared with the predicted number due to incoherent muons of 2·2. There is now a further experimental test that can be applied: an examination of the number of knock-on electrons (δ rays) produced by the particles. The 6 tracks have accordingly been examined in detail for the occurrence of extra flashes due to knock-on electrons, a knock-on being defined as two adjacent flashes occurring in one layer of flash tubes. Of the 6 quark candidates, two possessed no observable knock-on electrons (KO's). The remaining 14 tracks, taken to be due to incoherent muons, had a mean KO number of 1·79, three of the tracks having no KO's. Now since an $e/3$ quark would produce $\frac{1}{9}$th the number of KO's that a muon would produce, a quark track should be virtually free of KO's. With the information obtained from the incoherent muon tracks, it is deduced that the expected number of incoherent muons simulating quarks, (ie having no KO's along the track) will be $2{\cdot}2 \times \frac{3}{14} = 0{\cdot}47$. This figure is to be compared with the observed number of two events which satisfy all the above criteria (table 3). The probability of observing two pseudoquarks is therefore 8 %. A print of event E34-117 is shown in figure 4 (plate).

Table 3. Details of the six events shown in figure 3 with $F2+F3 \leqslant 50$

Event	$F2+F3$ for quark candidate	Number of shower tracks in picture excluding quark candidate	Angle quark candidate track makes to other shower tracks	Number of KO's (ie pairs of adjacent flashes)
E8-48	31	1	3°	1
E16-66	39	2	4°	7
E19-45	28	3	5°	0
E34-117	38	3	5°	0
E53-125	47	2	0°	1
E69-95	41	2	0°	1

5. Conclusion

Two tracks have been observed with values of $F2+F3$ in the region expected for quarks which are both consistent with zero knock-on electron flashes associated with them. The most likely interpretation is that they are background incoherent muon tracks but it is possible that they are genuine quarks (the possibility of their being spurious is of the order of 8 %).

Based on two possible events the upper limit to the flux of $e/3$ quarks in air showers where the electron density is greater than 40 m^{-2} is less than $1{\cdot}4 \times 10^{-11}$ $cm^{-2}\,s^{-1}\,sr^{-1}$. This limit is calculated using an aperture of 1·57 m^2 sr (defined by the middle of F1b and the middle of F4a shown in figure 1) and neglects the loss of quarks due to inelastic interactions in the chamber material. The limit of less than $1{\cdot}4 \times 10^{-11}$ $cm^{-2}\,s^{-1}\,sr^{-1}$ is considerably lower than our previous limit of less than $2{\cdot}6 \times 10^{-10}$ $cm^{-2}\,s^{-1}\,sr^{-1}$ (Ashton *et al* 1971c). Assuming a quark–nucleon inelastic cross section of one third the nucleon–nucleon inelastic cross section, the probability of a quark traversing the chamber without interacting has been calculated to be 0·165. Taking this effect into account raises the upper limit quoted above to less than $8{\cdot}0 \times 10^{-11}$ $cm^{-2}\,s^{-1}\,sr^{-1}$.

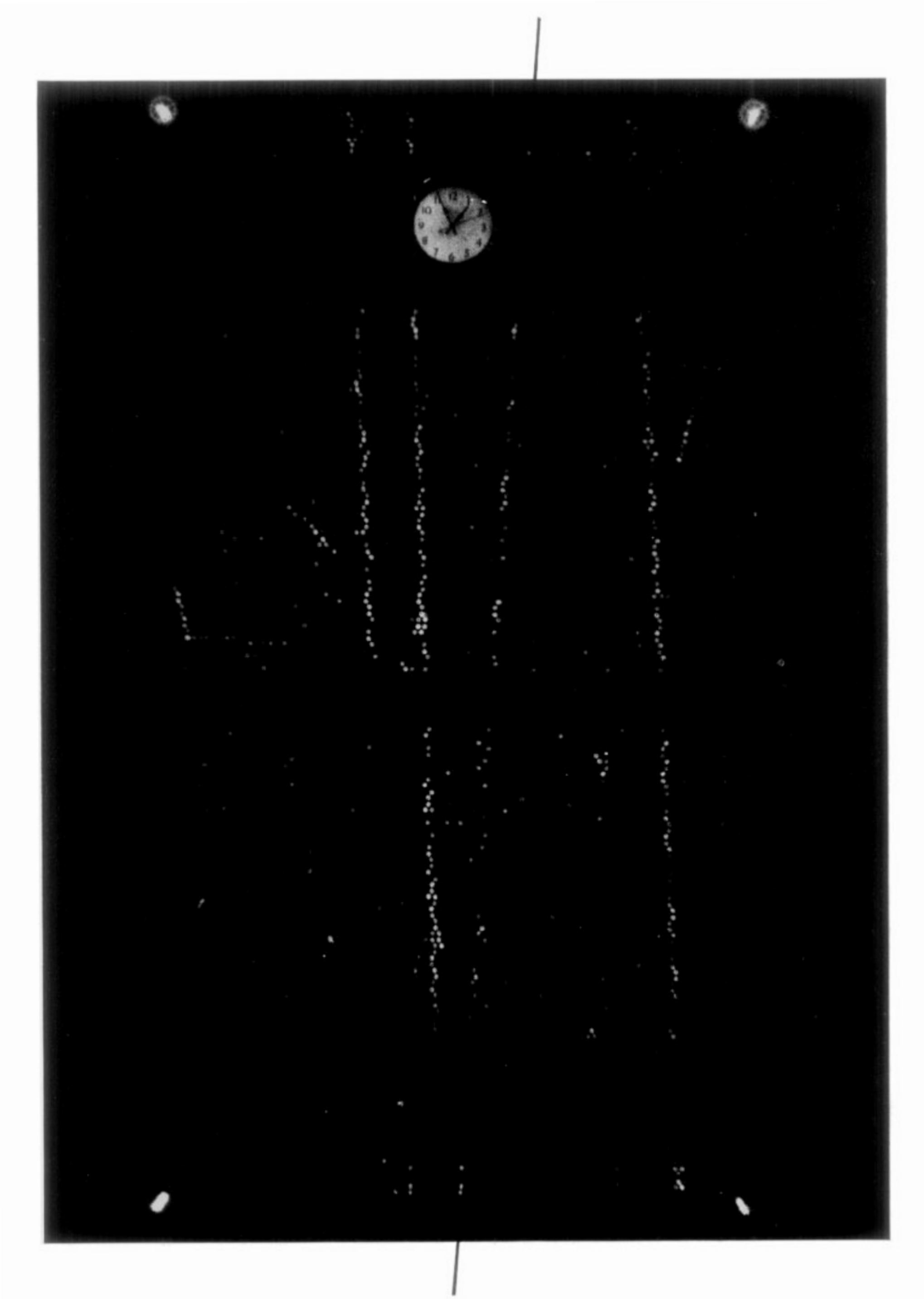

Figure 4. Event E34-117. A possible $e/3$ quark track is indicated.

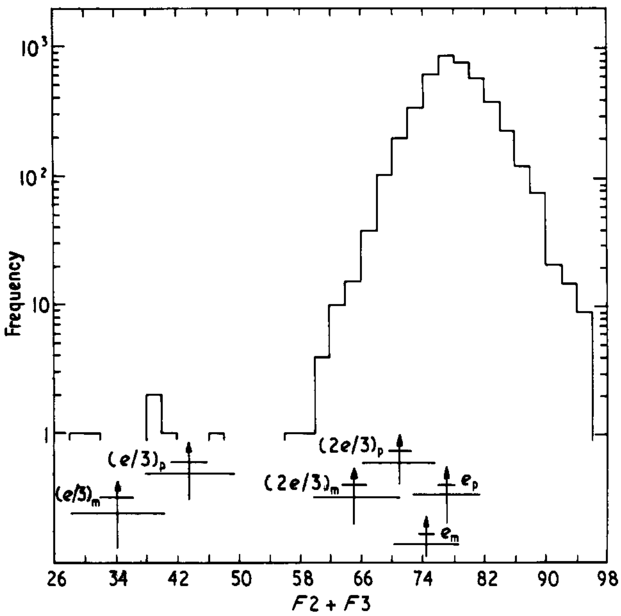

Figure 3. Same as figure 2 except that only events with $F2+F3$ in the range 20–60 are plotted if they are parallel ($\pm 5°$) to shower tracks.

Using the cloud chamber technique Clark *et al* (1971) give the following limits for the flux of $e/3$ and $2e/3$ quarks in regions of showers where the electron density is greater than $86\ m^{-2}$:

$$e/3 \qquad <3\times 10^{-10}\ cm^{-2}\ s^{-1}\ sr^{-1}$$

$$2e/3 \qquad <3\times 10^{-11}\ cm^{-2}\ s^{-1}\ sr^{-1}.$$

Both the present work and that of Clark *et al* (1971) has failed to detect quarks at a flux level of $5\times 10^{-10}\ cm^{-2}\ s^{-1}\ sr^{-1}$ which is suggested by the observations of Cairns *et al* (1969) and McCusker *et al* (1969). It is suggested that the most likely explanation of the Sydney work is that the 5 events they attributed to charge $2e/3$ quarks were minimum ionizing charge e particles with a downward fluctuation of ionization loss.

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