Search for Quarks in High-Energy Air Showers

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Quarks of charge $\frac{1}{3}e$ and $\frac{2}{3}e$ have been searched for in air showers of energies between 10^{13} and 10^{15} eV. A hodoscope of proportional counters was placed under 15 cm of Pb. Scintillation counters on top of the lead triggered on high-multiplicity showers. No quark was detected in 2120 h. The upper limit of the quark flux in showers between 10^{14} and 10^{15} eV is, with 90% confidence, 1.0×10^{-10} cm^{-2} sec^{-1} sr^{-1} for either charge.

Since the first suggestion[1,2] that fractionally charged particles, the quarks, might be the basic constituents of matter, they have been searched for with a variety of methods.[3] Reports about observations of quarks with charge $\frac{2}{3}e$ in high-energy air showers[4] met with criticism,[5] and could not be confirmed in recent cloud-chamber studies.[6,7]

The present study avoids the shortcomings of visual techniques by measuring the ionization of cosmic-ray shower particles in a hodoscope of proportional counters.[8] The first search had been made for quarks of charge $\frac{1}{3}e$ in small air showers.[9] Since then the apparatus has been improved in two respects[10]: (1) The number of proportional-counter layers has been increased from six to twelve, thereby permitting the recognition of both $\frac{1}{3}e$ and $\frac{2}{3}e$ quarks. (2) By triggering on high-multiplicity air showers impinging on a lead filter placed on top of the hodoscope, the apparatus was made sensitive to shower energies up to some 10^{15} eV.

The apparatus is schematically shown in Fig. 1. The hodoscope consists of twelve layers of twenty proportional counters. The six innermost counter layers are crossed at right angles with respect to the 2×3 outer layers. A trigger signal was given by the eight scintillation counters on top of the lead, whenever five of them were struck simultaneously. This trigger favored showers with high particle density. Their spectrum (curve A in Fig. 2) was computed by Monte Carlo techniques using the energy spectrum of air showers[11] and their lateral distribution.[12] The trigger rate was measured to be 4.00 ± 0.05 min^{-1}, in agreement with the Monte Carlo expectation of 3.6 ± 1.1 min^{-1}.

The lead filter had the task of attenuating the electronic component of a shower, but letting the quarks pass. The thickness of 15 cm was chosen on the basis of a Monte Carlo calculation, which averaged over primary energies, lateral distributions, and the spectra of the soft component as given by Kameda, Toyoda, and Maeda.[13] According to this calculation the lead attenuates the average number of charged particles (with an energy >1 MeV) to about 3%.

The apparatus took data for 2120 h. 523 725 triggers were registered. 107 500 events showed a nonvanishing pulse height in at least five proportional counters. They were written on magnetic tape for later off-line analysis.

The off-line analysis purports to distinguish quark tracks from those due to ordinary particles on the basis of their lower ionization. Figure 3 shows the pulse-height distribution of minimum

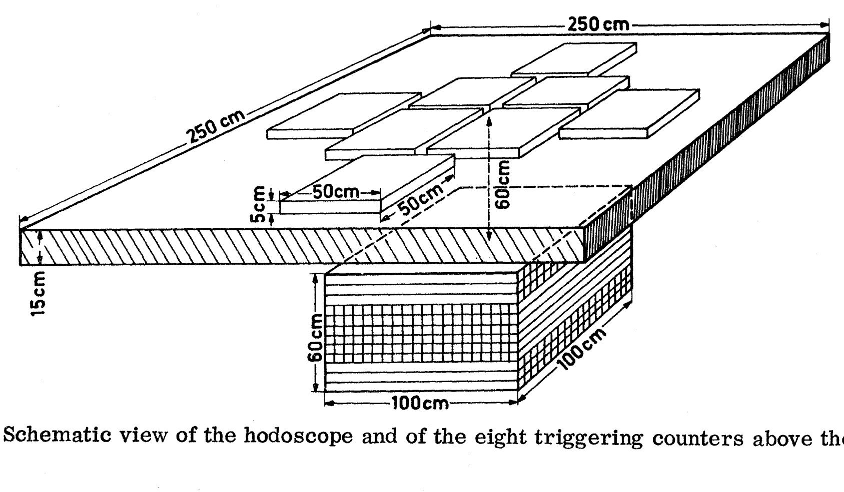

FIG. 1. Schematic view of the hodoscope and of the eight triggering counters above the lead.

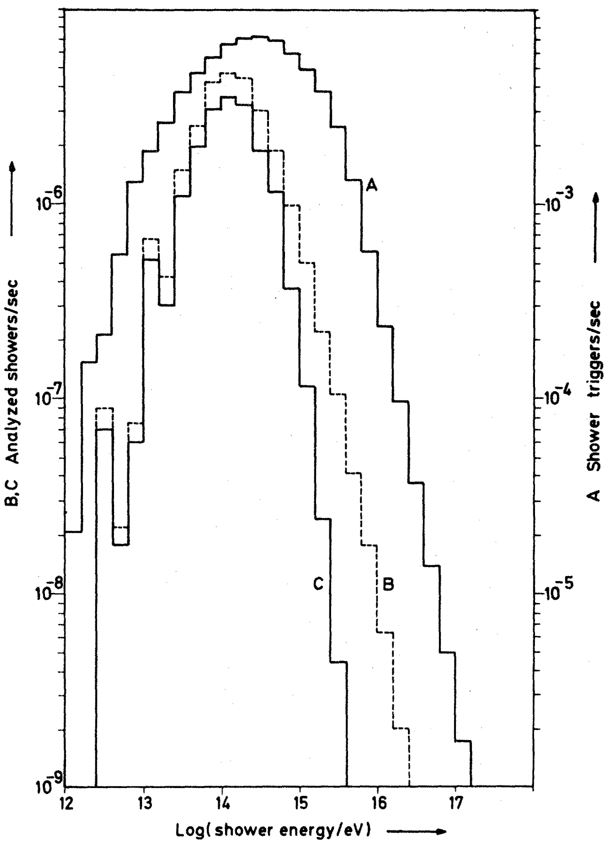

FIG. 2. A, computed spectrum of triggering showers. B, rate of analyzed showers under the assumption of 100% detection efficiency for quarks. C, the same with the efficiencies for $\frac{2}{3}e$ quarks computed assuming an average quark transverse momentum of $\frac{1}{5}M_q$.

ionizing quarks of charge $\frac{2}{3}e$ and $\frac{1}{3}e$. The quark curves were obtained, with cosmic ray muons, in counters scaled down to $\frac{4}{9}$ and $\frac{1}{9}$ in linear dimensions[9] for charges $\frac{2}{3}e$ and $\frac{1}{3}e$, respectively.

The pulse-height distributions of Fig. 3 give the probability $P_X(h)$ that a certain pulse height h had been caused by a particle of type X.[14] The probability of obtaining a set of n pulse heights h_i in n independent counters is

$$L_X = \prod_{i=1}^{n} P_X(h_i). \quad (1)$$

Hence the probability ratio for a given set of pulse heights to be caused by a particle of type X rather than of type Y is

$$R_{X/Y} = \prod_{i=1}^{n} P_X(h_i)/P_Y(h_i). \quad (2)$$

This ratio has been used as a test quantity. X stands for a quark of either charge $\frac{2}{3}e$ or $\frac{1}{3}e$, and Y for a minimum ionizing particle of unit charge.

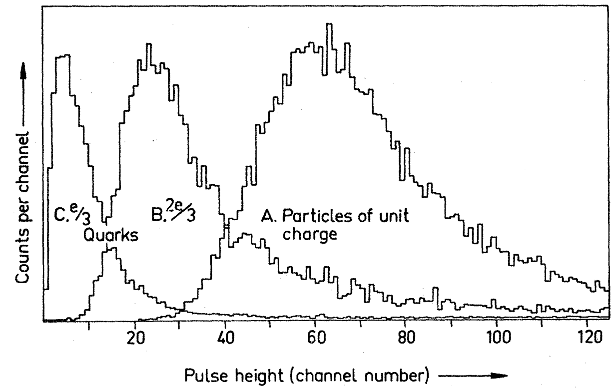

FIG. 3. Experimental pulse height distributions. A, minimum ionizing particles of unit charge; B, $\frac{2}{3}e$, and C, $\frac{1}{3}e$ quarks, simulated by muons (with $1.1 I_{min}$) measured in counters built to $\frac{4}{9}$ and $\frac{1}{9}$ scale, respectively.

The application of the test is complicated if several tracks in one event overlap. This has been accepted in order to retain good efficiency for high-energy showers. Besides, for events with more than one track the association of the two spatial "views" becomes ambiguous. In order not to lose any possible quark, the most advantageous combination of quark-like tracks was accepted.

The selection criteria were as follows: (1) The total number of proportional counters struck had to be less than eighty in order to keep overlapping of tracks down to a tolerable level. As a consequence, at most five simultaneous tracks could be analyzed. (2) The average pulse height of a track had to be smaller than fifty for $\frac{1}{3}e$ and sixty for $\frac{2}{3}e$ quarks in both views. (3) In each view the track had to be more likely to be caused by a quark than by a particle of unit charge. This means that the probability ratio $R_{X/Y}$, defined in Eq. (2), had to be >1. This cut was necessary, as the counters have end zones of reduced sensitivity.[8,9] Thus, a normal particle traversing the six inner layers near to the end can simulate a quark track in that view. This particle is recognized as a normal particle in the crossed layers and is removed by the cut. (4) The total likelihood ratio for the two views combined must be $>10^{10}$ for $\frac{1}{3}e$ and $>10^{8}$ for $\frac{2}{3}e$.

The efficiencies for identifying quarks on the basis of these criteria were computed using Monte Carlo techniques as a function of the number of additional particles K. They are, for $\frac{1}{3}e$ quarks, 81%, 64%, 52%, 38%, and 25%, and for $\frac{2}{3}e$ quarks, 78%, 54%, 38%, 26%, and 18%, for, respectively,

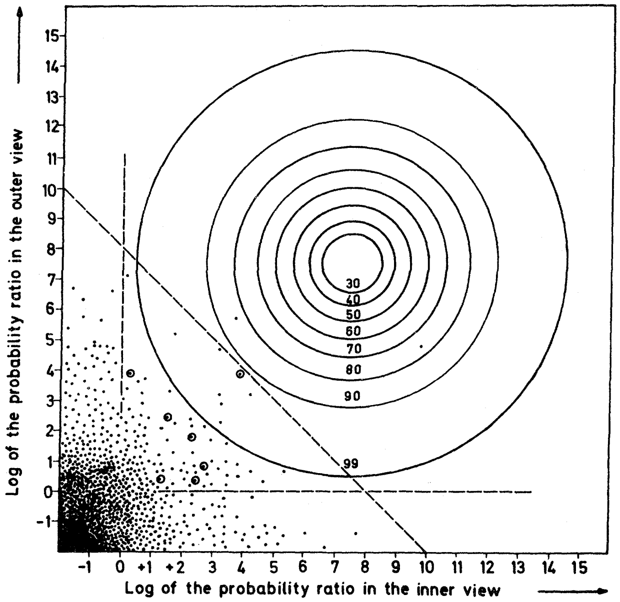

FIG. 4. Scatter diagram of the measured probability ratios of tracks resembling $\frac{2}{3}e$ quarks in either view. Small points represent tracks surviving criterion (1); circled points, tracks passing criteria (2) and (3). Final cut is the line at 45° (with respect to the axis). Contour lines for $\frac{2}{3}e$ quarks are shown; the numbers give the percentage of quarks contained.

$K=0$, 1, 2, 3, and 4.

The result of the experiment is given in Fig. 4. Each track is plotted there as a point in a scatter diagram with the two probability ratios of the two independent views as coordinate axes. Making cuts separately in the two views [criterion (3)] already removes part of them. After appl ing the cut in the combined probability [criterion (4)], no quark candidate was left over.

The quantitative significance of this statement may be assessed as follows: Each analyzed event scans a small part of an air shower. Taking the relevant energy and angular distributions from our Monte Carlo calculations, we may infer the total number of showers of a certain primary energy E_0 which have been totally scanned in the course of the experiment [Fig. 2(b)]. This curve is modified by our limited efficiency to recognize a quark inside a shower [see Fig. 2(c)]. This efficiency is a very sensitive function of the lateral distribution assumed for the quarks. One could imagine that quarks have the same lateral distribution as the other hadrons.[15] But a better model is probably the assumption of a Maxwell-type distribution[16] of transverse momenta p_T, with the average transverse momentum $\langle p_T\rangle$ depending

TABLE I. Results given in terms of the effective number of analyzed showers and of the corresponding upper limits for the frequency of $\frac{1}{3}e$ ($\frac{2}{3}e$) quarks. The frequency is expressed both in the number of quarks per shower and in units of 10^{-10} cm^{-2} sec^{-1} sr^{-1}. Results depend on the assumed lateral distribution of quarks.

Shower energy (eV)	Analyzed showers		Quarks/ shower		Quark flux	
Assuming $M_q/\langle p_T\rangle = 5$						
$10^{13}-10^{14}$	37	(35)	0.062	(0.066)	12	(13)
$10^{14}-10^{15}$	40	(36)	0.058	(0.063)	0.92	(1.0)
$10^{15}-10^{16}$	0.82	(0.64)	2.8	(3.6)	1.5	(2.0)
Assuming lateral distribution same as hadronic components						
$10^{13}-10^{14}$	53	(47)	0.044	(0.048)	8.6	(9.5)
$10^{14}-10^{15}$	15	(14)	0.15	(0.17)	2.4	(2.7)
$10^{15}-10^{16}$	1.7	(1.5)	1.4	(1.5)	0.75	(0.83)

linearly on the produced particle mass.[17] Extrapolation of previous data[17] to high masses indicates a value for $M/\langle p_T\rangle$ close to 5. Table I lists the effective number of analyzed showers, together with the 90% confidence limits on the number of $\frac{1}{3}e$ ($\frac{2}{3}e$) quarks per shower, computed under these two assumptions.

Since the absolute flux of showers of a certain energy is known,[11,15] the limits on the quark frequency per shower may be converted into corresponding limits on absolute quark fluxes.

In deriving these limits it has been assumed that the quarks are not absorbed by the 15-cm lead filter. This seems plausible, since the analysis of high-energy scattering in terms of the quark model[18] indicates a total cross section for quark nucleon interactions of $\sigma_{qN} = \frac{1}{3}\sigma_{NN} = 13$ mb. This would cause only about 20% of the quarks to interact.

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