SEARCH FOR FRACTIONALLY CHARGED PARTICLES IN SHOWERS OF LOW DENSITY

H. Faissner, M. Holder, K. Krisor, G. Mason,* Z. Sawaf, and H. Umbach
III. Physikalisches Institut, Technische Hochschule Aachen, Aachen, Germany
(Received 13 April 1970)

A search was made for relativistic quarks of charge $e/3$ in cosmic-ray showers at sea level. A hodoscope of wire proportional counters was used, which was capable of measuring location and specific ionization of several particles arriving simultaneously. An upper limit for the flux of quarks observed singly in the apparatus was established, with 90% confidence, at 1.9×10^{-9} $\sec^{-1}$ cm^{-2} sr^{-1}. Corresponding limits were set for quarks with one and two accompanying particles at, respectively, 6.5×10^{-10} $\sec^{-1}$ cm^{-2} sr^{-1} and 2.2×10^{-9} $\sec^{-1}$ cm^{-2} sr^{-1}.

Gell-Mann[1] and Zweig[2] were first to suggest that the basic constituents of matter might be fractionally charged particles: the quarks. The quark model describes the properties and interactions of elementary particles surprisingly well.[3] This would be most naturally explained, if quarks existed as real particles and not merely as mathematical fictions.

Quarks have been searched for at accelerators,[4] by physico-chemical methods,[5] and in cosmic rays.[6] Each of these approaches is open to criticism: Available accelerator energies may be too low, the physico-chemistry of quarks is unknown, and the cosmic-ray experiments performed prior to 1969 could detect quarks only if they arrived singly at the detector and if they did not interact in it. Indeed, the only reported positive evidence for quarks (of charge $2e/3$) was obtained in air showers of high particle density.[7] But there were objections against the experimental method.[8-11] Besides, the quark flux of 5×10^{-10} $\sec^{-1}$ cm^{-2} sr^{-1} derived from that experiment[7] is hard to reconcile[8] with the limits of some 10^{-10} $\sec^{-1}$ cm^{-2} sr^{-1} obtained for single quarks in previous experiments.

The present experiment was meant to improve upon these previous cosmic-ray experiments in two respects: (1) The detector should be capable of detecting a charge $e/3$ quark, even if it was accompanied by a few normal particles. (2) It should present a minimum amount of mass to the impinging cosmic rays. This would not only prevent a quark from interacting, but also minimize the background from soft photons.

A moderate spatial resolution seemed adequate, since current models of quark production,[12] combined with the rapidly falling cosmic-ray spectrum, lead one to expect a typical primary energy of some 10^{12} eV, corresponding to a particle density of a few per square meter at sea level. Thus a "massless" proportional-counter hodoscope was used with an on-line computer.

The experimental apparatus has been described in detail elsewhere.[13] It consists of 120 proportional counters arranged in six layers inside a Lucite frame (see Fig. 1). Each layer covers an area of 1 m^2. The counters are made of wires only; five wires at ground potential separate two adjacent counters. The whole array is flushed by a mixture of argon and methane at atmospheric pressure. The stopping power of this hodoscope is only 0.12 g/cm^2. The counters have a uniform response (to ± 3 %) except within a 5-cm zone at each end. In this end zone the response falls off rapidly. A temperature-stabilized Faraday cage surrounds the counters. The apparatus is placed underneath a plastic skylight of 1 g/cm^2.

The pulse heights in the proportional counters are recorded whenever a trigger signal is given by the two layers of scintillation counters underneath the hodoscope. A trigger is defined as a coincidence of pulses from two scintillators arranged one above the other. The electronic threshold is set to half of the most probable $e/3$-quark pulse height expected in the least sensitive zone of the counters. The corresponding trigger-

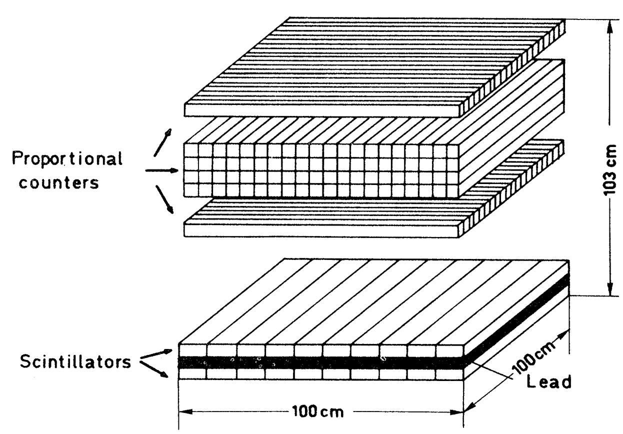

FIG. 1. Schematic view of hodoscope and scintillators.

ing efficiency for quarks was found to be $(90\pm 1)\%$. The scintillator pairs are separated by 2 cm of Pb in order to avoid triggers by γ rays. The aperture of the system is 0.428 m^2 sr. The trigger rate of 126/sec was managed by the on-line program with a deadtime of 1.4%. The apparatus was run for 1580 h, and 1.9×10^8 particles were analyzed.

The performance of the proportional counters and the associated electronic system was checked once a day by measuring a pulse height distribution of vertically incident muons in each counter. Variations in gas amplification up to 10% due to changes in atmospheric pressure were corrected by corresponding changes of the anode potential of the proportional counters. The response of the counters to relativistic particles of unit charge can be judged from the pulse-height distributions shown in Fig. 2. The right-hand curve represents pulse height measurements of 30 000 cosmic-ray particles combined from the 80 counters in the central four layers of the hodoscope. The most probable energy loss, corresponding to the peak in channel 72, is 8.2 keV. For the off-line data analysis described below a straight line was fitted to the 42 pulse heights measured between channels 0 and 16. This shape is consistent with the flat distribution of small pulse heights in these channels observed over a much longer period of time during the quark search. The analysis is not very sensitive to this approximation. A 50% increase in this region made no difference in the result. Also shown in Fig. 2 is a simulated pulse height distribution for quarks. This curve was measured with particles of unit charge in counters scaled down to $\frac{1}{9}$ in linear dimension. The calibration was done by means of an Fe^{55} 5.9-keV x-ray source.

Events were accepted by the on-line program, if the following selection criteria were satisfied:

(1) A track has to be found, in the four central layers of proportional counters, which is separated from other tracks by at least one empty counter in each layer. If the track traverses two counters in the same layer, these pulse heights are added.

(2) The track must have two pulse heights in the channel range 3 to 29 or four pulse heights in the range 3 to 39. These requirements are met by 97% of all $e/3$ quarks.

The pulse-height recording system for the proportional counters has an electronic threshold in channel 2. The requirement that the quark is registered in all six layers of proportional counters and in the two layers of scintillators yields an overall electronic detection efficiency of 50%.

24 951 events fulfilled the selection criteria. They were stored on magnetic tape.

The off-line treatment of these events had two aspects: first, to clean the sample from particles which pass through the less sensitive end zone of a counter, and second, to calculate the probability that an observed set of pulse heights is due to a quark. Particles in the end zone are in principle recognized by a pulse in one of the border counters of the crossed layers. These

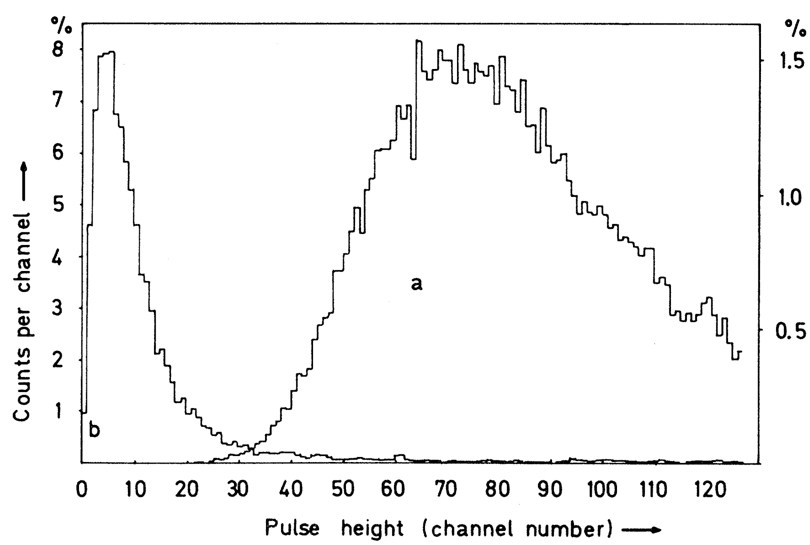

FIG. 2. Measured pulse height distributions for (a) particles of unit charge and (b) quarks. The distribution for quarks was simulated by observing particles of unit charge in counters built to $\frac{1}{9}$ scale.

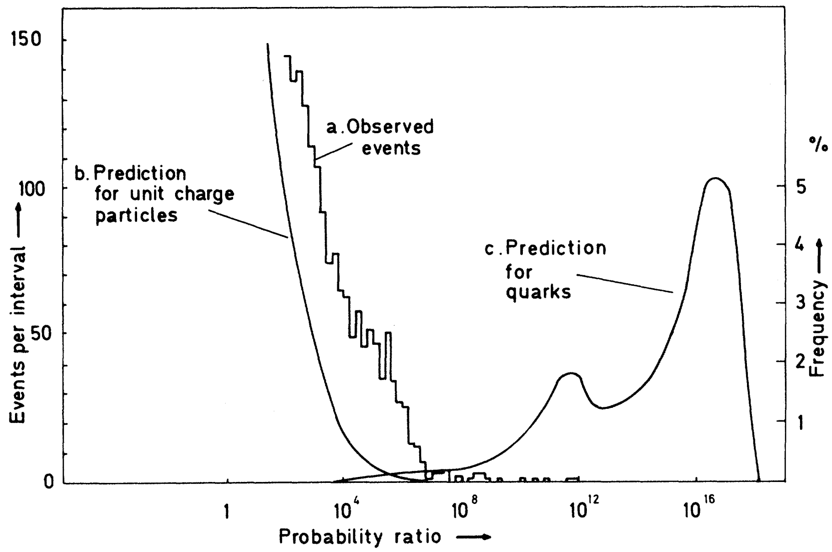

FIG. 3. Distributions of probability ratios: (a) tail of observed distribution, (b) Monte Carlo prediction for unit-charge particles normalized to the total number of particles observed, and (c) Monte Carlo expectation for quarks.

counters are therefore used in anticoincidence. A particle may, however, fail to hit them, if it enters through the Lucite wall in the 10-cm insensitive space between the crossed counters and the four inner layers. Therefore, three counters next to the border of the crossed layers were required to be empty.

The surviving 3995 tracks were submitted to a maximum-likelihood test previously employed by Ramana Murthy and DeMeester.[14] The probability that a given pulse height was caused by a particle of unit charge was taken from the pulse-height distribution of Fig. 2. The product of four such probabilities yields the probability that a particle of unit charge gave rise to the set of pulses observed in the four central layers of counters. A similar probability can be calculated for a quark giving rise to such a set of pulse heights. The ratio of quark probability to unit charge probability was calculated for each track. The tail of the distribution of these ratios is shown in Fig. 3. Except for the highest probability ratios it compares well with the Monte Carlo expectation for particles of unit charge.

The Monte Carlo calculation for quarks is shown to the right in Fig. 3. There the computer created 100 000 "tracks" by drawing four pulse heights from the $e/3$ charge curve of Fig. 2, and submitted them to the same procedure as the experimental tracks. The small peak near 10^{12} is caused by events with three small pulse heights, and it is a consequence of the similar shape of the quark and of the unit-charge pulse height distribution. To apply the test a cutoff value must be chosen to separate unit-charge particle background from quarks. A cutoff at 10^8 was considered reasonable, as it admits 96% of all quarks. 14 tracks survived this cut.

These tracks were submitted to an identical maximum-likelihood test except that pulse heights in the topmost and bottommost (crossed) layers were now considered in addition to those of the four central layers. Lacking an unambiguous correspondence between multiple tracks as seen in two different views, the smallest pulse heights in the two extra layers were taken to belong to the quark track under test. All of the surviving candidates failed to survive a cutoff which would have included 99% of all quarks.

Thus no quark was observed in the experiment. Assuming Poisson statistics this places a limit on the single $(e/3)$-quark flux of 1.9×10^{-10} sec^{-1} cm^{-2} sr^{-1} with 90% confidence. This is close to the best limits obtained previously.[6]

The efficiency for accepting a quark in a multiple-track event falls off as the number of tracks increases. In order to determine this efficiency samples of multiple-track events were scanned by hand. One of the tracks in each event was randomly assumed to be a quark track and the number of acceptable events was tallied on the basis of the same geometrical selection criteria as applied to all events of the experiment. In addition it was required that the quark candidate be within the aperture of the detector and thus capable of triggering. The tally was made separately for two- and three-track events. As a result the efficiencies for accepting a quark accompanied by one or two particles, respectively, were found to be $(30.1 \pm 3.8)\%$ and $(10.3 \pm 2.5)\%$ whereby the errors refer to counting statistics only. Hence the limits for a $e/3$ quark accompanied by one and two particles are, respectively, 6.5×10^{-10} $\sec^{-1}$ cm^{-2} sr^{-1} and 2.2×10^{-9} $\sec^{-1}$ cm^{-2} sr^{-1}. These values are of the same order of magnitude as the flux of $2e/3$ quarks reported by McCusker's group.[7] We are going to increase the number of layers and shall search for this charge too.

We wish to acknowledge the contributions of Bernd Eiben and Rudolf Veuskens to the earlier phases of this work. We appreciate the precise work of our technicians, in particular that of Mr. Bosseler and Mr. Prillwitz. This research was supported by the Landesamt für Forschung des Landes Nordrhein-Westfalen. We extend our thanks to Staatssekretär Professor Dr. Leo Brandt and his co-workers.

---

*Present address: Physics Department, University of Utah, Salt Lake City, Utah.

[1]M. Gell-Mann, Phys. Letters 8, 214 (1964).

[2]G. Zweig, CERN Report No. 8419/TH 412, 1964 (unpublished).

[3]See, for example, R. H. Dalitz, in *Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966* (University of California, Berkeley, 1967), p. 215; G. Morpurgo, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 225; J. J. J. Kokkedee, *The Quark Model* (Benjamin, New York, 1969).

[4]Yu. M. Antipov *et al.*, Phys. Letters 30B, 576 (1969), performed the most recent accelerator experiment at a proton energy of 70 GeV. The older accelerator experiments are listed in T. Massam, CERN Report No. 68-24, 1968 (unpublished), which gives a comprehensive account of methods and results up to that date.

[5]D. D. Cook, G. DePasquali, H. Frauenfelder, R. N. Peacock, F. Steinrisser, and A. Wattenberg, Phys. Rev. 188, 2092 (1969). For older measurements see Massam, Ref. 4.

[6]F. Ashton, R. B. Coats, G. N. Kelly, D. A. Simpson, N. I. Smith, and T. Takahashi, J. Phys. A: Proc. Phys. Soc., London 1, 569 (1968). For older experiments see Massam, Ref. 4.

[7]C. B. A. MuCusker and I. Cairns, Phys. Rev. Letters 23, 658 (1969); I. Cairns, C. B. A. McCusker, L. S. Peak, and R. L. S. Woolcott, Phys. Rev. 186, 1394 (1969).

[8]R. K. Adair and H. Kasha, Phys. Rev. Letters 23, 1355 (1969).

[9]H. Frauenfelder, U. E. Kruse, and R. D. Sard, Phys. Rev. Letters 24, 33 (1970).

[10]D. C. Rahm and R. I. Louttit, Phys. Rev. Letters 24, 279 (1970).

[11]P. Király and A. W. Wolfendale, Phys. Letters 31B, 410 (1970). We are indebted to Professor Perkins for informing us about these considerations in advance of publication.

[12]See, for example, R. Hagedorn, Nuovo Cimento, Suppl. 6, 311 (1968).

[13]B. Eiben, H. Faissner, M. Holder, J. König, K. Krisor, and H. Umbach, Nucl. Instr. Methods 73, 83 (1969).

[14]P. V. Ramana Murthy and G. D. DeMeester, Nucl. Instr. Methods 56, 93 (1967).