New York, 1964), pp. 3-13.
[4]Recommended Unit Prefixes; Defined Values and Conversion Factors; General Physical Constants, National Bureau of Standards Miscellaneous Publication No. 253 (U. S. Government Printing Office, Washington, D.C., 1963).
[5]C. V. Boys, Phil. Trans. Roy. Soc. (London), Ser. A 186, 1 (1895), and Proc. Roy. Inst. Gt. Brit. 14, 353 (1894).
[6]J. H. Poynting, "Gravitation," in Encyclopedia Britannica, 11th ed., and Collected Scientific Papers (The Macmillan Company, New York, 1920).
[7]P. Heyl, J. Res. Natl. Bur. Std. (U.S.) 5, 1243 (1930); P. Heyl and P. Chrzanowski, J. Res. Natl. Bur. Std. (U.S.) 29, 1 (1942).
[8]J. W. Beams, A. R. Kuhlthau, R. A. Lowry, and H. M. Parker, Bull. Am. Phys. Soc. 10, 249 (1965).
[9]Procured from Micrometrical Division of Bendix Company.
[10]W. R. Towler and E. V. McVey, to be published.
[11]R. V. Jones and J. C. S. Richards, J. Sci. Instr. 36, 90 (1959).
[12]J. H. Nash, A. C. Neeley, and P. J. Steger, Atomic Energy Commission Research and Development Report No. Y-1654 (unpublished), Oak Ridge Y-12 Plant, Union Carbide Company Nuclear Division.
[13]J. W. Beams, D. M. Spitzer, and J. P. Wade, Jr., Rev. Sci. Instr. 33, 131 (1962).

EVIDENCE OF QUARKS IN AIR-SHOWER CORES*

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In a study of air-shower cores using a delayed-expansion cloud chamber, we have observed a track for which the only explanation we can see is that it is produced by a fractionally charged particle.

It is well known that a considerable number of experiments using high-energy accelerators or low-energy cosmic radiation have failed to find the quark.[1] However, much higher energies occur in cosmic-ray air showers. Moreover, several groups have reported the occurrence of very large transverse momenta in interactions in these showers.[2-5] These momenta imply the operation of a very strong force and this might be the quark-quark interaction. Accordingly, we have looked for quarks in air-shower cores using a delayed-expansion Wilson cloud chamber.[6,7] In one year from July 1968 we found four tracks whose appearance was that expected for a quark of charge $\frac{2}{3}e$.[8] Several alternative explanations could be ruled out. For instance, the appearance of the tracks could not be due to a statistical fluctuation in the number of ions produced because the numbers involved were much too large. They could not be due to the Chudakoff effect because the track length at half-minimum ionization was greater than 10 cm in all cases and greater than 20 cm in one case. They could not be due to poor illumination because adjacent tracks were well illuminated. Another possible explanation of a track having half the normal specific ionization is that it is due to a particle that traversed the cloud chamber before the clearing field was removed. It would then be possible for ions of one sign to drift out of the illuminated region while ions of the other sign remained in that region. However, it is also obvious that the extra time spent in the chamber before the clearing field was removed would increase the diffusive width. In subsidiary experiments we had determined the rate of increase of the width with delay time and also measured the mean ionic mobility in the argon-alcohol-water gas mixture. Using these results we were able to show that this explanation also was unlikely.

In this Letter we report an event which we believe greatly strengthens this conclusion.

Figure 1 shows the left-hand view of a stereoscopic pair of photographs of part of event 66 240. Tracks 1 to 5 form part of a "beam" of nine parallel tracks passing through the chamber. These tracks are typical of the tracks of singly charged, relativistic particles. The diffusive widths of tracks 2, 3, 4, and 5 (measured on the original negatives with a Leitz scanning microscope with $2\frac{1}{2}\times$ objective and $10\times$ micrometer eyepiece) were 1.72, 1.74, 1.73, and 1.74 mm, respectively, with a standard deviation of 0.02 mm. In addition to these, we have the track labeled R which is parallel to the beam direction. The diffusive width of R is the same as the other five tracks, namely 1.73 ± 0.02 mm. It is well within the illuminated region, from top to bottom of the chamber. There are well-illuminated tracks behind it, in front of it, and on both sides of it.

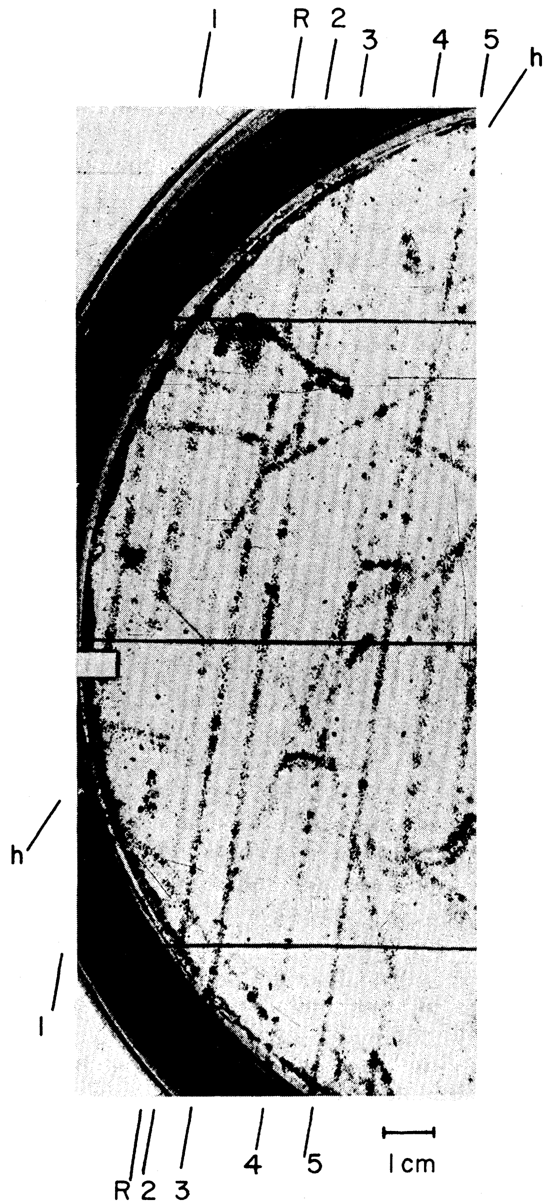

FIG. 1. A Wilson cloud-chamber photograph of event 66 240. The cloud chamber was expanded 100 msec after the arrival of the air shower. The photograph was taken 200 msec after the expansion. Tracks 1 through 5 are part of a parallel beam of singly charged relativistic particles. Track R is parallel to this beam but is appreciably less ionizing. Track h extends from well behind to well in front of track R.

For a particle to have produced this track by the field-doubling mechanism it would have had to (a) be parallel, within the errors of measurement, to the particle beam in the air shower and (b) give a measured width of 1.73 ± 0.02 mm compared with width derived from the necessary time in the clearing field plus the 100-msec delay between field removal and expansion of 2.59 mm. We believe these to be impossible and the only other explanation we can see is that the track is due to a fractionally charged particle. The ratio of the ionization of this track R to the tracks of singly charged particles is 0.48 ± 0.05. The number of droplets counted along track R was 110. Only sections not containing δ rays were counted. We estimate the number of δ rays along R to be 3 and along an equal length of track 3 to be 9. The response of our air-shower array puts the core of the shower on the cloud chamber. The energy of the primary particle[5] was $\sim 3.5 \times 10^6$ GeV; the core structure is consistent with its being an α particle.

If the onset of quark production and the appearance of high transverse momenta in air showers are related (as seems probable) then this onset occurs at ~100 000 GeV. This suggests a rather large mass for the quark.

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[1]T. Massam, CERN Report No. 68-24, 1968 (unpublished).

[2]M. Oda and Y. Tanaka, J. Phys. Soc. Japan 17, Suppl. A III, 282 (1962).

[3]S. Miyake, K. Hinotani, M. Ito, S. Kono, H. Sasaki, H. Yoshii, H. Sakuyama, and E. Kato, Can. J. Phys. 46, S25 (1968).

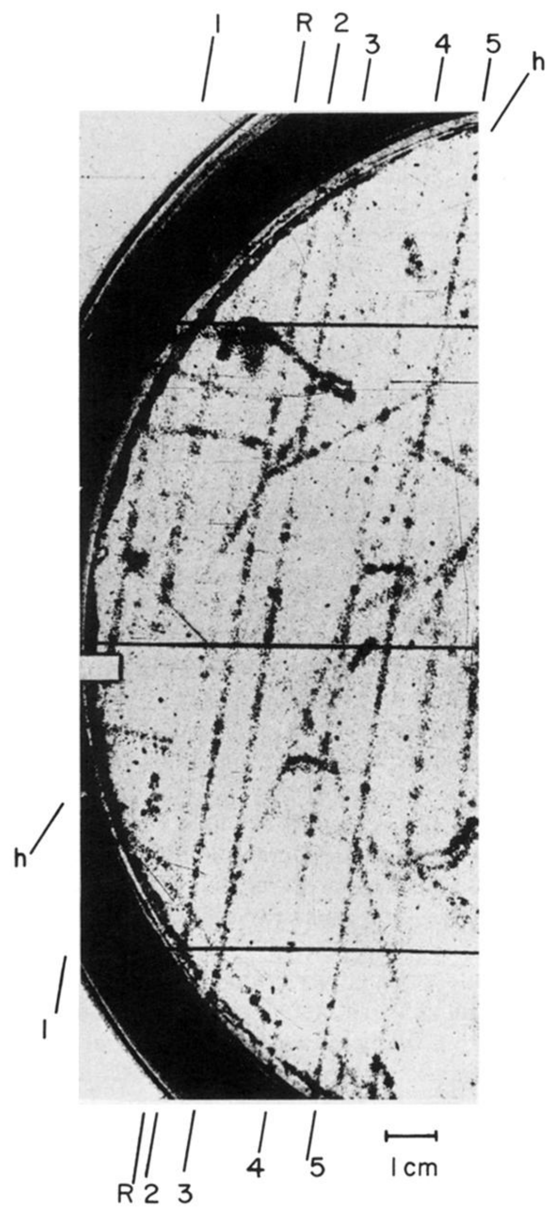
[4]Japanese and Brazilian Emulsion Chamber Group, Can. J. Phys. 46, S660 (1968).

[5]C. B. A. McCusker, L. S. Peak, and M. H. Rathgeber, Phys. Rev. 177, 1902 (1969).

[6]W. E. Hazen, in Cloud Chamber Photographs, edited by G. D. Rochester and J. G. Wilson (Pergamon Press, London, 1952), pp. 4, 5.

[7]D. R. Corson and R. B. Brode, Phys. Rev. 53, 773 (1938).

[8]I. Cairns, C. B. A. McCusker, L. S. Peak, and R. L. S. Woolcott, Phys. Rev. (to be published).



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