Rev. Letters 24, 33 (1970).
[15]D. C. Rahm and R. I. Louttit, Phys. Rev. Letters 24, 279 (1970).
[16]W. T. Chu, Y. S. Kim, W. J. Beam, and N. Kwak, Phys. Rev. Letters 24, 917 (1970).
[17]W. W. Allison, M. Derrick, G. P. Hunt, J. D. Simpson, and L. Voyvodic, Phys. Rev. Letters 25, 550 (1970).
[18]S. Chin, Y. Hanayama, T. Hara, S. Higashi, and K. Tsuji, Nuovo Cimento 2A, 419 (1971).
[19]N. J. Papastamatiou, Phys. Rev. 164, 1784 (1967).
[20]L. I. Schiff, Phys. Rev. Letters 17, 612 (1966).
[21]J. Weyers, Phys. Rev. Letters 18, 1033 (1967).
[22]T. Bowen, E. P. Krider, and J. W. York, Nucl. Instrum. Methods 50, 349 (1967).
[23]D. A. DeLise and T. Bowen, Phys. Rev. 140, 458 (1965).
[24]J. J. J. Kokkedee and L. Van Hove, Nuovo Cimento 42A, 711 (1966).
[25]G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillithun, G. Matthiae, J. P. Scanlon, and M. A. Wetherell, Nucl. Phys. 79, 609 (1965); J. Engler, K. Horn, F. Monnig, P. Schludecker, W. Schmidt-Parzefall, H. Schopper, P. Sievers, H. Ullrich, R. Hartung, K. Runge, and Yu. Galaktionov, Phys. Letters 23B, 716 (1970); L. W. Jones, M. J. Longo, T. P. McCorriston, E. F. Parker, S. T. Powell, and M. N. Kreisler, Phys. Letters 36B, 509 (1971).
[26]G. Cocconi, in *Encyclopedia of Physics* edited by S. Flügge (Springer, Berlin, 1961), Vol. XVI/1, pp. 219–227.
[27]N. L. Grigorov, A. U. Podgarskaya, L. V. Poperkava, Z. H. Sonclyeva, G. A. Skuridin, and A. F. Tikenkov, in *Proceedings of the Eleventh International Conference on Cosmic Rays, Budapest, 1969,* edited by T. Gêmesy *et al*. (Akademiai Kiado, Budapest, 1970).

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Search for $\frac{4}{3}e$ Charged Diquarks in the Cosmic Radiation at 2750-m Altitude*

W. T. Beauchamp, T. Bowen, A. J. Cox,† and R. M. Kalbach
Department of Physics, University of Arizona, Tucson, Arizona 85721
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A large-area 3.35-m^2 scintillation-counter telescope consisting of eight scintillation counters and four wide-gap spark chambers was arranged to detect single particles with charges $\pm\frac{4}{3}e$ which might be present in the cosmic radiation at 2750 m above sea level. The upper limit for the vertical flux of such particles is found to be 4.1×10^{-10} cm^{-2} sr^{-1} sec^{-1}. Estimates of the corresponding sea-level flux are made for comparison with previous results.

I. INTRODUCTION

The idea has been proposed by Gell-Mann[1] and by de Swart[2] that a combination of any two quarks (or antiquarks) with a resulting net charge of $\pm\frac{1}{3}e$, $\pm\frac{2}{3}e$, or $\pm\frac{4}{3}e$ might have lower mass than a single quark. Previous experiments set upper limits on the flux of $\frac{1}{3}e$ and $\frac{2}{3}e$ charged states for the diquark, but the present flux limits on the $\frac{4}{3}e$ state are subject to considerably more uncertainty both at mountain altitude and at sea level.

If a diquark has a mass of the order of the nucleon mass, then the negative results of the cosmic-ray experiments to date (most of which were done at sea level) could be explained by the large attenuation experienced by a low-mass diquark in the atmosphere. The attenuation could easily slow cosmic-ray diquarks to nonrelativistic velocities, making the sea-level cosmic-ray searches less sensitive to them. Furthermore, a low mass in association with a highly repulsive barrier in the quark-quark interaction potential could account for the apparently high production threshold energy suggested by accelerator searches.

In order to reduce the effects of atmospheric attenuation for light diquarks, the $\frac{4}{3}e$ cosmic-ray search reported here was performed at an altitude of 2750 m (9000 ft) above sea level. Since this experiment is not sensitive to the sign of the charge of a particle, all references to quarks or diquarks in this paper will refer to both the particle and antiparticle states.

II. APPARATUS

The apparatus for this experiment consisted of a scintillation-counter telescope and an on-line computer for analysis of the signals from individual counters of the telescope. Because the energy loss dE/dx of a relativistic charged particle traversing matter is to a good approximation independent of particle energy and because this energy loss is proportional to the square of the charge of the particle, a relativistic $\frac{4}{3}e$ charged diquark will produce ionization $\frac{16}{9}$ times as great as that characteristic of a relativistic unit-charge particle. The detec-

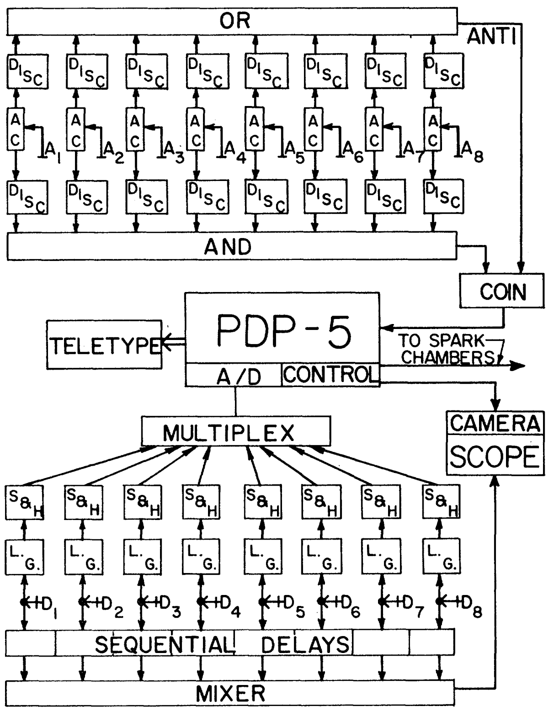

FIG. 1. Block diagram of the electronics. DISC represents a discriminator; A C an attenuator; S&H a sample and hold circuit; L. G. a linear gate; A_1–A_8 the counter anode signals; D_1–D_8 the dynode signals; COIN a coincidence circuit; and A/D, an analog-to-digital converter.

tor, therefore, consisted of an array of eight scintillation counters for measuring dE/dx and four interleaved wide-gap spark chambers. The spark chambers were included to eliminate the primary source of background for $\frac{4}{3}e$-type events: that which arises mainly from the simultaneous passage of two or three particles of unit charge through the array resulting from a cosmic-ray shower near the apparatus. The apparatus was the same as that reported by Cox *et al.*[3] (hereafter referred to as I) with the exception of certain components of the electronic logic circuitry. The arrangement of apparatus is shown schematically in Fig. 1 of I.

The electronics circuitry for the experiment was divided into two main parts; a logic section and a pulse analysis section (see Fig. 1). The anode pulses from the six photomultiplier tubes in each counter box were passively mixed to form a counter anode pulse, and the last-stage dynode signals were passively mixed to form a counter dynode pulse. The eight counter anode pulses were used to initiate fast logic operations and for initial pulse-height selection, while the counter dynode signals were delayed, digitized, and transmitted to the computer for pulse-height analysis. For each event with eight coincident anode signals corresponding to dynode signals with pulse heights I in the range $1.5I_0 < I < 3.0I_0$, the spark chambers were triggered and photographed and the dynode signals were analyzed both by the computer and by photography of corresponding oscilloscope traces as in I. (I_0 is the most probable pulse height for minimum-ionizing unit-charge particles passing through a counter, and was experimentally determined for each counter using a multichannel analyzer.)

In order to permit determination of the efficiency of the electronics for detecting hypothetical $\frac{4}{3}e$ particles, each anode signal was fed to discriminators through an attenuator circuit which was designed to give either the full counter anode signal or $\frac{9}{16}$ of that signal to each of the discriminators. During data taking the attenuator switch was in the $\frac{9}{16}$ position. If the attenuators were switched to their unattenuated (calibrate) position, the discriminators would receive a signal for the passage of a unit-charge particle equivalent to that for a $\frac{4}{3}e$ charged particle when the switch was set at the $\frac{9}{16}$ position. In this way the numerous unit-charge particles incident upon the array could be used to simulate $\frac{4}{3}e$ charged diquarks. The discriminator levels for each counter were adjusted by switching the appropriate attenuator to the calibrate position and measuring the corresponding dynode signals. The discriminator thresholds were then raised or lowered until the dynode signals satisfied the calibration requirement, $\frac{9}{16}(1.5I_0) < I < \frac{9}{16}(3.0I_0)$. The triggering efficiency of the system could also be directly determined by switching all the attenuators to the calibrate position.

III. DATA ANALYSIS

Total running time for the experiment was 1500 h. After correcting for dead time (as explained in I) a sensitive time of 1420 h was obtained. Only those events for which the pulse height I from each counter was determined to fall in the range $1.5I_0 < I < 3I_0$ were subjected to further analysis. A total of 25 000 events satisfying this criterion was recorded. When subjected to the restriction that, for acceptable events, only one particle track should be recorded in each spark chamber, all but ten of these events were rejected. When the particle trajectories for these ten events were reconstructed, all but two, those identified as 45/1216 and 32A/1062, were rejected on the basis that the trajectories did not pass through the active area of all counters. Pulse heights and statistical data for these two surviving events are shown in Table I. The quantity R in Table I is defined as

TABLE I. Pulse heights, P_i, and their average, $\bar{P}$, in the eight scintillation counters, in arbitrary units, for the two events satisfying pulse-height and trajectory criteria. The most probable pulse height for a unit-charge relativistic particle is 1250 units, and that for a $\frac{4}{3}e$ charged diquark is 2200 units. The quantity R is explained in the text.

Event	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	$\bar{P}$	R
45/1216	3450	3620	2888	3408	2734	2138	2431	2450	2890	0.177
23A/1062	1800	1872	1945	2153	1955	2355	2126	2150	2044	0.084

$$R = \frac{1}{\bar{P}}\left(\frac{1}{8}\sum_{i=1}^{8}(P_i - \bar{P})^2\right)^{1/2},$$

where P_i are the individual pulse heights, and $\bar{P}$ is the average pulse height of the eight counters. Small values of R correspond to small deviations from the mean pulse height in the individual counters.

Figure 2 is a plot of the experimentally determined fraction of unit charge events and simulated $\frac{1}{3}e$ and $\frac{2}{3}e$ events with R values less than a specified value. The curve representative of charge-$\frac{4}{3}e$ diquarks would lie to the left of the unit-charge curve so that we can use the curve for unit-charge events to set a minimum value for the fraction of $\frac{4}{3}e$ events that would correspond to each value of R. At least 40% of all $\frac{4}{3}e$ events would have $R \geq 0.18$ (as for event 45/1216), and at least 88% of all $\frac{4}{3}e$ events would have $R \geq 0.08$ (as for event 23A/1062), indicating that both events have acceptable values of R. The average pulse heights for the two diquark candidates are represented by the squares in the $\frac{4}{3}e$ charged particle energy-loss distribution shown in Fig. 3, which was calculated on the basis of the experimentally determined distribution for unit-charge particles.

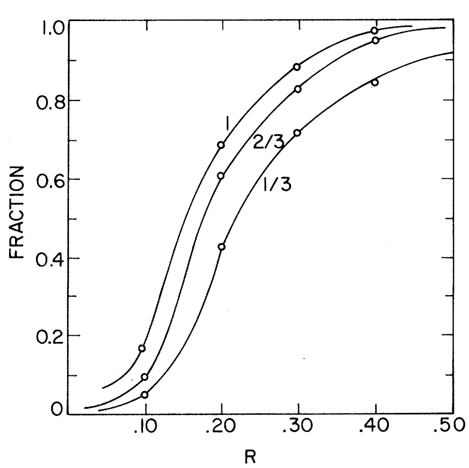

FIG. 2. Fraction of unit-charge events, and simulated $\frac{1}{3}e$ and $\frac{2}{3}e$ events, with R values less than a given value.

IV. BACKGROUND

The possible sources of background consist of three types: (1) simulation of $\frac{4}{3}e$ diquarks by particles in the unit-charge energy-loss distribution with $I \geq 1.5 I_0$ (i.e., pulses arising from the tail of the unit-charge Landau distribution); (2) pulses due to passage through the array of slow unit-charge particles; and (3) pulses resulting from the simultaneous passage of two unit-charge particles through appropriate sections of the array. The last of these background types was the primary source of charge-$\frac{4}{3}e$ triggers for this experiment. The distribution of all the event triggers is shown in Fig. 4. The peak of this distribution is at a pulse height which is twice the value corresponding to the most probable pulse height of a unit-charge particle. Events associated with the simultaneous passage of two unit-charge particles were readily identified in the spark chamber pictures and rejected.

The expected number of events arising from pulses associated with the tail of the unit-charge distribution can be calculated. Figure 5 shows the expected pulse-height distribution for unit-charge and $\frac{4}{3}e$ charged particles in any one scintillation counter. From this distribution the probability of observing a pulse height greater than $1.5 I_0$ for a unit-charge particle is approximately 0.07, so that the probability of having eight coincident pulses of this type is of the order of 6×10^{-10}. Since the

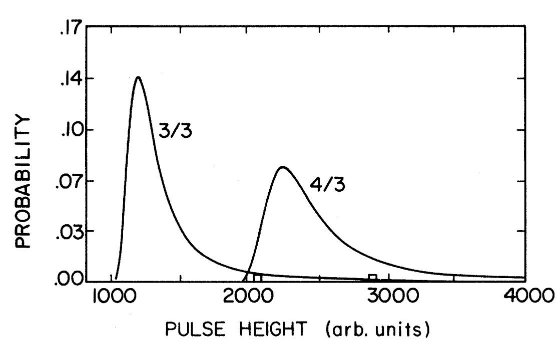

FIG. 3. Pulse-height spectra for single and $\frac{4}{3}e$ minimum ionizing particles for a single scintillation counter.

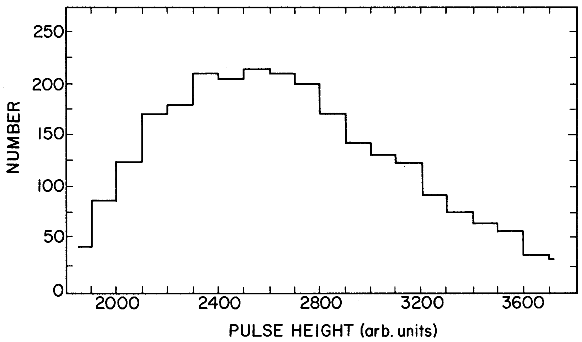

FIG. 4. Average pulse-height distribution for all event triggers. A minimum ionizing, unit-charge particle would give a pulse height of 1250 units.

counting rate for unit-charge particles was about 100 $\sec^{-1}$ and the total running time was about 5×10^6 sec, one would expect to see 0.3 events associated with this type of background.

The last type of background is due to slow, unit-charge particles. In order for a muon, pion, proton, or deuteron to produce pulses with heights $\frac{16}{9}I_0$, such particles with kinetic energies of approximately 13.5, 18, 300, and 590 MeV, respectively, are required. The ranges associated with such particles would be approximately 1.35, 1.8, 56, and 120 g/cm^2, respectively. The muon, pion, and proton components of this background would be absorbed by the 120 g/cm^2 of matter in the array. The deuterons, on the other hand, could penetrate the array, but would most likely be rejected by the logic. This can be seen by examining the average energy losses in the top and bottom counters. A deuteron with an energy of 590 MeV ($I=1.77I_0$) would have average energy losses in the top and bottom counters of 3.11 MeV/g cm^{-2} and 6.02 MeV/g cm^{-2}, respectively. This would produce a pulse in the last counter of height $3.4I_0$, which would not satisfy the triggering logic. This type of rejection would occur for most of the slow deuterons traversing the array.

If, however, one considers the most unfavorable case of a deuteron entering the array at approximately 720 MeV ($I=1.6I_0$), then the last pulse would be approximately $2.3I_0$. In the range from 720 to 820 MeV ($1.6I_0$ to $1.5I_0$, respectively) deuterons could produce a set of pulse heights representative of a $\frac{4}{3}e$ diquark, and not be rejected by the logic. It is therefore necessary to know the approximate flux of deuterons in this energy range at 2750 m altitude, and the detection effeciencies for these particles. Figure 6 shows the dependence of the intensities of secondary deuterons and protons on the depth in the atmosphere in the energy range of 20–106 MeV.[4] If we extrapolate this graph

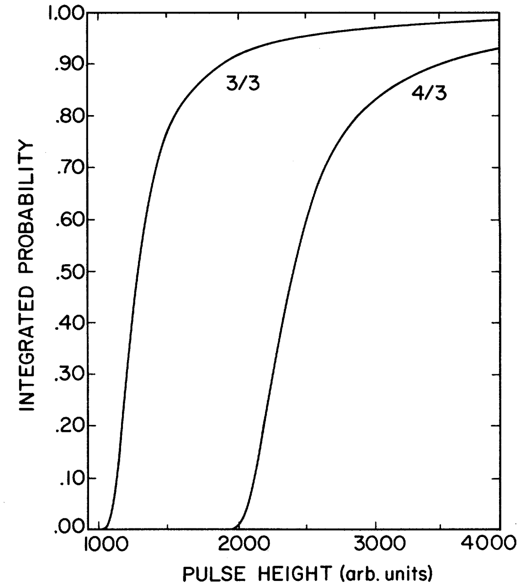

FIG. 5. Integrated pulse-height distributions for single and $\frac{4}{3}e$ minimum ionizing particles for a single scintillation counter.

from 200 g/cm^2 to the depth of 750 g/cm^2 (2750 m altitude) we find that for deuterons the intensity is approximately 5.6×10^{-4} (m^2 sr sec MeV)$^{-1}$, where an attenuation length for the deuterons in air of 94 g/cm^2 has been used. Because of the limited amount of data on the deuteron intensity spectrum it is necessary to extrapolate this flux (measured at an average energy of about 100 MeV) to get an estimate for the flux in the energy range of 700–800 MeV. This extrapolation was made using the

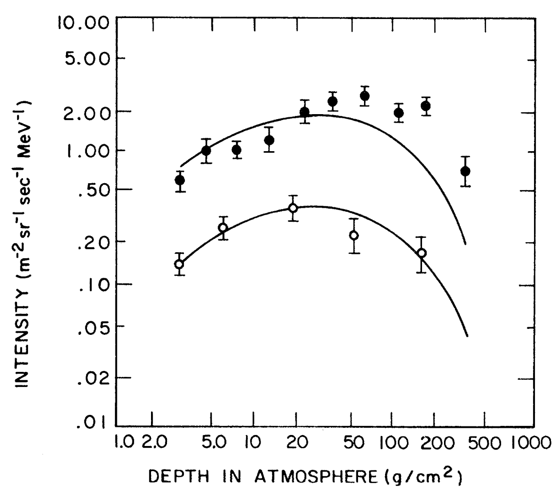

FIG. 6. Intensity of secondary protons and deuterons with energies between 20 and 106 MeV as a function of depth in the atmosphere from Ref. 4. The dots are for protons and the circles are for deuterons.

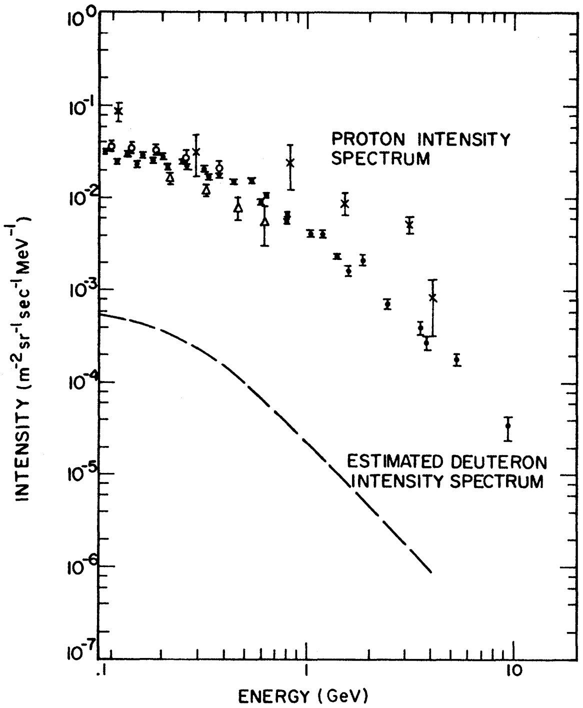

FIG. 7. Intensity spectrum for protons and the estimated intensity spectrum for deuterons. [The data points marked by triangles were taken at 2740 m above sea level (Ref. 5); by dots at 3200 m (Ref. 6); by circles at 3250 m (Ref. 7); and by crosses at 5200 m (Ref. 8).]

energy spectrum for protons[5–8] shown in Fig. 7 and assuming the same general shape for the deuteron spectrum. If it is positioned so as to match the estimated intensity for deuterons at about 100 MeV, one obtains the curve shown by the dashed line in Fig. 7. The spacing of the two curves is in rough agreement with the measured value for the ratio of the number of deuterons to protons in mountain-altitude cosmic rays of about $\frac{1}{15}$.[9] From this curve one can estimate the intensity for deuterons at 700 MeV to be of the order of 10^{-9} $(cm^2\,sr\,sec\,MeV)^{-1}$. Therefore, for the 100-MeV spread in energies for deuterons which can simulate a $\frac{4}{3}e$ diquark, one arrives at a deuteron flux of the order of 10^{-7} $(cm^2\,sr\,sec)^{-1}$. With this flux one would expect to see of the order of 1000 simulated $\frac{4}{3}e$ events during the run. However, there are two effects which reduce the probability of detecting these events relative to diquarks.

First, the interaction mean free path of a deuteron with the material in the array would be of the order of 60 g/cm^2 compared to 120–140 g/cm^2 assumed for a diquark. Therefore, deuterons would be attenuated by an order of magnitude relative to diquarks in traversing the array itself. Second, the detection efficiency for deuterons producing signals in the range $1.5–1.6I_0$ would be severely reduced relative to the measured efficiency of 37% for $\frac{4}{3}e$ diquarks due to the statistical nature of the energy loss: The single-counter detection efficiency can be determined from the area of the energy-loss distribution curve between the limits on energy loss defined by the logic circuitry. In the case of $\frac{4}{3}e$ diquarks, the single-counter detection efficiency is of the order of 88% so that the over-all efficiency is then 37% for the eight counters. However, the energy-loss distribution associated with each pulse from a slow deuteron (similar in magnitude to a unit-charge Landau distribution but more symmetric) would not be centered with respect to the limits on energy loss, $1.5I_0 < I < 3.0I_0$, so that the expected efficiency for deuteron detection would be lower than the 88% associated with each relativistic $\frac{4}{3}e$ diquark. This reduction in efficiency for each counter could give an over-all reduction of an order of magnitude in deuteron detection efficiency. When combined with the interaction attenuation in the array this reduces the expected number of slow deuteron events to the same order of magnitude as the number of apparent $\frac{4}{3}e$ events in this experiment. Despite the probability that these events are due to the deuteron background, they will be counted as "real" events in the flux limit calculations.

V. FLUX LIMITS

The method used for determining the equivalent sea-level flux limits for this experiment is the same as that given in I, with the exception of the value for the attenuation length λ_Q used in the formula for the flux of diquarks at a given atmospheric depth. To estimate the attenuation length in air for cosmic-ray diquarks, we assume that the interaction of two hadrons at high energies can be considered as an interaction between the two corresponding groups of quarks, and that the strength and character of the interaction would come from the sum of the individual quark-quark interactions. This would mean that the interaction of a pion and a proton, for instance, could be considered as the interaction of two- and three-quark clusters, and that the interaction of two protons is represented by the interaction of two three-quark clusters. If charge exchange and quark-antiquark annihilation become negligible at high energy, then quark-proton, quark-neutron, antiquark-proton, and antiquark-neutron cross sections become identical, and the hadron-nucleon cross section becomes an integral multiple of the quark-nucleon cross section. This argument has been used to explain the high-energy data which suggest that the ratio of the pion-nucleon and proton-nucleon cross sections is equal to $\frac{2}{3}$.[10] An extension of this idea suggests that the diquark-nucleon inelastic cross section is equal to two thirds of the nucleon-nucleon inelastic cross section. If the inelastic part of an assumed 39-mb proton-proton total cross section is about 31 mb, the high-energy diquark-nucleon inelastic cross section would be approximately 21 mb.

To obtain a value for the attenuation length of diquarks in air, the inelastic interaction cross section in an average air nucleus (atomic weight = 14.5) must be estimated. Using a simple geometrical model of the nucleus as a sphere of radius $1.4A^{1/3}$ fm in which the nucleon has an inelastic interaction length of 2.5 fm, an inelastic cross section in good agreement with accelerator results on C^{12} is obtained.[11] This corresponds to a nucleon-air nucleus interaction length of 81.6 g/cm^2. Assuming that the diquark has an interaction length of $\frac{3}{2}(2.5\text{ fm}) = 3.75$ fm, the diquark interaction length in air would be 97 g/cm^2. However, we might expect the attenuation length in air to be somewhat longer than the interaction length, since diquarks could retain considerable energy after each collision. Assuming that this effect is the same as for nucleon-air nucleus collisions, where the attenuation length is observed to be 120 g/cm^2, the estimated diquark attenuation length is $(120/81.6) \times (97) = 143$ g/cm^2.

In calculating the weighted flux limits for this experiment it is useful to consider three cases: (1) no attenuation ($\lambda_Q = \infty$), (2) the case of light diquarks with the attenuation constant calculated above ($\lambda_Q = 143$ g/cm^2), and (3) attenuation greater than that for protons ($\lambda_Q \leq 120$ g/cm^2). Assuming that two events were observed, the limits on the equivalent sea-level flux of diquarks at a 90% confidence level become

Case (1):

$$I_Q < 4.1\times10^{-10}\ (\text{cm}^2\ \text{sr sec})^{-1},$$

with $\lambda_Q = \infty$ and $(A\Omega)_{\text{geo}} = 0.626\times10^4$ cm^2 sr;

Case (2):

$$I_Q < 6.7\times10^{-11}\ (\text{cm}^2\ \text{sr sec})^{-1},$$

with $\lambda_Q = 143$ g/cm^2 and $(A\Omega)_{\text{eff}} = 3.85\times10^4$ cm^2 sr;

Case (3):

$$I_Q < 4.7\times10^{-11}\ (\text{cm}^2\ \text{sr sec})^{-1},$$

with $\lambda_Q \leq 120$ g/cm^2 and $(A\Omega)_{\text{eff}} = 5.51\times10^4$ cm^2 sr.

In each case the geometric area–solid-angle product, $(A\Omega)_{\text{geo}}$, or the effective area–solid-angle product, $(A\Omega)_{\text{eff}}$, of the apparatus (as calculated in I) has been quoted. Case (1) is the flux limit for $\frac{4}{3}e$ charged diquarks in the cosmic radiation at 2750 m above sea level as well as the equivalent flux limit at sea level if $M_Q \gg 1$ GeV and $\lambda_Q = \infty$. If, on the other hand, diquarks have low mass and are attenuated by the atmosphere, then Case (2) is the appropriate weighted sea-level flux limit corresponding to $M_Q \approx 1$ GeV and $\lambda_Q = 143$ g/cm^2. Case (3) is the flux limit if $\lambda_Q \leq 120$ g/cm^2, an unlikely possibility within the framework of the quark model.

The results obtained at mountain altitudes by this experiment are consistent with the results obtained in other published experiments sensitive to $\frac{4}{3}e$ charged particles, which were all obtained at sea level: Buhler-Broglin *et al.*[12] found $I_Q < 1.6\times10^{-7}$ diquarks (cm^2 sr sec)$^{-1}$, Kasha *et al.*[13] found $I_Q < 1.3\times10^{-10}$ diquarks (cm^2 sr sec)$^{-1}$, and by a different technique Ashton and King[14] found $I_Q < 8.2\times10^{-10}$ diquarks (cm^2 sr sec)$^{-1}$.

Since this experiment is sensitive to single-particle events only, it would be possible for a diquark to escape detection if it is produced in close association with a cosmic-ray air shower. This experiment is sensitive to diquarks, in this instance, if the energy of the air shower primary is less than about 10^{14} eV. The energy of air showers which affect the sensitivity of the experiment is somewhat dependent on the assumed value of the diquark mass and transverse momentum, which is discussed in more detail in I.

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†Present address: University of Redlands, Redlands, California.

[1]M. Gell-Mann, Phys. Letters 8, 214 (1964).
[2]J. J. de Swart, Phys. Rev. Letters 18, 618 (1967).
[3]A. J. Cox, W. T. Beauchamp, T. Bowen, and R. M. Kalbach, preceding paper, Phys. Rev. D 6, 1203 (1972).
[4]B. Teegarden, J. Geophys. Res. 72, 4857 (1967).
[5]A. Z. Rozen, Phys. Rev. 93, 211 (1954).

[6]N. M. Kocharian, Zh. Eksp. Teor. Fiz. 28, 160 (1955) [Sov. Phys. JETP 1, 128 (1955)].
[7]A. G. Meshkovskii and L. I. Sokolov, Zh. Eksp. Teor. Fiz. 31, 752 (1956) [Sov. Phys. JETP 4, 629 (1957)].
[8]O. C. Allkofer and E. Kraft, Nuovo Cimento 39, 1051 (1965).
[9]A. I. Alikhanov, A. V. Khrimayan, V. K. Kosmaohevsky, V. V. Avakyon, Yn. V. Gorodkov, K. Sh. Egiyan, and N. A. Nalbandyan, in *Proceedings of the Moscow Cosmic Ray Conference, 1959,* Vol. I, edited by N. M. Gerasimova (International Union of Pure and Applied Physics, Moscow, 1960).
[10]J. J. J. Kokkedee and L. Van Hove, Nuovo Cimento 42A, 711 (1966).
[11]G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillithun, G. Matthiae, J. P. Scanlon, and M. A. Wetherell, Nucl. Phys. 79, 609 (1965); J. Engler, K. Horn, F. Monnig, P. Schludecker, W. Schmidt-Parzefall, H. Schopper, P. Sievers, H. Ullrich, R. Hartung, K. Runge, and Yu. Galaktionov, Phys. Letters 32B, 716 (1970); L. W. Jones, M. J. Longo, T. P. McCorriston, E. F. Parker, S. T. Powell, and M. N. Kreisler, Phys. Letters 36B, 509 (1971).
[12]A. Buhler-Broglin, G. Fortunato, T. Massam, and A. Zichichi, Nuovo Cimento 49A, 209 (1967).
[13]H. Kasha, R. C. Larsen, L. B. Leipuner, and R. K. Adair, Phys. Rev. Letters 20, 217 (1968).
[14]F. Ashton and J. King, J. Phys. A 4, L 31 (1971).

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Velocity Distribution of Secondary π Mesons from 22.6-GeV/c Proton-Nucleus Interactions in Emulsion

T. Roy and I. K. Daftari
Department of Physics, Jadavpur University, Calcutta-32, India
(Received 15 November 1971)

Emulsion plates exposed to a 24-GeV proton beam are scanned. A velocity distribution of the secondary π mesons produced in such nuclear interactions is obtained. A Gaussian-type function is observed to simulate the experimental data and the usual phenomena of isotropy in the center-of-mass frame. Our results indicate that the assumption of the constant velocity for all the secondary particles is only an approximation to the real world.

I. INTRODUCTION

An analysis of secondary π-meson production and determination of the primary energy of the cosmic-ray nucleon was first done by Duller and Walker[1] in a successful and elegant way. Their assumption regarding the isotropy of the secondary π-meson production has been verified amply by various workers. There is also another assumption in Duller and Walker's derivation with regard to momentum distribution of the secondary particles. Duller and Walker and others assumed that secondary particles come out with almost the same momentum. That this is not far from the truth comes from our investigations. We have analyzed the momentum distribution of the secondary particles and have seen that in the center-of-mass frame the distribution is almost Gaussian.

Our analysis has been solely confined to the emulsion plates exposed to the 22.6-GeV/c proton beam.

Various theoretical predictions have been made according to various theories, and the first theoretical proof of this meson production has been given by Fermi[2] who based his work on statistical theory. Takagi[3] and Kraushar and Marks[4] have suggested a two-center model for the production of mesons in high-energy nuclear collisions, which has been successfully followed by Lindenbaum and Sternheimer[5] and Holmquist.[6] In 1954 Duller and Walker[1] studied the angular distribution of penetrating showers through lead and carbon in a cloud chamber in the energy range 10–40 BeV. Aly and Fisher[7] have shown the isotropic nature of the secondary mesons in the c.m. system obtained at 6-GeV/c proton interactions with emulsion nuclei.

In the present experiment we have studied the velocity distribution of secondary π mesons in the c.m. system of 22.6-GeV/c proton–emulsion-nuclei interactions. It is seen that with the increase of the velocity of secondary mesons, the number of particles also increases up to a certain limit and then becomes almost constant. All the quantities such as velocities, ranges, and space angles of secondary particles have been measured in the laboratory and then converted into the c.m.