Search for Massive Particles in Cosmic Rays*

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(Received 29 June 1967)

A search for heavy particles with a mass greater than that of a nucleon, the existence of which has been suggested by higher-symmetry schemes, was performed with an apparatus set up at Echo Lake, Colorado (elevation 10 600 ft). The search was sensitive to strongly interacting particles with masses in the range 5–15 BeV, with no restriction imposed on their electric charge. The method used was to measure the time interval between the arrival of strongly interacting particles and accompanying air shower particles. This information, coupled with information from a measurement of the particle's energy and range of absorption in a total absorption spectrometer, enabled a distinction to be made between massive elementary particles, nucleons, and nuclei. In an operating period of 1542 h and with an aperture of 0.78 m^2 sr, one delayed event was found whose behavior in the total absorption spectrometer was atypical of a nucleon or nucleus. If one considers this event to represent the arrival of a massive particle, then its mass, calculated assuming that its production occurred 1 km above the apparatus, is approximately 6.5 BeV. This one event corresponds to a flux of the order of 10^{-10} (cm^2 sec sr)$^{-1}$, where a correction for detection efficiency has been included. As there is also an 8% probability that this event was a nucleon, we do not regard this as significant evidence for the existence of a massive elementary particle, but rather as setting an effective upper limit to the flux of such particles.

I. INTRODUCTION

FOLLOWING the success of $SU(3)$ and $SU(6)$ symmetry schemes in the classification of known hadrons, theoretical speculations have arisen concerning the possible existence of fundamental subunits of particles.[1–6] In these speculations, hadrons are considered to be composites of these hitherto undiscovered fundamental subunits, and in the simplest schemes[1,2] there is a triplet of them, called "quarks," where the elements

* Supported in part by the National Science Foundation and the U. S. Office of Naval Research Contract No. Nonr. 1224(23).

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** Supported in part by the U. S. Atomic Energy Commission.

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of the triplet have fractional charges. In other versions there are more than three elements, and the charges carried by these are integral.[3–6] Theoretical conclusions[5] suggest that the masses of these fundamental elements are likely to be of the order of 10 BeV.

There have been several searches that used accelerators or cosmic rays to find fractionally charged particles[7–18] and a few to find fractionally or integrally charged particles.[18–22] Other searches for naturally occurring stable quarks have been performed that used mass spectrometric, optical spectroscopic, and other methods.[23–28] The results of these searches were negative and have thus set lower limits for the masses of these fundamental subunits, of the order of 5 BeV, and corresponding upper limits for their production cross section. Calculations have been performed concerning the production cross section for these heavy particles in nucleon-nucleon collisions,[29,30] and an estimate based on the peripheral model predicts a cross section of the order of 1 μb/nucleon for a particle with a mass of 6 BeV.

The method adopted in the present search is similar to the one suggested by Damgaard *et al.*[31] and consists of measuring the time interval between the arrival at the apparatus of strongly interacting particles and their accompanying air showers. The distribution in the time-delayed arrival of a particular strongly interacting particle with respect to the associated air shower arrival is a measure of the mass of the particle and will be explained in the next section. The merits and defects of the technique are also discussed there.

II. THE METHOD

A particle of mass M and energy E produced in the atmosphere in a collision at a height Z above the apparatus will arrive at the apparatus delayed in time with respect to the arrival of the associated air shower of extremely relativistic particles (muons, electrons, etc.) by a time

$$t=\psi(\gamma,Z)=Z/2\gamma^2c,\quad \gamma\gg1 \tag{1}$$

where $\gamma=E/M$ and c is the velocity of light. If one assumes a Z of 1 km, corresponding to about one nuclear interaction mean free path in the atmosphere at 10 000 ft, and a γ of 10, then Eq. (1) gives $t=17$ nsec as the order of magnitude of time delays that can be expected. Also, in the production of massive particles with mass M, the mean energy E_v of the particles when produced in pairs in nucleon-nucleon collisions near the threshold energy E_{th} is

$$E_v\sim\tfrac{1}{2}E_{\text{th}}\simeq\tfrac{1}{2}(2M)^2/2M_{\text{nucleon}}=M^2/M_{\text{nucleon}}.$$

Thus, with $M=10$ BeV, one finds that E_v is of the order of 100 BeV, so that one has to use a device for detecting and measuring particles with energies of the order of 100 BeV.

The distribution in the atmosphere of points of production of detected massive particles depends on the intensity $\varphi_1(x)$ of hadrons at various heights x (measured in g cm^{-2}) in the atmosphere; on the density distribution $\varphi_2(Z)$ of the atmosphere itself; and on the survival probability $\varphi_3(x)$ for the massive particles to reach the apparatus from a height x above it. To a first approximation, one can write

$$\varphi_1(x)\propto e^{x/\lambda_a},$$
$$\varphi_3(x)\propto e^{-x/\lambda_h},$$

where λ_a and λ_h are the attenuation mean free paths (measured in g cm^{-2} of air) of hadrons capable of producing massive particles and of the massive particles, respectively. The distribution in the atmosphere of the

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points of production of the massive particles $\varphi(x)$ is given as the product of $\varphi_1(x)$ and $\varphi_3(x)$, namely,

$$\varphi(x) \propto \exp[x(1/\lambda_a - 1/\lambda_h)],$$

which can be rewritten in terms of linear units (i.e., in cm) as

$$\varphi(Z) \propto \varphi_2(Z) \exp[x(1/\lambda_a - 1/\lambda_h)]$$
$$\propto e^{-Z/Z_0} \exp[x(1/\lambda_a - 1/\lambda_h)].$$

For the case where $\lambda_h = \lambda_a$, $\varphi(Z)$ is a function of Z alone and is

$$\varphi(Z) \propto e^{-Z/Z_0},$$

where Z_0 is the scale height of the atmosphere, taken to be 7 km. This distribution upon transformation from Z to t via Eq. (1) becomes

$$\Phi(\gamma,t) \propto e^{-t/t_0(\gamma)}, \qquad (2)$$

the distribution in arrival times of massive particles with $\gamma = E/M$. Here $t_0(\gamma)$ is the mean arrival time and is given by

$$t_0(\gamma) = Z_0/2\gamma^2 c. \qquad (3)$$

The distribution $\Phi(\gamma,t)$ was calculated for particles with a mass of 10 BeV and an energy of 100 BeV for three choices of λ_h, and the results are shown in Fig. 1. The actual distributions will be somewhat steeper because of the poor detection efficiency for air showers with an origin high in the atmosphere. There have been efforts to calculate the distribution $\Phi(\gamma,t)$ in greater detail,[32,33] and, while the results are qualitatively similar to Eq. (2), they are not directly applicable to this experiment. With these results, then, a measurement of t_0 and E leads to the mass of the particle via the relation

$$M = (2E^2 c t_0/Z_0)^{1/2}, \qquad (4)$$

with contributions to the error in the determination of the mass given by

$$\Delta M/M = \Delta E/E + \Delta t_0/2t_0. \qquad (5)$$

The method imposes certain requirements that the hypothetical particles must satisfy in order that they can be detected. First, they must have a mean lifetime that is greater than about 10^{-6} sec so that they can reach the apparatus at all. Second, they must lose a significant fraction ($>5\%$ per interaction) of their energies through nuclear interactions so that they can be detected in the total absorption spectrometer used in this experiment to measure event energy. And, third, they should acquire only about the same order of magnitude of the transverse momentum that is acquired by nucleons in nuclear collisions, so that the massive particles are not greatly displaced spatially from their associated air shower when they reach the apparatus.

In the present method, the search for massive particles could be made without reference to their electric charge. However, this made it necessary to use other methods to distinguish massive particles from the nuclei of elements like helium and carbon that are present among cosmic-ray primaries and which have a small but non-negligible probability of being observed at mountain altitudes.

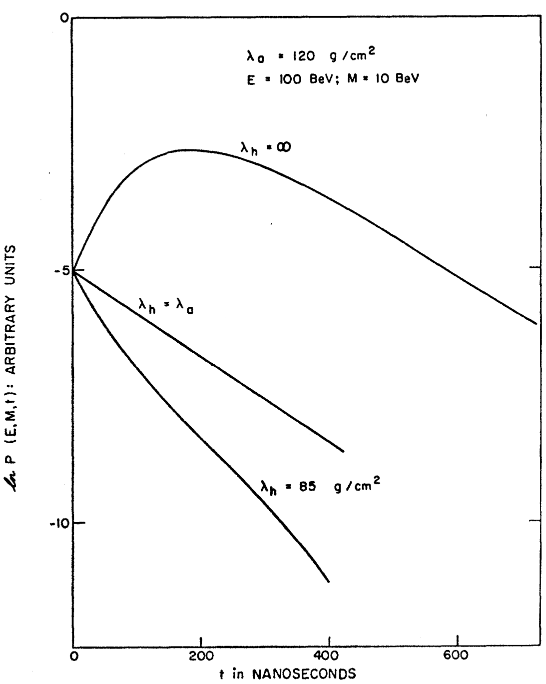

FIG. 1. Some possible distributions in the time of arrival of massive particles, with respect to the associated air shower arrival. λ_a and λ_h are the attenuation mean free paths measured in g/cm² of air of hadrons and massive particles, respectively. $P(E,M,t)$ is the probability that a massive particle of mass M and total energy E is delayed by t.

III. EXPERIMENTAL ARRANGEMENT

The arrangement of the apparatus used to search for massive elementary particles is described below and is shown in Fig. 2. The central element of the apparatus was a total absorption spectrometer which was used to measure the energy of nuclear active particles incident on it. The spectrometer was fabricated from an iron stack with a thickness of 1070 g/cm² and an area of 3 ft×6 ft, with plastic scintillators $\frac{3}{4}$ in. thick as probes placed at seven levels in the absorber material. Each of the six uppermost scintillators was viewed by four photomultiplier tubes so that there was a nearly uniform response for varying positions of the passage of ionizing particles. The bottom scintillator was 4 ft×8 ft in area and was viewed by six photomultiplier tubes. The scintillators were calibrated in terms of the energy loss of cosmic-ray muons passing through them, so that the level of ionization recorded by a scintillation counter

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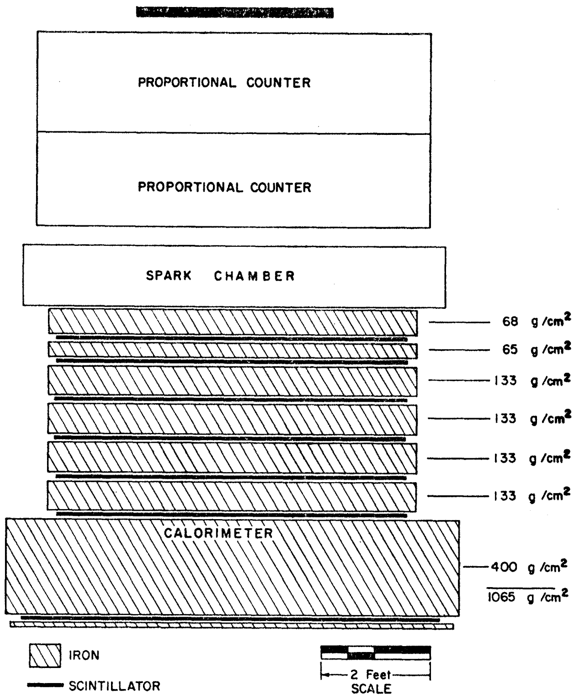

FIG. 2. Experimental arrangement. The air shower counters, not shown, were arranged in 30 ft^2 groups deployed on all four sides of the apparatus, slightly above the spark chamber location.

could be turned into the level due to an equivalent number of relativistic muons, that lose an energy in iron of 1.7 MeV (g/cm^2)$^{-1}$. A minimum level in the sum of pulses from the scintillators served to select triggers that corresponded to hadron energies of the order of or greater than 10 BeV.

The spectrometer was flanked by several scintillation counters to detect accompanying air showers. The total area presented by these air shower counters, which was 130 ft^2, was divided into four groups of counters of approximately equal area. A typical counter in each group consisted of a 2-ft$\times$2-ft$\times$2-in. plastic scintillator viewed by one photomultiplier tube.

Additional elements of the apparatus included a wide gap spark chamber and a system of six gas proportional counters. In cases of interest the spark chamber provided the direction and number of charged particles incident on the spectrometer, and in cases of a single incident charged particle the gas proportional counters yielded the charge. Here, the level of ionization corresponding to unit charge was determined from the level recorded when relativistic muons passed through the counter system.

The signals from the seven counters in the total absorption spectrometer were logarithmically digitized, and the signals from the six gas proportional counters were linearly digitized into seven binary bits of information per counter. The time delay between the spectrometer trigger signal and the signal from each of the four air shower counter groups, measured with respect to the spectrometer signal, was digitized through a system of time to height converters and an analog to digital circuit. All digital information was then recorded on punched paper tape. The dynamic recording ranges for the various elements of the apparatus were 1 to 1000 minimum ionizing muons, -200 nsec to $+200$ nsec, and 0 to twice minimum ionization, for the spectrometer, time interval, and gas proportional counter signals, respectively.

The apparatus was housed in a wooden building, and the associated electronics in an adjacent trailer. The equipment was operated at Echo Lake, Colorado (elevation 10 600 ft), during the fall and winter of 1966–67.

IV. PERFORMANCE OF THE APPARATUS

It should be noted at the outset that the time distributions presented herein are from the point of view of the shower counters so that massive particle-like events appear with $t<0$.

A. Time Resolution

Errors in the measurement of the time interval between a signal from the spectrometer and a signal from the air shower counters arose from (a) coincidence and discriminator jitter, (b) electron transit time jitter in the phototubes, (c) transit time variations of light in the counters, and (d) the spread in the arrival time of particles belonging to the air shower. The weights of these effects in determining the time resolution of the apparatus were measured and the results summarized in Table I(a). The conclusion is that the time resolution of the apparatus was approximately 16 nsec and that this was mainly due to the spread in time of the arrival of the air shower particles. This resolution is to be compared to the experimental time resolution that has been taken to be given by the full width at half-maximum of the accompanying air shower time distribution plotted using events whose energies, as measured in the spec-

TABLE I. Width of time distribution.

(a) Due to various sources

Cause of spread	Γ (nsec)
Circuitry	0.8
Electron time jitter between two phototubes	5.0
Light transit in scintillator	4.4
Shower front	10.0

(b) Actually observed; to be compared with an expected half-width $\frac{1}{2}\Gamma=8$ nsec.

Case of signal from	Width of left half of the distribution (nsec)
One shower counter	9.0
Two shower counters	7.7
Three shower counters	7.3
Four shower counters	5.9

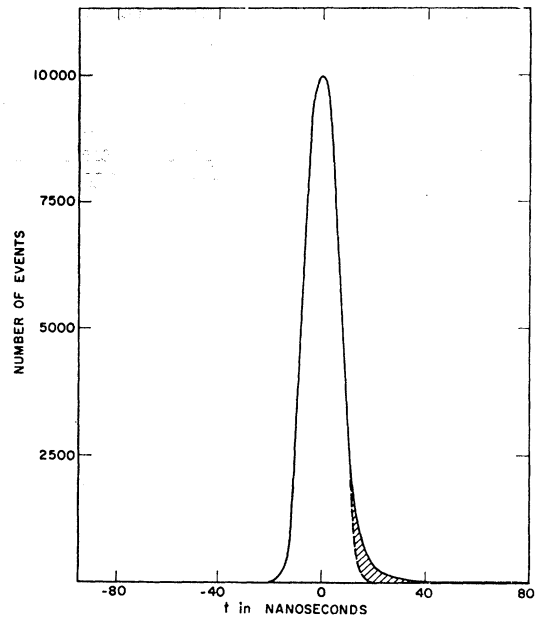

FIG. 3. The time of arrival distribution for events whose calculated energy was greater than 100 BeV. This distribution is taken to be the experimental time resolution in the experiment.

trometer, were greater than 100 BeV. This experimental distribution is shown in Fig. 3.

The distribution shown in Fig. 3 is a mixture of events in which either two, three, or four shower counter groups gave signals, all within a time spread of 40 nsec. What was plotted, then, is the average time "delay" of the shower counters with respect to the spectrometer, averaged over two, three, or four shower counter groups. The half-widths for the separate distributions contributing to Fig. 3 are given in Table I(b) and are to be compared to the expected half-width of $\frac{1}{2}\Gamma=8$ nsec. The broadest of these contributing distributions is the distribution for events where only two shower counter signals were within the 40 nsec allowed time spread, and the widths naturally decrease as the averaging is done over more shower counter groups.

The asymmetry of Fig. 3 seems to stem from the fact that signals from the spectrometer were used in conjunction with signals from the air shower counters since in the studies made to obtain the values for Table I(a) no asymmetric distribution was observed. An interpretation of the asymmetry is that the shower counters were triggered by slow neutrons ($\sim$200 MeV/c) or other backward-going particles from the nuclear cascade in the spectrometer. The relative frequency of such events, though, as judged from the size of the asymmetry of Fig. 3, was only of the order of 3%. Also, the asymmetry becomes negligible if only those events are included in the plot where shower counter averaging was done over three or four groups. This can be interpreted as an effect of averaging or as a real effect stemming from the relatively lower probability that backsplash from the spectrometer would give signals in three or four shower counter groups.

B. Energy Resolution

The energy of each recorded event was calculated using the relation

$$E_c=f\beta[\tfrac{1}{2}N_1x_1+\sum_{i=2}^{5}\tfrac{1}{2}(N_{i-1}+N_i)x_i+\Lambda N_5]. \quad (6)$$

Here, the N's are the equivalent number of particles with specific ionization β, the x's are the thicknesses of the absorber between adjacent counters, and f, taken to be 1.3, is a factor to account for unsampled energy losses in the absorber. Also, it was assumed that experimental absorption prevailed at large thicknesses so that the last term in Eq. (6) represents an extrapolated area of the shower curve beyond the fifth probe:

$$\int_0^\infty e^{-x/\Lambda}N_5dx=\Lambda N_5.$$

The absorption mean free path Λ was either calculated from $N_7=N_5e^{-533/\Lambda}$, when possible, or an average value of $\Lambda=200$ g/cm^2 was used. The reason for not including the count N_6 in the calculation of energy is that the output from this counter was found to be erratic.

The error in the estimate of energy had two sources: (1) error in integration of the ionization curve and (2) fluctuations in the division of the incident energy into sampled and unsampled energy losses. The energy resolution that resulted from these sources of error, as discussed in a separate paper,[34] was $\pm20\%$, which is small compared to the mass ratio of massive particles to nucleons that this experiment is seeking to distinguish [see Eq. (5)]. However, it should be emphasized that since massive-particle events are expected to be rare, the validity of their existence is related to the tail of the energy resolution function rather than to its width. That is, one must estimate the probability that nucleons with an energy of a few BeV, for example, could give a spectrometer cascade characteristic of cascades where $E_c\sim30$ BeV. Also, if the massive particles dissipate a smaller fraction of their energies in the spectrometer than do nucleons, the effective energy resolution for them deteriorates because their calculated energy then drops into a range where they may not be distinguished from lower energy nucleons. This is discussed below in evaluating the significance of the results obtained.

V. DATA COLLECTION AND ANALYSIS

A. Data Collection

The collection rate for events whose calculated energy was greater than 10 BeV and that had an accompanying air shower was 4 per min. Here, the 10-BeV trigger

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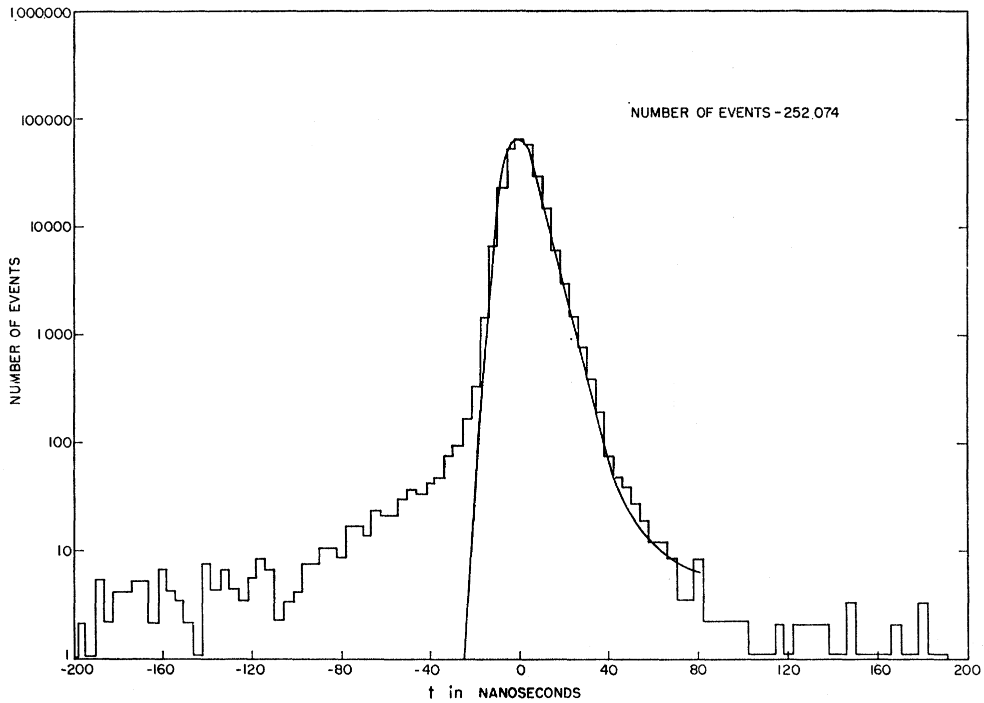

FIG. 4. The time of arrival distribution obtained for all events collected in the experiment. The smooth curve is the experimental time resolution.

threshold level was determined by summing the signals from counters two through six of the spectrometer, counting from the top, and discriminating the summed pulse for an ionization level corresponding to the equivalent of 30 or greater minimum ionizing muons (counter 1 was excluded from the trigger threshold sum in order to prevent triggering on air showers). The "definition" of an accompanying air shower was that signals from the air shower counter groups should occur within ± 200 nsec of the spectrometer signal and that at least two of these should be within 40 nsec of each other. The effective area times solid angle of the spectrometer was 0.78 m^2 sr, where the calculation includes a small correction for the zenith angle dependence of the nucleon flux in the atmosphere. During 1542 h of operation, 3×10^5 events were collected.

B. Data Analysis

To examine the behavior of the events collected, a three-parameter distribution of the observable characteristics of an event was studied. The parameters used were t, the hadron arrival time with respect to its accompanying air shower arrival, E_c, the calculated energy of the event, and n, the number of counters in the spectrometer that registered an ionization level greater than that due to the passage of one minimum ionizing muon. This last variable, n, is a measure of the range of the secondaries in the spectrometer and is related to the true energy of the hadron responsible for the event. The distribution in these three parameters can be represented by

$$P(E_c,n,t)=\int G(E_c,n,E_t)e^{-t/t_0(\gamma_t)}S(E_t)dE_t\,,$$

where E_t is the true energy, γ_t is E_t/M, $S(E_t)$ is the energy spectrum of the detected hadrons, and G is a function that gives the correlations between calculated energy, range of secondaries, and true energy. Also, it was assumed that the calculations producing Eq. (2) hold. For a given E_c, n, and M, then, and with a Gaussian-like correlation function, the distribution in the variable t is mainly exponential.

The distribution in t for events whose E_c was of the order of or greater than 10 BeV, and for all n, is shown in Fig. 4. Here, a large tail is observed in the region $t<0$, which is not due to chance coincidences. Chance coincidences should produce a flat background in the sensitive window width displayed, and they should only occur at the rate of 4 events per 10^5 triggers, as judged from the rate of air shower signals obtained with this apparatus.

The distribution in E_c for these delayed events, which was found to be independent of the delay, has a mean value of about 10 BeV and is shown in Fig. 5. The mean value of 10 BeV makes it unlikely that lighter particles like kaons or pions contribute to the events in this delayed spectrum. In fact, a calculation of the mass of the particles responsible for the delayed spectrum, using Eq. (4) with t_0 taken from Fig. 4 and $E=10$ BeV, gave

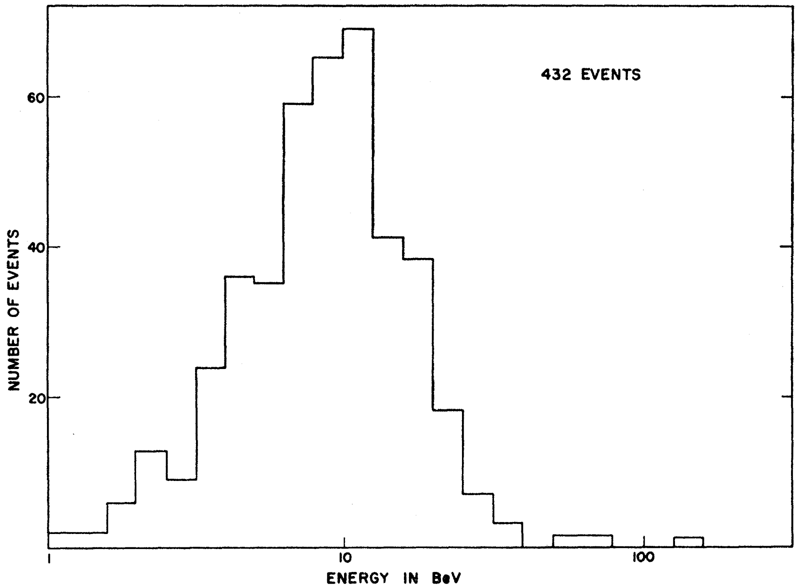

FIG. 5. The distribution in E_c for events delayed with respect to the air shower arrival by more than 30 nsec.

the value 0.7 BeV, so that the majority of the delayed events give a distribution that is at least consistent with a low-energy nucleon distribution.

The projection of $P(E_c,n,t)$ onto the n axis is shown in Fig. 6 for five energy bins. Note that this distribution in n for events that are predominantly "prompt" events and thus typical of nucleons is peaked strongly at $n=1$–2 in the $E_c<10$-BeV plot, and that the distribution shifts so that in the $E_c>100$-BeV plot the peak is at $n=6$. This makes it very probable that low-energy nucleons ($E_c<10$ BeV) will give signals usually in only one or two counters so that the correlation between n and E_c can be used to evaluate the "reality" of energetic, delayed events. Figure 7 shows the n distribution for events where $t<-30$ nsec and for two energy ranges. Here the main distribution in each plot is representative of the distribution for low-energy nucleons so that for these it is probably true that $E_t \ll E_c$. Since the delayed events are mainly of the type $n=1$ or 2 and their t distribution is consistent with that of low-energy nucleons, we believe that they are virtually all nucleons with energies less than 10 BeV appearing to have greater energies, and that this arises because a nucleon of only a few BeV can give anomalously large pulses in one or two counters from nuclear stars in or close to the scintillators.

There was one event in the delayed spectrum ($t<-30$ nsec), however, whose calculated energy was 36 BeV and whose delay was -45 nsec, that registered greater than minimum ionization levels in six counters. That this one event which appears in the $E_c>30$-BeV plot of Fig. 7 shows $n=6$, and that it is separate from the main distribution there is taken to mean that for this event E_t may be close to E_c. In fact, from the frequency distribution of n for events with $E_c<10$ BeV, shown in Fig. 6, the probability for such events to be of the type $n=6$ was calculated and the result was 0.34%. With a total of 6 events on the $E_c>30$-BeV plot of Fig. 7, then, the expected probability of observing one such event in this experiment is about 2%. Also, the expected probability of observing one event due to chance coincidence between a delayed air shower and a spectrometer signal of the type $E_c>30$ BeV and $n=6$, in the sample of 3×10^5 events, is 6%. Thus, there is an 8% probability that this delayed, $n=6$ event was a nucleon. This is sufficiently high so that we do not believe that the event constitutes evidence for a new, massive particle. We will nevertheless explore the properties of this event assuming that it might have been a massive particle.

For this one interesting delayed event, all four shower counter groups gave signals within 5 nsec of each other, and the proportional counters gave signals which saturated the ADC circuits. Table II(a) lists the available information on the event. If it is assumed that the apparatus had unit efficiency for the detection of such particles, then this one event corresponds to a flux of 2.3×10^{-11} (cm^2 sec sr)$^{-1}$. Also, the mass of the hadron responsible for the event, calculated using Eq. (4) and assuming that the origin of the particle was 1 km above the apparatus, is 6.5 BeV.

VI. CONCLUSIONS

Heavy nuclei exist among the cosmic-ray primaries, and there is the possibility that these nuclei could be responsible for the one interesting event. For example, the flux of α particles with an energy per nucleon of 10 BeV that reach the depth in the atmosphere at which the apparatus is located is estimated to be of the order of 10^{-8} (cm^2 sec sr)$^{-1}$. These could give time-delayed signals of the order of -45 nsec, thus simulating massive particle-like events. However, while it is the total detectable energy, E_c, that is measured in the spectrometer, the range of the nuclear cascade that de-

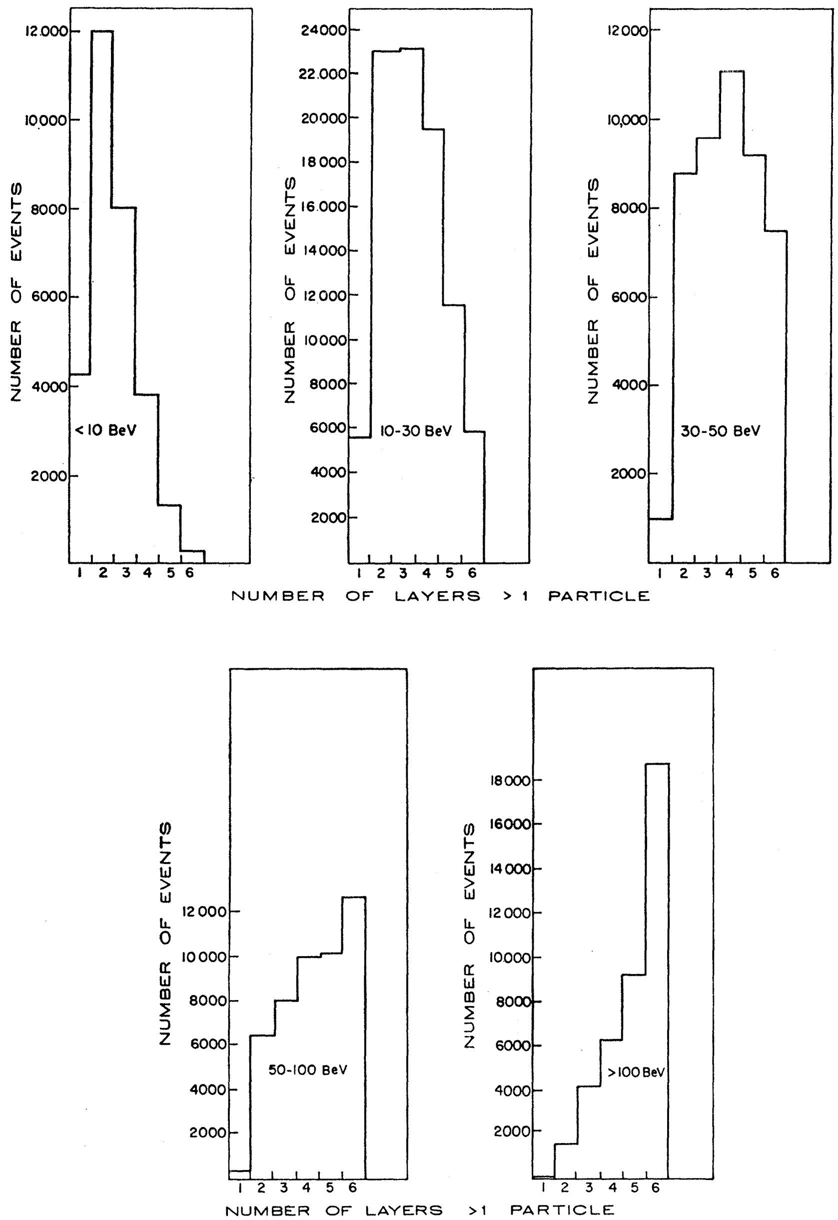

FIG. 6. Distributions in n for all events, in various energy bins.

velops depends on E_c/A, where A is the mass number. Therefore, the n distribution for nuclei with an energy E_c is expected to be peaked more toward low n values than the n distribution for nucleons with the same E_c. There are three delayed events in our data, other than the interesting one, with calculated energies of about 100 BeV. Details concerning these other events are listed in Table II(b). They are all $n=2$ events and are listed as examples of what one expects of heavy nuclei.

In our judgment, therefore, the $n=6$ event mentioned above as a candidate for a massive particle-like event exhibits a nuclear cascade curve that is not characteristic of the behavior expected from heavy nuclei, and, thus, cannot be attributed to such sources. To support this conclusion, we point out that events giving delays >30 nsec would have to be produced at least 2 km above the apparatus, and with the true energy per nucleon limited to about 10 BeV it is doubtful whether accompanying showers of detectable size would be generated at all, even by iron nuclei. Also, from the discussion in the preceding section, the probability is low that the interesting event is due to a low-energy nucleon where $E_c \gg E_t$, or due to the chance coincidence of a delayed air shower with the $E_c \approx 30$ BeV and $n=6$ spectrometer signal. However, since one event cannot be construed to be evidence for the existence of the hypothetical particles sought, we believe that this one unusual event is a nucleon wherein the total probability for observing one such event in this experiment is 8%, and then use the event to establish upper limits for the

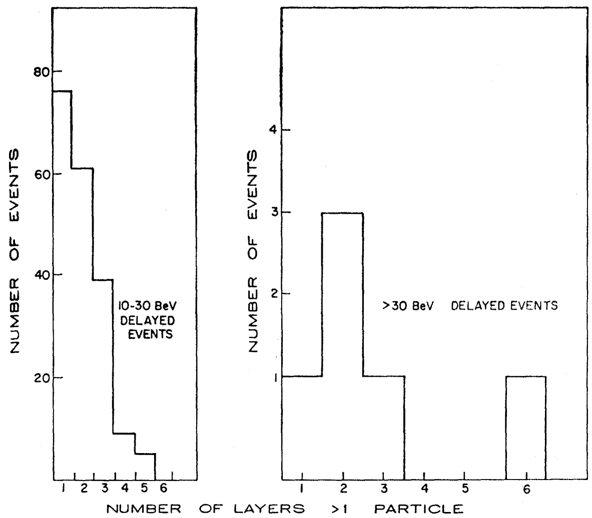

FIG. 7. Distributions in n for events delayed by more than 30 nsec.

flux and cross section of fractionally or integrally charged massive particles.

A calculation of the total and detectable flux of massive particles, presented in the Appendix to this paper, was performed, and the results are listed in Table III, for the choices $\lambda_h=\infty$ and $\lambda_h=\lambda_a$. It is the calculated detectable flux that was compared with the observed flux of 2.3×10^{-11} (cm² sec sr)$^{-1}$ to obtain a value for the cross section for massive-particle production as a function of the mass. The resulting sensitivity of this work is shown in Fig. 8, and our upper limit to the massive-particle flux is compared to those obtained in other experiments in Table IV.

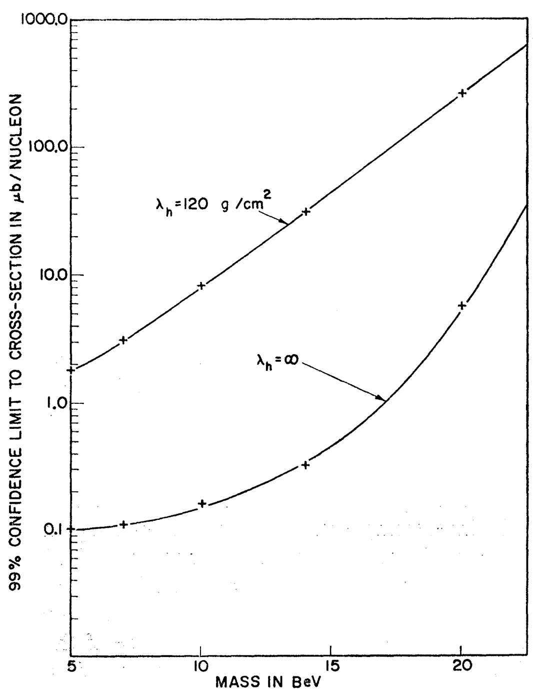

FIG. 8. Upper limits (99% confidence level) to the cross section for the production of massive particles (in pairs) in nucleon-nucleon collisions.

TABLE II. Characteristics of certain events.

		(a) Anomalous event	(b) Events in the tail of Fig. 5		
Energy (BeV)		36	158	58	59
Delay (nsec)		−45	−41	−37	−58
Ionization in equivalent numbers of muons	1	18	498	277	321
	2	23	381	71	53
	3	81	0	0	0
	4	6	0	0	0
	5	5	0	0	0
	6	3	0	0	0
	7	0	0	0	0
Delay (nsec)	1	−43	−31	−40	···
	2	−47	···	···	−11
	3	−46	···	61	−55
	4	−44	−52	−35	−61
Proportional counter output (average height for minimum-ionizing particles was 50)	1	100	91	94	94
	2	101	29	90	96
	3	114	3	2	108
	4	117	106	109	115
	5	118	62	118	115
	6	121	76	124	121

TABLE III. Calculated total and detectable flux.

Mass in BeV	σ_H μb/nucleon	Calculated flux at $X=715$ g/cm² in (cm² sec sr)$^{-1}$ [a] Total	Detectable	Cross section in μb/nucleon (99% confidence level)	Upper limit to flux at 90% confidence level
				$\lambda_h=\infty$	
5	49	2.9×10^{-6}	7.5×10^{-8}	0.10	3.2×10^{-9}
7	25	4.8×10^{-7}	3.2×10^{-8}	0.11	1.2×10^{-9}
10	12	7.0×10^{-8}	1.1×10^{-8}	0.16	5.0×10^{-10}
14	6	1.1×10^{-8}	2.8×10^{-9}	0.32	3.3×10^{-10}
20	3	1.6×10^{-9}	2.9×10^{-10}	1.57	4.5×10^{-10}
				$\lambda_h=\lambda_a$	
5	49	4.5×10^{-8}	4.1×10^{-9}	1.8	8.8×10^{-10}
7	25	7.4×10^{-9}	1.1×10^{-9}	3.1	5.2×10^{-10}
10	12	1.1×10^{-9}	2.2×10^{-10}	8.3	4.0×10^{-10}
14	6	1.7×10^{-10}	2.9×10^{-11}	31.1	4.8×10^{-10}
20	3	2.5×10^{-11}	1.7×10^{-12}	263.0	1.2×10^{-9}

[a] From calculations in the Appendix.

TABLE IV. Present limits on flux of triplets.

Type	Altitude	Upper limit (cm² sec sr)$^{-1}$	Reference
Quarks: $\frac{1}{3}e$	Sea level	1.7×10^{-10} [a]	d
$\frac{2}{3}e$	Sea level	3.4×10^{-10} [a]	d
Massive particles integral or fractional charges	3.2 km	5.0×10^{-10} [a,b]	e
"Muonic quarks": $\frac{2}{3}e$	Underground (60 mwe[c])	1.5×10^{-10}	f
$\frac{2}{3}e$	Underground (2200 mwe[c])	1.5×10^{-10}	g

[a] 90% confidence level.
[b] From last column of Table III.
[c] Meters of water equivalent.
[d] Reference 37.
[e] Present work.
[f] Barton and Stockel, Ref. 22.
[g] Barton, Ref. 22.

APPENDIX: FLUX AND CROSS SECTION

The calculation of the flux of massive particles with an energy E at a depth x, in g/cm^2 in the atmosphere, is developed below and is based on a model developed earlier by some of us.[21] In the model, we assume that massive particles of mass M are produced in pairs in nucleon-nucleon collisions and that they are produced at rest in the c.m. system of the interacting nucleons, with an energy-independent cross section σ_H that above threshold is equal to $\pi(\hbar/Mc)^2$. Other calculations of the flux of massive particles based on similar models have been performed and exist in the literature.[32,35]

A. Intensity Distribution

The source spectrum of the massive particles (i.e., the number of massive particles produced in 1 g/cm^2 at a depth y, with a mass M and in the energy range E to $E+dE$) can be written as

$$S(E,y,M)=\int_{E'_{\min}}^{\infty} N(E',y)W(E,E',M)dE'/\lambda_{\text{in}}.$$

Here λ_{in} is the inelastic nucleon collision mean free path in the atmosphere, $N(E',y)$ is the nucleon intensity distribution, and $W(E,E',M)$ is the differential production spectrum for massive particles of mass M produced with an energy E in a nucleon-nucleon collision where the incident nucleon energy was E'. The depth in the atmosphere is to be measured from the top in g/cm^2, and energies are to be measured in BeV. Also, the nucleon intensity distribution is given by

$$N(E',y)=KE'^{-(\epsilon+1)}e^{-y/\lambda_a},$$

where the form of N and the values of the constants appearing are taken from experiment and are $K=1$ and $\epsilon=1.7$. The absorption mean free path in the atmosphere for nucleons, denoted by λ_a, has the value of 120 g/cm^2.

In nucleon-nucleon collisions, the "gamma," $\gamma_{\text{c.m.}}$, of the c.m. system is given by $\gamma_{\text{c.m.}}^2\simeq E'/2M_N$, if $E'\gg M_N$, where M_N denotes the mass of the nucleon, so that if massive particles are to be produced at rest in this system the laboratory energy E of each must be related to the incident nucleon energy E' by

$$E=M(E'/2M_N)^{1/2}.$$

The differential production spectrum then has the form

$$W(E,E',M)=2(\sigma_H/\sigma_{\text{in}})\delta[M(E'/2M_N)^{1/2}-E],$$

where the 2 represents the fact that the massive particles are to be produced in pairs, and σ_{in} is the inelastic nucleon collision cross section corresponding to λ_{in}. Then, for nucleon energies above the threshold for the pair production of massive particles, given by $E_{\text{th}}\simeq 2M^2/M_N$ and corresponding to a minimum laboratory energy for each massive particle of $E_{\min}\simeq M^2/M_N$, the source spectrum becomes

$$S(E,y,M)=4K/\lambda_H(2M_N/M^2)^{-\epsilon}E^{-(2\epsilon+1)}e^{-y/\lambda_a},$$

where we have put $\lambda_{\text{in}}\sigma_{\text{in}}/\sigma_H=\lambda_H$. The intensity distribution for massive particles, assuming for them an absorption mean free path in air of λ_h, is thus

$$H(E,x,M)=\int_0^x S(E,y,M)e^{-(x-y)/\lambda_h}dy.$$

For the choices $\lambda_h=\lambda_a$ and $\lambda_h=\infty$, corresponding to the assumptions that massive particles attenuate in the atmosphere like nucleons, and that they do not attenuate at all, respectively, the H distributions are

$$H^{\lambda_h=\lambda_a}(E,x,M)=4K/\lambda_H(2M_N/M^2)^{-\epsilon}E^{-(2\epsilon+1)}xe^{-x/\lambda_a},$$

and

$$H^{\lambda_h=\infty}(E,x,M)=4K\lambda_a/\lambda_H(2M_N/M^2)^{-\epsilon}\times E^{-(2\epsilon+1)}[1-e^{-x/\lambda_a}].$$

Integration over E then gives the expected flux of massive particles with energies greater than the minimum possible energy, at the depth x in the atmosphere. That is,

$$H^{\lambda_h=\lambda_a}(x,M)=\int_{M^2/M_N}^{\infty} H^{\lambda_h=\lambda_a}(E,x,M)dE,$$

and

$$H^{\lambda_h=\infty}(x,M)=\int_{M^2/M_N}^{\infty} H^{\lambda_h=\infty}(E,x,M)dE.$$

Table III lists the expected values of H at the depth in the atmosphere $x=715$ g/cm^2, the level of observation in this experiment, for various choices of the mass of the particles.

B. Detectable Intensity

The detectable flux will be less than the expected values because of the finite inefficiency of the apparatus for the detection of massive particles. This inefficiency arises from two sources: one, the associated air shower detection efficiency that results from the finite areas used for shower detection and, two, the massive-particle detection efficiency that results from the restricted time window width for delays present in the apparatus. That is, one must evaluate both the probability that the associated air shower is detected in our apparatus and the probability that the time-delayed arrival of the massive particle is within the sensitive window width of -40 to -130 nsec (the range $t<-130$ nsec was excluded because of noise problems with the time-to-height circuits).

The shower detection efficiency was calculated by

[35] R. K. Adair and N. J. Price, Phys. Rev. **142**, 844 (1966).

expanding the nucleon intensity distribution as

$$N(E',y)=N(E',0)e^{-y/\lambda_{\rm in}}\sum_{n=0}^{\infty}\left(\frac{y}{\lambda_{\rm in}}\right)^n\frac{\eta^{n\epsilon}}{n!},$$

where $\lambda_a=\lambda_{\rm in}/(1-\eta^{\epsilon})$, and η is the nucleon inelasticity. Mutually consistent values for the constants appearing are $\lambda_a=120$ g/cm^2, $\lambda_{\rm in}=83$ g/cm^2, and $\eta=0.5$. The jth term N_j in this expansion represents the number of nucleons arriving at the depth y that have suffered j collisions in the atmosphere in degrading to the energy E'. Thus, for each term one can calculate the energy transferred to the air shower and the corresponding probability for detection of it.

Assuming, then, that the energy left over after production of the massive-particle pair also contributes to air shower production, the energy transferred to the air shower after j collisions can be written as

$$E_{\rm sh}^{(j)}=E'/\eta^j-2E,$$

where E'/η^j is the laboratory energy of the incident primary cosmic-ray nucleon, E' is the energy of the incident cosmic-ray nucleon (after j collisions in the atmosphere), and E is the laboratory energy of each massive particle. Assuming that the number of electrons in the shower at the observation level is given by $\frac{1}{2}E_{\rm sh}^{(j)}$, the shower size at cascade maximum, one can find the density of shower particles at the shower detectors from $\Delta_j(r)=E_{\rm sh}^{(j)}f(r)/2R_1^2$, where $f(r)$ is the Nishimura-Kamata lateral distribution function with age parameter unity and R_1 is the so-called scattering length.[36] If the area of each shower detector is S, then with four detectors in our apparatus

$$P_j(E')=1-e^{-4S\Delta_j}-4e^{-3S\Delta_j}(1-e^{-S\Delta_j})$$

represents the corresponding probability that two or more shower counters will "fire" and is the shower detection efficiency for nucleons that have j collisions before producing a massive-particle pair.

The detectable flux of massive particles at the depth x can then be written as

$$H_D(x,M)=\frac{2}{\lambda_H}\int_{M^2/M_N}^{\infty}dE\,P_t(E,M)\times\int_0^X dy e^{-y/\lambda_{\rm in}}e^{-(x-y)/\lambda_h}\times\int_E^{\infty}dE'N(E',0)\left[\sum_{n=1}^{\infty}\left(\frac{y}{\lambda_{\rm in}}\right)^n\frac{\eta^{n\epsilon}}{n!}P_n(E')\right]\times\delta\left[M\left(\frac{E'}{2M_N}\right)^{1/2}-E\right].$$

Here, we have neglected the contributions to the air shower from the massive particles, as they traverse the remaining distance from their point of production to the apparatus. Also, $P_t(E,M)$ is the probability that the massive particle will arrive at the apparatus with a delay that is within the time window and is given by

$$P_t^{\lambda_h=\lambda_a}(E,M)=e^{-40/t_0(\gamma)}-e^{-130/t_0(\gamma)}$$

or

$$P_t^{\lambda_h=\infty}(E,M)=\int_{40}^{130}dt\exp[-t/t_0(\gamma)+x(1-e^{-t/t_0(\gamma)})/\lambda_a]\Big/\int_0^{\infty}dt\exp[\cdots],$$

where $t_0(\gamma)$ is given by Eq. (3).

It is useful to note that a calculation was performed using the method outlined above to estimate the detectable shower-associated nucleon flux. The ratio of the detectable shower-associated flux to the total expected nucleon flux was compared to the experimentally observed ratio and found to agree to within 5%. This gives one some confidence in the method, particularly in the use of the Nishimura-Kamata lateral distribution function. Further, an experimental determination of $S\Delta$ was made using the observed ratio of the frequency of the events in which any two shower counter groups recorded counts to the frequency where any three groups recorded counts. This ratio varied from 1:1 at an event energy of about 100 BeV to 1:2.5 at 500 BeV. Thus, from the relation

$$R=3e^{-S\Delta}/2(1-e^{-S\Delta}),$$

the values of $S\Delta$ were found to vary from 1 to 2. This means that on the average less than 18% of the nucleon shower-associated flux present goes undetected by not setting off at least two shower counter groups.

ACKNOWLEDGMENTS

It is a pleasure to express our appreciation to Professor M. Iona, R. Venuti, and the University of Denver for their hospitality and cooperation with us in the use of the Echo Lake High Altitude Laboratory. We would also like to thank R. T. Brown of Midwestern Universities Research Association for his vigilant operation and maintenance of the equipment. One of us (P. V. R. M.) would like to acknowledge the support of the University of Michigan Institute of Science and Technology. We would like to thank the National Bureau of Standards, Boulder, for making available to us their computing facility. Also, two of us (D. E. L. and A. S.) would like to thank M. L. Good for many helpful discussions regarding the experiment and the analysis of the data. We would also like to thank T. Novey at Argonne National Laboratory for the use of the plastic scintillator used in the calorimeter.

[36] See for example W. Galbraith, *Extensive Air Showers* (Academic Press Inc., New York, 1958), p. 29.

[37] R. Gomez, H. Kobrak, A. Moline, J. Mullins, C. Orth, J. VanPutten, and G. Zweig, Phys. Rev. Letters **18**, 1022 (1967).