Search for heavy long-lived particles in high-energy cosmic rays

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We present the results of an experimental search for energetic particles which arrive at sea level delayed with respect to the shower front, with an order of magnitude greater exposure than previous experiments. The experiment was sensitive to showers from cosmic rays between 10^5 and 10^7 GeV per nucleus. Events with signals greater than 20 equivalent particles and delayed more than 20 ns were observed and studied. A four-dimensional Monte Carlo simulation of cosmic-ray showers combined with accelerator calibration data showed that the observed events as well as previously reported observations of this type can be accounted for by rare fluctuations in signals from low-energy hadrons in the air shower. No evidence for the existence of heavy long-lived particles in air showers was found. We set an upper limit to the flux of these particles at the 90% confidence level of 1.4×10^{-12} cm^{-2}sr^{-1}s^{-1}.

I. INTRODUCTION

The experimental search for heavy long-lived particles, such as heavy leptons, heavy quark matter, supersymmetric particles, and magnetic monopoles, is of great current interest. The cosmic-ray beam may provide particles with sufficiently high energy to produce such objects by their interactions in the atmosphere. It is also possible that the cosmic-ray beam may contain heavy stable particles of very large mass ($\geq 10^3$ GeV) as a minor component. Heavy cosmic rays such as these would have escaped detection in searches for ultraheavy nuclei if they had a small net charge.

Several cosmic-ray experiments have been carried out to search for such particles. The technique used is to detect energetic hadrons delayed with respect to the fast electrons ($\beta=1$) in the air shower.[1-4] All have reported candidate events.

The time delay between a heavy particle with a Lorentz factor γ and the fully relativistic electrons of the shower depends on the distance h in which the delay is acquired. It is given by

$$\tau=(1667h/\gamma^2)\ \text{ns}\ ,$$

with h in km. If such events were to be interpreted as heavy long-lived particles that are produced in atmospheric interactions, then these objects must have a Lorentz factor less than 20, a lifetime greater than 10^{-7} s, and must produce a cascade in condensed matter (a calorimeter). Another interpretation of these events is that they are caused by a primary cosmic ray with a Lorentz factor <20 but with a large enough mass ($>10^3$ GeV) so as to generate in the atmosphere a detectable shower which runs ahead of the heavy particle, and the heavy particle or its progeny produces a signal in a calorimeter.

In the delayed-particle experiments a search is made for the presence of a substantial signal in scintillation counters placed inside a calorimeter which is delayed with respect to the shower front by a time interval in the range $20<\tau<200$ ns. This signal can be due to the heavy particle itself or due to its hadronic decay products or due to a secondary hadron produced in an interaction by the heavy particle which had acquired the delay. In this sense, these experiments do not require a specific charge assignment for the heavy object or a specific decay mode.

We have carried out a new experiment at sea level to search for delayed large calorimeter signals with a total exposure factor ~ 20 times greater than previous experiments. Approximately 100 events were observed which have a delay greater than 20 ns and a calorimeter signal greater than 20 equivalent particles. We determined the response of the detector to low-energy hadrons by a direct calibration of a prototype detector at Brookhaven National Laboratory and obtained a quantitative measure for the small probability ($\sim 10^{-4}$) of low-energy hadrons giving an exceptionally large signal. As there are many low-energy hadrons present in an air shower, and as these low-energy hadrons have $\gamma\leq 10$, they can be responsible for the observed signals. We find that the observed delayed signals can indeed be accounted for by rare fluctuations in signals in the detector from low-energy hadrons present in the air shower.

In Sec. II we describe the experimental arrangement and the data collected, in Sec. III we describe the simulation of the experiment, and in Sec. IV we discuss the implications for the existence of a minor component of heavy particles in the cosmic-ray beam.

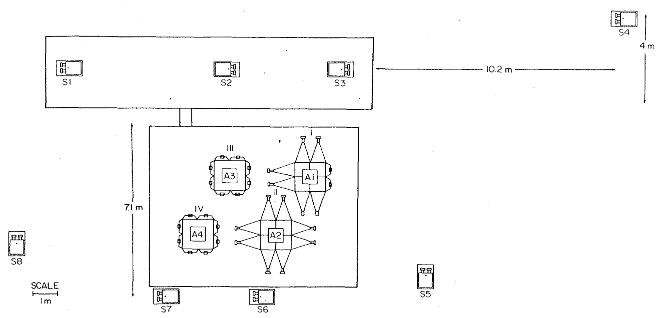

FIG. 1. A plan view of the experimental arrangement for the search for heavy long-lived particles in high-energy cosmic rays.

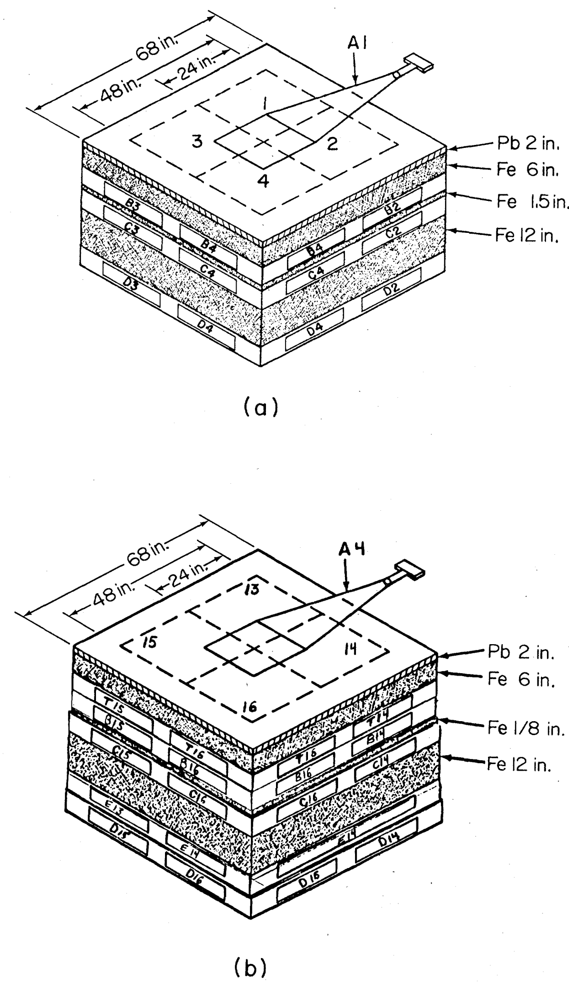

FIG. 2. Perspective drawings showing the longitudinal and lateral distribution of counters and absorbers in the two configuration of the calorimeters used in the experiment.

II. EXPERIMENTAL TECHNIQUE AND DATA SAMPLE

A. The arrangement

A set of twelve unshielded counters were used to sample shower particles and determine the times of arrival of the shower front. Eight of the shower counters were of 0.36 m^2 each and had a thickness of 7 cm of liquid scintillant. These counters are labeled S_1 through S_8 in Fig. 1 which shows a plan view of the experimental layout.[5,6] The remaining four counters, labeled A_1 through A_4, were placed directly over four calorimeters which sampled the hadrons in the shower. These counters were 0.64 m^2 in area and had 1.25 cm thickness of NE102 scintillators.

Perspectives of the structure of the two configurations of the calorimeters used in the experiment are shown in Fig. 2. Counters were placed in the calorimeter at several depths to sample hadronic cascades. The longitudinal depth in radiation lengths of the counters for the two configurations is given in Table I. We note three features of the design. (1) The top absorber consisting of 2 in. of Pb and 6 in. of Fe has a sufficient number of radiation lengths to absorb the electromagnetic component of the air shower so that the *B* counters will not be triggered by the shower front. (2) The absorber in the first layer extends 25.4 cm beyond the *B* and *C* counters in all lateral directions so that the electromagnetic component from side showers will not trigger them. (3) Each detector layer is divided into four quadrants in order to allow a measurement of the lateral spread of the hadronic cascades.

Signals from all counters were integrated using analog-to-digital converters (ADC's) with a 250-ns gate and timing was recorded using 2228A LeCroy time-to-digital converter (TDC) units for S_1 through S_8, A_1 through A_4, *T*, *B*, *C*, and *E* (but not *D*). The TDC discriminator level

TABLE I. Calorimeter profiles.

Counter	Material	Size (in.)	Depth (in radiation lengths) Calorimeter I,II,III	IV
A	NE114	$22\times44\times\frac{1}{2}$	0	0
T	NE102	$24\times24\times\frac{1}{2}$		17.7
B	NE114	$24\times24\times\frac{1}{2}$	17.7	17.7
C	NE114	$24\times24\times\frac{1}{2}$	19.9	17.9
E	NE114	$22\times44\times\frac{1}{2}$	37.2	35.1
D	Liquid scintillator	$24\times24\times\frac{1}{2}$	37.2	35.1

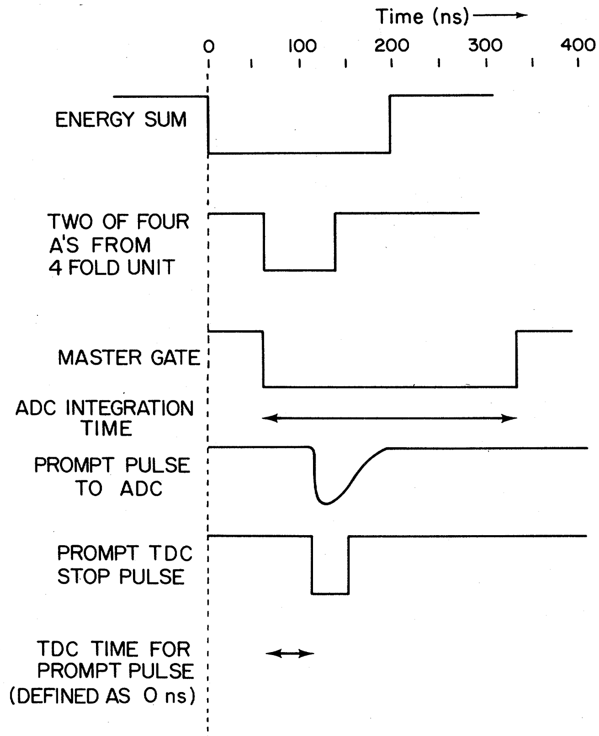

FIG. 3. The time structure of allowed signal configurations for triggers (see text).

was placed at ~ 1 equivalent particle level for S_1 through S_8 and 0.1 equivalent particle for A_1 through A_4. The TDC threshold for the B and C counters was set at the three equivalent particle level to reduce the probability of vetoing by prompt signals at the single particle level of energetic delayed hadron signals. All calorimeter and A counters were calibrated once a week using cosmic-ray muons.

B. The trigger

The experiment was triggered when two conditions were satisfied. (1) The sum of the signals from the B and C counters in at least one of the calorimeters exceeded 70 equivalent particle level and (2) there was a signal in two A counters in "coincidence" with the $B+C$ pulse. The time structure of allowed signal configurations is shown in Fig. 3. In order to study delayed hadrons near cores of air showers further off-line cuts were made. This required that the average signal in the A counters corresponded to 8 particles or a density of 13.6 particles/m^2 and a signal in $B+C$ counters of one calorimeter was greater than 75 particles. At least two A's were required to have this density thus eliminating unwanted triggers due to single unaccompanied energetic hadrons which produce a large signal in a single A and a small signal in another A due to backscatter. On the average, the summed $B+C$ signal was approximately equal to twice the hadronic energy in GeV.

C. The data

In 9266 h, 179 102 events triggered the array. Of these events, 29 182 passed the off-line cuts. For each event we calculated the time difference between the arrival times of B and/or C counters from that of the A counter immediately above the calorimeter associated with the B and/or C counter. In Fig. 4 we display the scatter plot of signal size in B versus time differences as calculated above. Negative time differences correspond to signals arriving in B prior to the shower front while positive time differences correspond to signals delayed with respect to the shower front.

Two main features of the data are as follows. (1) For the majority of events the calorimeter counter signal is prompt. (2) There is a well-defined small signal (<20 equivalent particles) delayed (>20 ns) event "tail." In addition there are 72 events with signal (in at least one B or C counter) $S>20$ equivalent particles and delay $\tau>20$ ns.

The 72 large-signal, large-delay (LSLD) events can be divided into three classes:

(1) Single-counter delays (SCD). Large signal in a single counter with little or no energy deposited in neighboring counters separated by as little as 1 g/cm^2.

(2) Single-quadrant delays (SQD). Large signal in one B or C counter with delay, with other B or C counters also delayed in the *same* quadrant.

(3) Multiple-quadrant delays (MQD). A large signal delayed counter and at least one counter in another quadrant delayed.

Of these types, the most promising candidates for the presence of an energetic delayed hadron are those where some penetration by the cascade is evident (all SQD and some MQD). There were 27 events of this type. Characteristics of these events are shown in Table II. Column two gives the total $B+C$ particle sum in all calorimeters,

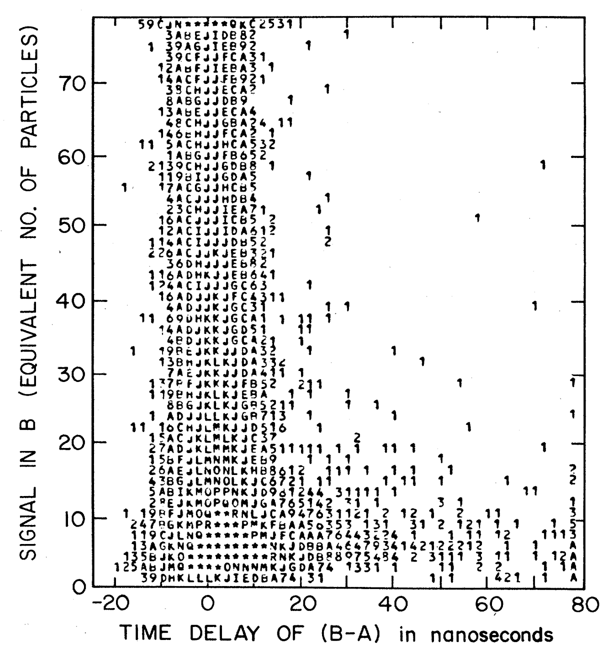

FIG. 4. A scatter plot of signal size in B counter versus time delay between the A counter immediately above the calorimeter associated with B counter. A heavy long-lived particle may give rise to an event with large time delay and a large signal size.

TABLE II. Characteristics of most promising candidate events for presence of an energetic delayed hadron.

Event number	Sum of signals of all B and C counters	Counter with delay	Signals in the delayed quadrant			Delay (ns)
			$B+C$	T	D[a]	
307 207	91	14	38	18	0.8	28
313 894	77	10	68		0	20
318 665	442	15	73	38	1.0	26
320 672	453	7	38		1.1	24
325 360	184	8	61		0	24
334 356	131	14	47	54	−1.8	76
354 538	138	14	73	29	−0.8	22
361 624	205	9	110		0.8	24
376 606	315	16	42	19	0	24
379 499	100	12	99		0	21
396 901	136	2	68		0	28
398 112	105	6	88		0	30
423 348	335	9	13		0.8	21
425 841	132	5	79		1.1	22
432 486	103	7	36		−2.0	38
434 251	624	11	101		0.9	27
437 680	94	7	68		−2.0	21
445 239	127	15	34		0	47
445 823	214	1	94		0.9	21
477 131	105	2	34		0	71
481 679	168	16	57		0	48
482 056	80	7	56		−5.0	27
487 594	2898	1	30		0	55
522 709	138	9	32		1.8	34
524 828	116	14	95	40	0	23

[a] The D counters with small negative signals are different from zero because of pedestal fluctuations.

column three gives the number of the counter which was delayed with large signal, column four gives the $B+C$ signal in the single quadrant, column five gives the signal in T counter for events in calorimeter number 4, column six gives the observed signal in counter D, and column seven gives the delay in ns. The D counters with small negative signals are different from zero because of pedestal fluctuations. The events are of two subtypes; those for which the delayed signal also provided the trigger in $B+C$ and those for which there was a prompt trigger from elsewhere. We emphasize one significant feature which will be used in the analysis in the last section, that *none of these events show a signal in counter D*. In other words, none of the cascades penetrate through to D as most "normal" high-energy hadron cascades are expected to.

Next we discuss the simulation of the experiment.

III. SIMULATION OF THE EXPERIMENT AND ANALYSIS

In order to determine the significance of these 27 events, whether they might indicate the presence of an unusual particle as discussed in the Introduction, a four-dimensional Monte Carlo simulation of the atmospheric cascades was carried out. These calculations used a particle production model which was based upon Fermilab,[7] CERN ISR,[8] and CERN SPS $\bar{p}p$ collider[9] data, an increasing cross section[10] for hadron-air inelastic processes, and a superposition model for primary nuclei other than protons. A detailed description of the model can be found elsewhere.[11,6] The model incorporates some scale breaking by increasing the exponent A in $E\,d^3\sigma/d^3p \propto e^{-Ax}$ logarithmically with energy above ISR energies. The fraction of nucleon-antinucleon pairs is also increased logarithmically with energy. All hadrons (nucleons, antinucleons, kaons, and pions) are followed down to an energy of 2 GeV unless they decay. The program records the energy, position, and arrival time for those hadrons which cross the detector altitude. Each π^0 is decayed into 2γ's and the electromagnetic cascade of each γ ray is calculated in approximation B and its contribution to shower density at the location of each hadron is obtained using a modified Nishumara-Kamata-Greisen lateral distribution.[12]

In simulating the actual trigger, the response of the calorimeter counters to hadrons, muons, and electrons incident upon the calorimeter was simulated. Three factors had to be evaluated using measured or calculated fluctuations: (1) time resolution, (2) time slewing for small signals, and, most importantly, (3) the fluctuations in cascade development. Details of the first two distributions obtained from the study of actual data with different cuts can be found elsewhere.[6]

To determine the third factor we exposed a prototype calorimeter to low-energy (1-to-10-GeV/c π and p) hadron beams at the BNL Alternating Gradient Synchrotron test beam in order to study fluctuations in cascade

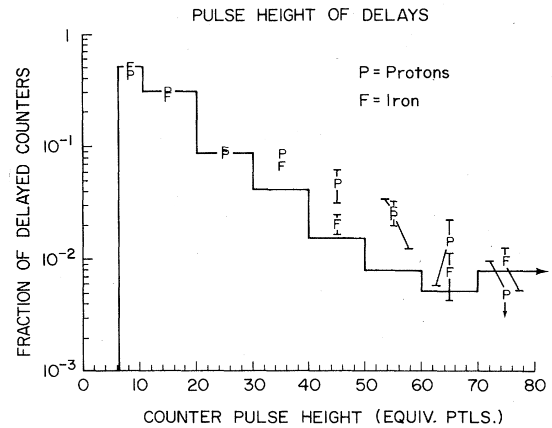

FIG. 5. Pulse-height distributions for delayed events (>20 ns, >7 particles) from simulations for proton and iron primaries. Note that the shape is the same for the two species.

development. We were able to measure fluctuations in the observed pulse height in the calorimeter counters at different depths to 10^{-4}-to-10^{-5} level.[13] At higher energies we used data obtained at Fermilab[14] in a calorimeter with counters at depths similar to our B and C counters. A detailed Monte Carlo simulation of hadronic cascades was done using the Oak Ridge code of T. Gabriel[15] to understand the observed fluctuations and to provide "Monte Carlo data" to use in our simulations at energies where no actual experimental data was available.

These measurements and calculations show that low-energy hadrons occasionally give a much larger than average energy deposit in the detector counters giving rise to abnormally large signals which are delayed. Our calibration and subsequent calculations showed that 7% of 3.5-GeV hadrons give a signal greater than 20 equivalent particles while 0.2% give a signal greater than 50 equivalent particles. (A full description of these measurements and calculations are given in Refs. 13 and 15.) Two mechanisms are responsible for these events. (1) Low-energy neutrons interacting in the absorber or the counter will occasionally eject a low-energy (100-MeV) charged nuclear fragment which loses most of its energy in a scintillation counter. These events give rise to SCD-type events. (2) Energetic neutral pions created within a few radiation lengths of a counter (say B) will give an event with large signal in T, B, and C counters. (The SQD events may be of this type.) Simulated MQD-type events arise from similar mechanisms.

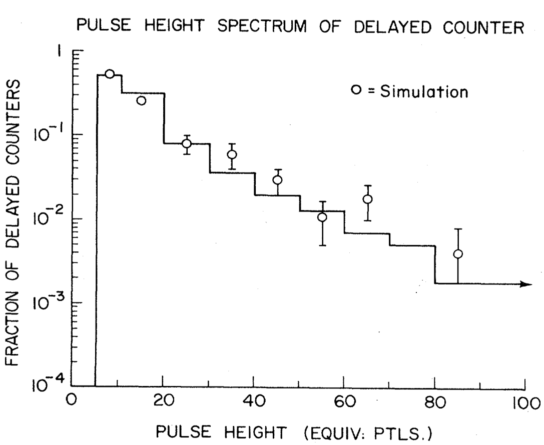

FIG. 6. A comparison of the data with the signals predicted for a composition obtained from a rigidity-confinement model of cosmic-ray propagation (Refs. 11 and 16).

TABLE III. Time distribution of large-pulse-height delayed events.

Delay (ns)	Data	Simulation
20–40	0.74±0.09	0.78 ±0.12
40–60	0.17±0.04	0.08 ±0.04
60–80	0.04±0.02	0.017±0.017
80–100	0.01±0.01	0.03 ±0.02

The Monte Carlo program was run on a set of incoming primaries of different nuclear species and picked according to energy spectra (typically $E^{-2.6}$) based upon different models.[16]

IV. DISCUSSION AND CONCLUSIONS

We have carried out simulations for the distribution of pulse heights for delayed events generated by proton and iron primaries. The predicted distributions are shown in Fig. 5. We note that the distribution shape is essentially the same for the two species. Therefore, the flux limit derived below is independent of the nature of the primary.

In Fig. 6 we compare the data with the signals predicted for a composition obtained from a rigidity-confinement model of cosmic-ray propagation.[11,16] One sees that the observed distribution can be accounted for both qualitatively and quantitatively without the need for the presence of either new particles or processes. In order to further substantiate this we show (1) a comparison of the time distribution of large signal events with Monte Carlo predictions in Table III and (2) a comparison of the relative fraction of large signal events in each of the three categories (SCD, SQD, and MQD) with Monte Carlo prediction in Table IV. Good agreement is seen.

We calculate the upper limit to the flux of "massive long-lived" particles, ϕ, from the observation in Sec. II that no events of the SQD or MQD type were seen to penetrate into the D counters giving a pulse height larger than one particle (see Table II). From our Monte Carlo

TABLE IV. Comparison of observed and simulated delayed events.

Event type	Fraction (%) Data	Simulated
Single counter (SCD)	56±9	41±9
Single quadrant (SQD)	24±6	31±8
Multiple counter (MCD)	20±5	28±8

simulation we can estimate that 54% of all signals generated by 20-GeV incident hadrons should give >2 particle signal in D if they generate >20 particle signal in $B+C$. Therefore since none were observed we estimate at the 90% confidence level that we have a flux of less than 2.3/0.54 particles in 9266 h with an area—solid-angle factor of 9.4 m^2sr,

$$\phi \leq 1.4\times10^{-12}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}\ .$$

We remark that the large-signal delayed events seen in a recent experiment reported by a Japanese group[17] and all other previous experiments can be explained in terms of fluctuations in cascades from low-energy delayed hadrons in air showers.

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