Search for grand unification monopoles and other ionizing heavy particles using a scintillation detector at the Earth's surface

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We present results from an experiment using an array of scintillators and time digitizing techniques to search in cosmic rays for grand unification magnetic monopoles and other ionizing heavy particles at the Earth's surface. An upper flux limit of 4.7×10^{-12} cm^{-2} sr^{-1} sec^{-1} for $2.7\times10^{-4}\leq\beta\leq5\times10^{-3}$ (90% C.L.) for such particles having an ionization $\geq\frac{1}{3}$ of minimum ionizing particles has been obtained. These results do not improve on the limits from underground experiments for heavy monopoles or other particles ($M\sim10^{16}$ GeV); however, they provide new flux limits for somewhat lighter particles ($M\sim10^{9}$ GeV) which cannot penetrate deep underground or come with large zenith angles. Our result implies that such electrically or magnetically charged particles have been excluded as the major component of the dark matter of the Universe.

I. INTRODUCTION

Since 't Hooft and Polyakov showed that magnetic monopoles exist as a stable solution of many non-Abelian gauge theories,[1] the interest in experimental searches for such poles has markedly increased. Monopoles associated with non-Abelian gauge theories are predicted to have mass of order of the unification mass scale divided by the coupling constant. Although most formulations of grand unified theories (GUT's) predict monopole masses of approximately 10^{16} GeV, there are models that have monopoles with mass ranging in value from as low[2] as 10^{5} GeV up to the Planck mass (10^{19} GeV).

The expected velocity of GUT monopoles depends on their mass and their origin. For example, 10^{16} GeV monopoles are expected to have $\beta\sim10^{-3}$ if they are galactic in origin (the usual expectation) as a result of galactic magnetic field acceleration and the drift velocity of our Galaxy. Monopoles would have $\beta\sim3\times10^{-3}$ if they originate extragalactically and could have $\beta\sim10^{-4}$ if they are trapped in our solar system. Monopoles lighter than 10^{10} GeV may have been accelerated to $\beta\sim1$ by the galactic magnetic field, but there are certain models in which the acceleration does not necessarily happen.[3]

The expected monopole flux is subjected to various cosmological and astrophysical constraints. The most stringent astrophysical constraint is set by the Parker bound,[4] based on the survival of the galactic magnetic field, which gives $F\lesssim10^{-15}$ cm^{-2} sec^{-1} sr^{-1}. Direct detection of such a small monopole flux requires a detector of an area of more than 10^{3} m^{2}. Although superconducting coil techniques, first used by Cabrera[5] for GUT monopole searches, would provide a clear and unique signature for magnetic monopoles, the possibility[6] for expanding to such large areas seems remote.

An alternative method, where covering very large areas is practical, is to use conventional scintillation or ionization techniques for particle detection. Of course, this is only possible if slow monopoles crossing the scintillator produce detectable scintillation yield. Recently calculations and empirical measurements have both confirmed this possibility. A conservative calculation of the scintillation yield of magnetic monopoles in ordinary scintillator has been reported by Ahlen and Tarlé,[7] which shows that for $\beta\geq7\times10^{-4}$ the scintillation yield of a monopole is comparable to or larger than for a minimal ionizing muon. Although the calculation shows an abrupt cutoff below $\beta\sim6\times10^{-4}$, another proposed mechanism[8] (e.g., Zeeman splitting and energy level crossing) implies considerable scintillation yield even at lower β. An experiment at Brookhaven National Laboratory[9] has directly measured scintillation yields for protons as slow as $\beta=9.4\times10^{-4}$ and a more recent experiment[10] has extended the measurements to $\beta=2.5\times10^{-4}$. These measurements are in accordance with the assumptions of charged-particle scintillation yield used by Ahlen and Tarlé at $\beta\gtrsim10^{-3}$, but with no indication of a sharp cutoff at lower β. Thus, scintillation techniques can be employed in large-scale GUT monopole searches.

A disadvantage of ionization techniques is that the signature is not totally unique, making it difficult to distinguish magnetic monopoles from, say, massive electrically charged particles. Examples of such electrically charged particles that have been hypothesized include strange-quark matter[11] (nuclearites), particles of $\frac{1}{5}$ charge from superstring theories,[12] and particles with unit charge.

This means that a search with a negative result has a broader interpretation and thus is particularly important for some physics questions such as what constitutes the dark matter of the Universe. This dark matter has been hypothesized to consist of nonbaryonic particles which exist as remnants of the early Universe. In order to explain the lack of observed flux the particles must be either very weakly interacting (and therefore neutral) or have very low number density. For the latter case, the dark matter particles must be very massive to make up the required mass density. Such massive particles are expected to have $\beta \sim 10^{-3}$ and can be detected in a scintillator detector if they carry electric charge. Therefore, results from scintillation or other ionization experiments can be used to detect or rule out heavy electrically or magnetically charged particles as the major contributers to the dark matter of the Universe.

II. THE DETECTOR

The basic scheme employed in our experiment was to use a GUT monopole's penetrating ability, ionization properties, and low velocity as signatures to distinguish them from cosmic-ray muons, other known particles, and backgrounds. A detector employing several separated layers of scintillator produces signals in each layer having relative times proportional to the ratio of the separation of the layers divided by the β of the traversing particle. A $\beta \sim 1$ cosmic ray produces signals in all the layers almost simultaneously, while a slow monopole will produce signals widely spaced in time. Furthermore, because of the transit time through a single layer, the signal produced by a slow monopole is expected to be a relatively wide pulse while a $\beta \sim 1$ cosmic-ray signal is a narrow pulse. For a monopole of very low β, the signal becomes a train of single photoelectron pulses spread over the transit time for the monopole to cross a scintillator layer (see Fig. 1).

The monopole detector reported here consisted of six planes of 2.5-cm-thick NE 114 scintillator, measuring 152 by 305 cm. Each plane was made up of two pieces of scintillator, each with two 56 DVP 2-in. photomultiplier tubes (PMT's) attached to BBQ wavelength shifter bars running along the sides, which were used to collect the light from the scintillator. The PMT's were summed, yielding a signal for a minimum ionizing muon in each scintillator plane ranging from 12 to 16 photoelectrons depending on the position the muon penetrates. The spacing between the first and the second planes was 9 cm while the other spacings were all 20 cm (see Fig. 2).

The geometrical acceptance for an isotropic flux, requiring the particle to cross all six planes in one direction (down going), is given by

$$A\Omega = 2b(a^2+c^2)^{1/2}\arctan\frac{b}{(a^2+c^2)^{1/2}} - 2cb\arctan\frac{b}{c} + 2a(b^2+c^2)^{1/2}\arctan\frac{a}{(b^2+c^2)^{1/2}} - 2ca\arctan\frac{a}{c} + c^2\ln\left[\frac{(a^2+c^2)(b^2+c^2)}{c^2(a^2+b^2+c^2)}\right], \quad (1)$$

where a and b are length and width of the detector and c is the separation between first and last planes. This yields a geometrical acceptance for the detector of 6.7 m^2sr.

For the search reported here, the signal from each PMT was discriminated at a threshold of 0.6 photoelectrons. The output of the discriminators was sent to trigger logic and a data-acquisition system which recorded the time of each pulse. This timing information allowed the identification of long pulse trains characteristic of slow monopoles. In addition, some pulse-height information could be obtained by counting the number of pulses in the train.

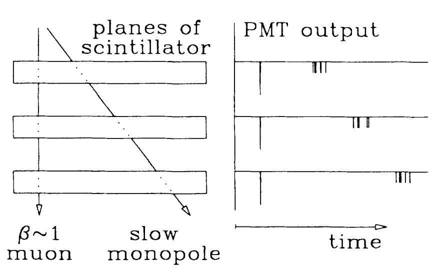

FIG. 1. Monopole signals are characterized by trains of pulses in each plane and a relative delay between planes proportional to the separation. Muon signals are characterized by narrow pulses occurring almost instantaneously in all planes.

The threshold setting of 0.6 photoelectrons resulted in some inefficiency due to the rather broad single-photoelectron distributions of the PMT's. In order to determine this "single-photoelectron discrimination efficiency," we measured the single-photoelectron pulse-height spectrum and determined that ~75% of the single photoelectrons yielded pulses above the 0.6-

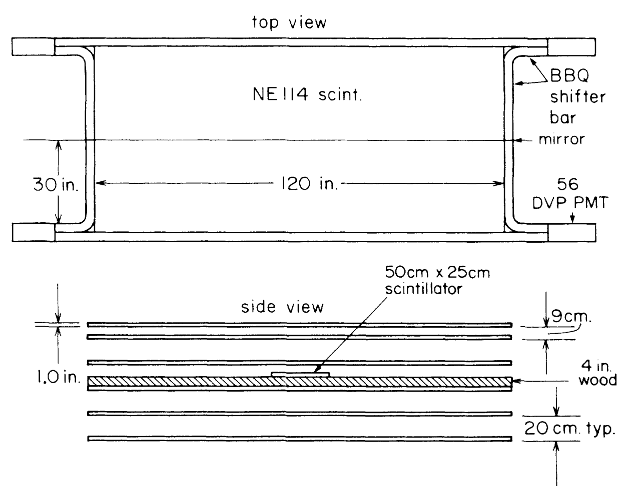

FIG. 2. Geometry of the Caltech scintillator monopole detector.

photoelectron threshold. At this level the probability of monopole in a given plane was very small since a monopole produces a train of many single or multiple photoelectron pulses. For instance, a monopole of $\beta \sim 6\times 10^{-4}$ is expected to produce a pulse train of at least 12 photoelectrons per plane ($\approx$ minimum ionizing) spread over ~ 140 nsec. The statistical probability of missing this signal is less than $\sim 10^{-4}$.

The detector had four types of triggers.

(1) Cosmic-ray muon trigger. This trigger was an efficient and unbiased fast coincidence of three out of four of the center planes. The raw trigger rate was 1.27 kHz; however, in actual data recording these triggers were prescaled by 10^{-5} which resulted in a total sample of about 10^5 events. The prescaling was to prevent this trigger from increasing the acquisition dead time. The recorded muon events were used to calibrate electronics and monitor efficiencies.

(2) Stopping muon trigger. This trigger was a fast coincidence between the top three planes and a small 25cm $\times$ 50 cm scintillator detector placed in the center of the array. In addition, this trigger was vetoed by any in-time signal from the lower three planes. Between the small scintillator and the fourth plane we placed 4 in. of wood as a low-Z muon target. Muons were thus selected that stopped in the wood and subsequently decayed, providing a valuable check on the timing measurements in our detector by measuring the muon lifetime. The stopping muon trigger rate was 0.15 Hz and it was prescaled by 10^{-2} in the actual data recording.

(3) Random trigger. This trigger was generated by a pulser set at about 0.03 Hz. Events produced with this trigger contained random samples of background signals from the PMT's within the readout gates and were useful for off-line analysis of backgrounds.

(4) Slow-particle (monopole) trigger. This trigger consisted of a set of delayed coincidences between all six planes of the detector. A pulse in the first plane generated a gate after a fixed delay; the pulses from the second plane arriving within this gate triggered a delay and gate for the third plane, etc. The delays were set at 70 nsec and the gate widths at 2.4 μsec, which gave a triggering sensitivity to monopoles in the range of β from 5×10^{-3} to 2.7×10^{-4}. The monopole trigger was vetoed by the

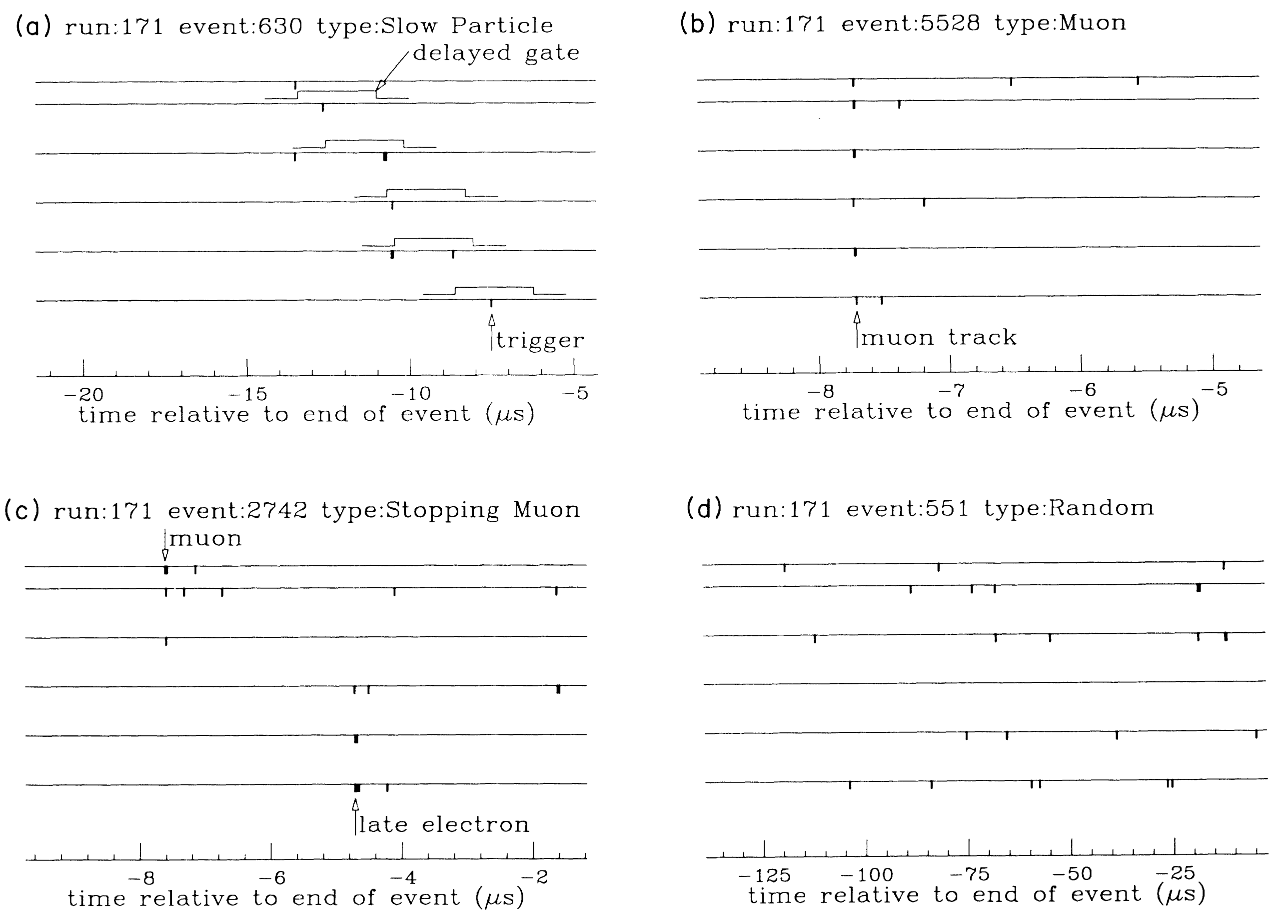

FIG. 3. Sample of events presented with different time scales: (a) slow particle trigger events with triggering window indicated; (b) muon trigger events with muon at -7.7 μsec; (c) stopping muon trigger with muon and decay electron indicated; (d) random trigger with background pulses from the 10–20-kHz rates in the photomultiplier tubes.

cosmic-ray trigger for about 30 μsec to prevent cosmic rays from generating an excessive number of false triggers. The dead time of this veto was calculated to be only 1.7%.

The data-acquisition system consisted of 12 data-acquisition (DAQ) timing modules. Two DAQ modules were used for each plane serving as a 32 bit $\times 15$ location memory stack. Sixteen bits were used to register the time of a 70-MHz greycode clock, 8 bits used to register a code indicating which PMT of the plane fired, and another 8 bits were reserved for future expansion. Any pulse occurring in the plane shifted the memory contents by one location and the contents of the last cell were pushed out. In this way the DAQ timing modules always contained the latest 15 pulses for each plane and covered approximately 450 μsec at typical singles rates. The online computer was a PDP 11/34 using a modified version of MULTI as a data-acquisition program. An event trigger latched the trigger type and started a delay. The delay allowed posttrigger data to be collected for a fixed length of time (≈ 7 μsec). The DAQ modules were then shut off, the PDP 11/34 interrupted, and the DAQ modules read out.

III. PERFORMANCE OF THE DETECTOR

The experiment was run for an effective running time of 8.2×10^6 sec. The 195 data runs contained 985 495 events which 959 697 were good events not subject to equipment failure or data errors. About half of the data consisted of slow particle trigger events, with the rest being from the various diagnostic triggers.

A sample of events (see Fig. 3) presented at a variety of time scales illustrates the type of data available for off-line analysis from individual events. Typical slow particle trigger events, cosmic-ray muons, stopping muons, and random triggers are shown. The tracks of cosmic rays through the detector are clear and distinctive [see Fig. 3(b)].

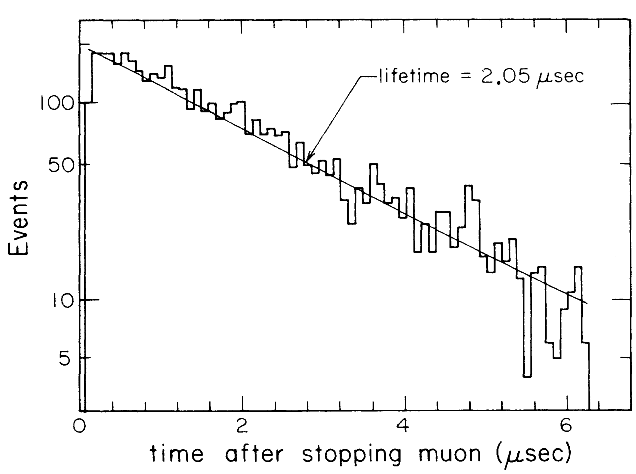

FIG. 4. Decay curve obtained from stopping muon events.

A convenient test of the performance of the detector was provided by the sample of stopping muons. The muon decay analysis software finds the "stopping muon track" in the upper three planes and the "decay product track" in the lower three planes, and then determines the time difference between them. The slope of the histogram of these time differences (see Fig. 4), which includes both μ^+ and μ^- components, gives a value of ≈ 2.05 μsec as expected.

As a further check that the detector was operating correctly we have analyzed the muon inefficiencies of the detector by finding muon tracks that miss a given plane, since the trigger only required three of four center planes. By this method we have determined that the muon inefficiency of each plane is only about 1%.

IV. ANALYSIS

The basic objective of the off-line analysis was to search for any ionizing particle that penetrated the detector with a low constant velocity. That is, we searched for pulse patterns that formed straight lines in a time versus distance graph. Since the scintillator planes had finite thickness, these straight lines were actually narrow bands with a width in the time direction that was determined by the time for a monopole or other slow particle to cross a plane. To ensure good efficiency we used bands 20% wider, which accounted for possible misalignments of the scintillator planes.

More specifically, our first pass through the data consisted of identifying slow particle candidate tracks by searching for the pulses within the 2.4-μsec triggering gates which had acceptable timing patterns between planes. We required the particle to go through all six planes and produce at least one pulse in each plane with relative timing indicative of a constant velocity. A high β cutoff at $\beta \approx 0.01$ was set in this analysis to eliminate residual muons and a low β cutoff was set at $\beta = 2\times 10^{-4}$ to speed up the search. This was still well beyond the triggering cutoffs so it did not contribute any inefficiency. This data selection reduced the original data sample of 959 697 good events to 1113 candidate events. The β distribution of these candidate slow particle tracks is shown in Fig. 5. The histogram is peaked

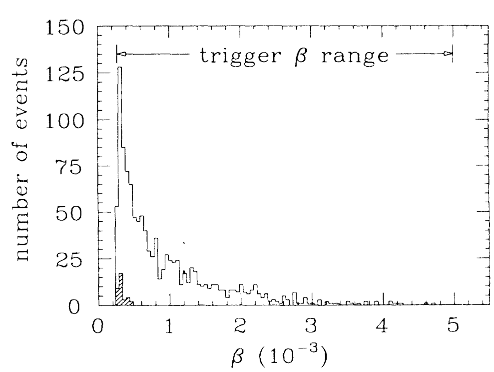

FIG. 5. Histogram of the β of the 1113 candidate events (unshaded) and the 35 final candidates (shaded).

toward the lowest acceptable β, which is characteristic of randomly distributed background pulses reconstructed in constant β bins. We note that even though we did not specifically require the monopole trigger type in the analysis (and roughly half of the original triggers were of the diagnostic types) all surviving events came from that trigger.

Examining the surviving 1113 candidate slow particle events that had hits giving satisfactory timing and geometry (see Fig. 6), we observe that most have a large number of extra pulses outside this window. The frequency of these extra pulses is well beyond the rate of the random pulses from the PMT's. We could not determine the cause of all the spurious pulse trains from the recorded information, but they probably correspond to cosmic-ray showers or some high-energy interactions inside or near the detector. Also, many events contain obvious muons which satisfy the triggers due to extra hits from PMT afterpulses.

In order to analyze these events systematically we made a second pass through this data. In this analysis we required that the events be "quiet": that the number of extra pulses around a monopole candidate track window not exceed a certain value about six times the typical random pulse rate. Care was taken to count only the pulses before the earliest candidate monopole track in order to avoid throwing away heavily ionizing slow particles that may give rise to a large number of afterpulses. It should be noted that for the case of magnetic monopoles, if they interact with matter (such as catalyzing baryon decays) with very large cross section, they could cause showers that arrive at the detector before the actual monopole. Such events are rejected in our analysis. However, according to the negative result of baryon decay experiments[13] and the limits set by neutron-star luminosity,[14] this possibility seems unlikely.

Additional requirements were applied to remove muon pulses and their afterpulses. Muon pulses were identified by fast coincidence between adjacent planes and afterpulses were defined as pulses happening 100 nsec or less after the muon pulses.

The analysis described above relied on veto schemes to filter out noisy events, and therefore it was crucial to determine the veto dead time. We have measured this in a realistic way by superimposing random trigger events onto Monto Carlo–generated monopole tracks. As shown in Fig. 7, 469 of the original 500 of these background superimposed Monte Carlo events survived the same analysis as was applied to the actual data. Therefore the analysis inefficiency for monopole events due to these veto requirements was only 6.2%.

Applying the second pass analysis to the 1113 candidate events surviving the first pass yielded 35 events, all having a measured $\beta < 5\times 10^{-4}$ (see Fig. 5). In order to study these candidates further we note that for such low β the signal from each plane must be either a wide pulse or a pulse train lasting for $\gtrsim 170$ nsec. The former corresponds to the case of relatively high ionization ($\sim I_{\min}$). Although in this case only one pulse per plane could be registered, the recorded pulses are expected to have small time jitter and lie very close to a straight line. This case has been ruled out, since all the slow particle tracks found in the 35 candidates had more than 90-nsec deviation from a straight line. In order to study the latter case we analyzed the 35 candidates to determine the number of planes that actually had pulse trains. A train is defined in the minimal way as having at least two

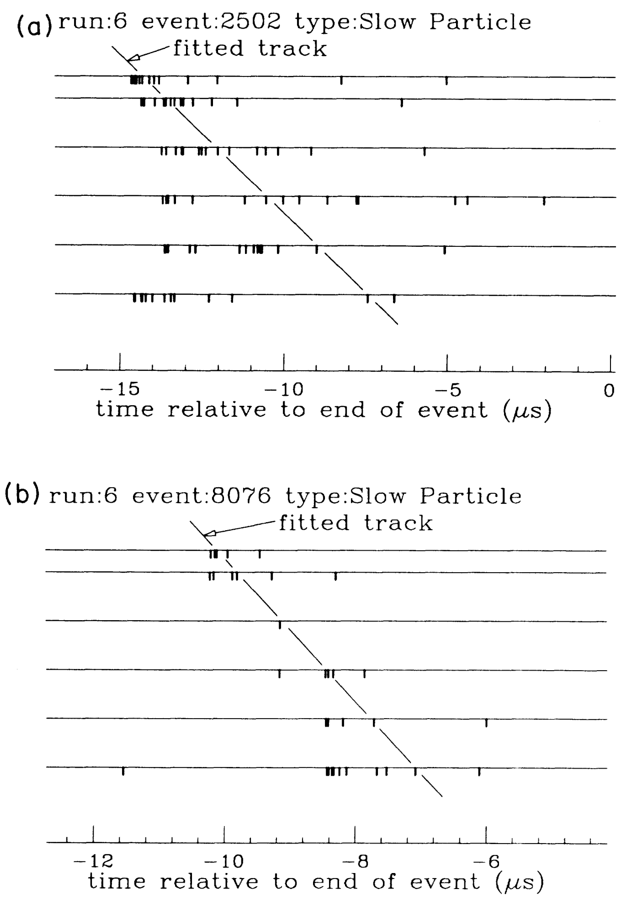

FIG. 6. Typical slow-particle candidate events.

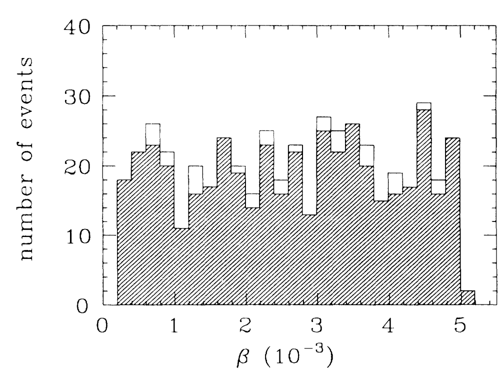

FIG. 7. Histogram of the β of the original 500 Monte Carlo events (unshaded) and the 469 events (shaded) that survived the same analysis that was applied to the actual data.

TABLE I. Number of planes having a pulse train (at least two pulses).

Number of planes having a pulse train	Number of events
0	15
1	16
2	4
≥ 3	0

pulses (note a single pulse is 15–20 nsec). The result is shown in Table I.

Therefore we conclude that there is no indication that any of the 35 events come from slow moving particles crossing the detector. These 35 events were apparently due to random coincidences, which is consistent with a statistical calculation.[15]

We note that the entire hardware β range is eliminated for slow particle candidates if we require at least three planes to have two or more pulses. This requirement and the requirement that each plane has to have at least one pulse set an ionization threshold (I_{thresh}) for the detector. At $\frac{1}{3}$ of the minimum ionization, each plane has $\langle N_{pe} \rangle = 4.5$ and the efficiency to satisfy these requirements drops to about 80%. We thus take $I_{\text{thresh}} = \frac{1}{3} I_{\min}$ as the ionization threshold of our detector, although the cutoff is not sharp and the detector has considerable sensitivity below this threshold.

The effective exposure time for the experiment, correcting for dead time, was 8.0×10^6 sec. Using this effective running time, the acceptance of the detector, and applying efficiency corrections, we determined an upper limit (90% confidence) for slow-monopole flux within our β acceptance:

$$\text{slow-particle (monopole) flux} < 4.7 \times 10^{-12} \text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1} \quad \text{for } 2.7 \times 10^{-4} \leq \beta \leq 5 \times 10^{-3} \,. \tag{2}$$

This result applies to monopoles or any other penetrating particles having ionization above $\frac{1}{3} I_{\min}$ in the indicated β region.

V. COMPARISON WITH OTHER EXPERIMENTS AND IMPLICATIONS

To compare our results with other reported ionization-scintillation experiments we divide them into two types: underground experiments and experiments at the Earth's surface. We note first that several underground experiments have reported lower flux limits than this experiment. Some cover different β and ionization regions (for instance, the Baksan experiment[16] had an ionization threshold of at least $5 I_{\min}$ due to their integration time[17]) and others actually have both a wider β range and lower ionization threshold than our experiment and have reported lower flux limits.[18] Therefore, the relevance of our measurement is for monopoles or other slow particles that would not be detected underground.

The differences in sensitivity between the experiments at the Earth's surface and the underground experiments are for particles having masses such that they penetrate the atmosphere with low velocity but do not penetrate to the depth of the deep underground detectors. We call such particles "medium heavy," with typical masses of $\sim 10^9$ GeV, in contrast with the more penetrating "superheavy" particles with masses $\sim 10^{16}$ GeV typical of the GUT scale.

For these medium heavy particles, the flux limits set by underground experiments do not rule out a much higher flux on the Earth's surface. Medium heavy monopoles might be expected to have $\beta \sim 1$ due to acceleration by the galactic magnetic field. However, this is not true in certain models involving symmetries or plasma oscillations.[3] If the galactic magnetic field acceleration is avoided, the Parker bound does not apply. The monopole candidates observed by Cabrera[19] and the Imperial College group,[20] which imply fluxes well above the Parker bound, have motivated such models. Furthermore, the galactic-magnetic-field acceleration does not apply to other possible massive particles that might be detected in ionization detectors at the Earth's surface. Therefore, even though the underground experiments set a lower flux limit for superheavy monopoles, searches at the Earth's surface have regions of sensitivity not available to the underground detectors.

As an example, Fig. 8 shows the lower-mass limit versus the original β outside the atmosphere for various particles that can be detected in our experiment. For comparison we show the limits of the experiment of Kawagoe *et al.*[18] in the Kamioka mine, which is the only published underground experiment that have reported lower flux limit and had wider β window and lower ionization threshold than ours. In generating the curves of Fig. 8 we used the Ahlen-Kinoshita model[21] for magnetic monopoles, the model of Lindhard, Scharff,

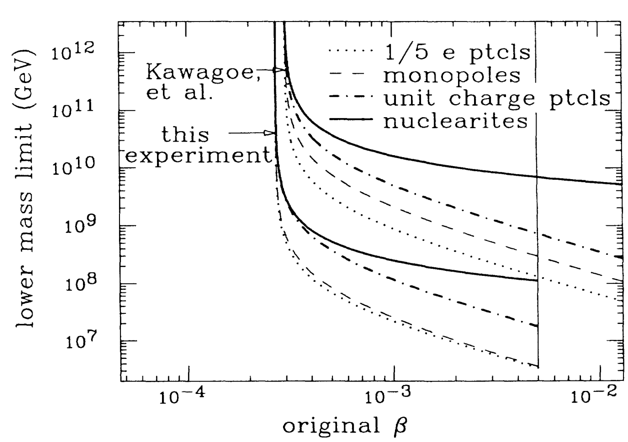

FIG. 8. The lower mass limit versus the original β of various particles detectable in our experiment. The similar limit of the experiment of Kawagoe *et al.* is also drawn for comparison.

TABLE II. Compilation of flux limits from monopole detectors at the Earth's surface.

Experiment	I_{thresh}/I_{min}	β range	Flux limit
BNL	2.0	$3\times10^{-4}-1.2\times10^{-3}$	3.4×10^{-11}
Tokyo	1.2	$10^{-2}-0.1$	1.5×10^{-11}
Tokyo	0.025	$2\times10^{-4}-5\times10^{-3}$	1.5×10^{-11}
BNL-Brown-KEK	0.3	$10^{-3}-0.2$	5.2×10^{-12}
Tokyo (Kajino)	0.05	$10^{-4}-10^{-2}$	1.6×10^{-12}
Akeno	10	$7\times10^{-4}-1$	1.2×10^{-13}
Indiana-Berkeley	0.6	$6\times10^{-4}-2.1\times10^{-3}$	9.4×10^{-13}
This experiment	0.33	$2.7\times10^{-4}-5\times10^{-3}$	4.7×10^{-12}

and Schiøtt[22] for electrically charged particles, and a simple formula given by de Rújula[23] for nuclearites. Note that our experiment is sensitive to particles of mass 2 orders of magnitude lower than what is accessible to underground experiments.

Table II is a compilation[24] of the upper flux limits of other experiments at the Earth's surface that have β range and ionization sensitivity similar to our experiment.

For superheavy particles our result does not improve on the limit set by the Tokyo experiment of Kajino; however, for the medium heavy particles that cannot penetrate deep underground, their limit (and the others) must be reconsidered. For example, their limit must immediately be doubled since their acceptance for up-going particles is no longer relevent. In addition, they primarily have sensitivity to large zenith angles due to their geometry using vertical layers. This greatly reduces the sensitivity to medium heavy particles since they must pass through a much larger amount of matter to reach the detector. Furthermore, since about 3-m iron absorber has been put between the scintillator and proportional counter layers, medium heavy particles can be slowed considerably in the detector and could be thrown away in an analysis which essentially looks for objects with constant velocity. Similar arguments apply to the BNL-Brown-KEK limits since they also have vertical layers. The limit from the Indiana-Berkeley experiment must also be doubled because of their up-going acceptance, making their limit comparable to ours but with somewhat different coverage in β and ionization threshold as shown in Table II. Lastly, the experiment in the Akeno Air Shower Observatory has yielded a limit one order of magnitude lower than ours but only for particles exceeding their ionization threshold which is 30 times higher.

Since medium heavy monopoles stop in matter, our flux limit might also be compared with the results of monopole searches in bulk matter. Monopole searches in lunar rock and iron ore have been reported with much lower flux limits;[25] however, these bulk matter searches are actually limits on the monopole density in certain samples. To interpret the results in terms of a monopole flux limit in cosmic rays many assumptions are necessary regarding the age of the samples: how deep they have been buried, whether or not they have been heated over a few million years, etc. The bulk matter monopole searches are based on detecting magnetic charges, and therefore only apply to magnetic monopoles and not to other massive particles.

In summary, our limit represents a flux limit for any ionizing ($>\frac{1}{3}I_{min}$) medium heavy particles that can penetrate the atmosphere but not deep underground. After correcting other results for their sensitivity to such particles, we expect none would be more sensitive than the result reported here, and none have actually been analyzed in detail for such medium heavy particles.

A major implication of our result is that it can be directly used to address the dark-matter problem. Assuming that the dark matter of the Universe has a density of 1.4×10^{-29} g cm^{-3} with an isotropic flux and a nominal velocity of $3\times10^{-3}c$, we calculate the maximum dark-matter fraction that can be attributed to heavy charged particles implied by our flux limit (see Fig. 9). Lower-mass cutoffs for different particles are determined using the stopping power models mentioned earlier. Our detector's β acceptance is truncated at 6.5×10^{-4} for monopoles and 8×10^{-4} for $\frac{1}{5}$ charge particles in accordance with the conservative light yield estimation of Ficenic *et al.*[10] It is clear that the major dark-matter component cannot be monopoles or $\frac{1}{5}$

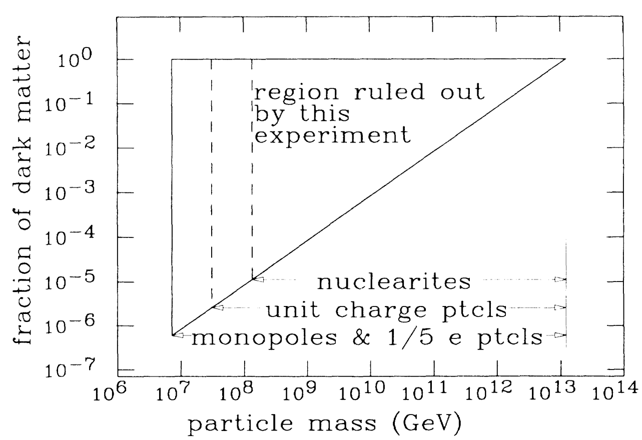

FIG. 9. The limit of the fraction of dark matter that can be attributed to heavy charged particles, as a function of mass.

charge particles of mass $7\times10^7 < M < 10^{12}$ GeV, nor can it be unit charge particles of $3\times10^7 < M < 10^{12}$ GeV or nuclearites of $1.4\times10^8 < M < 10^{12}$ GeV. For some particles and mass ranges, a fraction as low as 10^{-6} has been excluded.

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