# Limits on the Flux of Slowly Moving Very Massive Particles Carrying Electric or Magnetic Charge

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If electrically or magnetically charged particles of the Planck mass or the grand unification mass exist, a measurable flux of them could be reaching Earth but would probably have remained undetected. However, they should make a signature in a properly instrumented detector array. With a small proportional counter array, upper limits between 0.03 and 0.06 $m^{-2}$ $sr^{-1}$ $d^{-1}$ are set on their flux at velocities between 100 and 350 km/sec.

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Astrophysicists have speculated that particles of the Planck mass $M_P$ ($\cong 10^{19}$ GeV or $10^{-5}$ g) and electric charge of order unity might exist.[1] More recently, several authors[2] have pointed out that some grand unification theories predict the copious production of magnetic monopoles with mass of the order of the grand unification mass $M_{GU}$ (whose value is expected to be about $10^{-3}$ times the Planck mass). These particles would be moving with respect to Earth at speeds primarily determined by their gravitational interaction with matter; that is, less than 1000 km/sec. The purpose of this Letter is to point out that the flux of massive charged particles reaching Earth could be measurably large; that previous experiments would probably not have detected them; and that simple, available techniques can be used to set a limit on their flux.

An absolute upper limit on the average density of such massive particles in the universe is the mass density necessary to "close" the universe ($\sim 10^{-29}$ g/cm$^3$). The mass density of undetected particles in our own galaxy could be much greater than the average, since recent work has shown that "missing mass" appears to be concentrated in galactic halos.[3] It has been suggested that this unseen mass is in the form of neutrinos with rest mass,[4] but other undiscovered particles could contribute to it. With use of the formula given by De Rújula and Glashow,[4] a mass density of the order of $10^{-24}$ g/cm$^3$ is obtained at the position of Earth in our galaxy. If this were in the form of particles of mass $M_{GU}$ moving at 200 km/sec (the speed of Earth through the galactic halo) Earth would receive a flux of 0.1 $m^{-2}$ $s^{-1}$ $d^{-1}$. A density so large would be very unlikely for the monopoles since it would lead to an unacceptably high level of annihilation radiation and would also destroy observed galactic magnetic fields.[5] However, these effects would be reduced if the monopoles were bound in cosmic dust particles with net charge near zero. Primordial massive particles might also be found frozen in the material in the outer reaches of the solar system, the source of much of the meteoric matter that reaches Earth at speeds between 10 and 70 km/sec.

Particles of large mass reaching Earth with such low velocity would not make their presence obvious. They would probably not be found in ordinary matter on Earth's surface, since they would probably fall through it and would certainly penetrate far below Earth's surface even if they arrived at escape speed. They would make no signal in a Čerenkov counter and, for reasons to be discussed below, organic scintillators would respond to them with low efficiency. Since they would take microseconds to move one meter, the coincidence timing in large arrays used in cosmic-ray work and quark searches, aimed at detecting relativistic particles, would exclude them. Their tracks in emulsion would not stand out from the background of muon tracks. However, they should produce enough ionization to be detected in a proportional counter array designed for that purpose.

At velocities much below the Bohr orbital velocity ($c/137$), the ionization and energy loss of charged particles passing through some medium behave differently from the way they behave at the more familiar relativistic velocities. There is a good semiempirical theory for these effects[6] which divides the total energy loss into two components: (1) Excitation and ionization of the electron clouds of the atoms of the medium. Energy loss per unit path length from this cause $(-dE/dx)_e$ is directly proportional to velocity and for a unit-charge particle is about 40 times that of a minimum-ionizing muon at 300 km/sec. It is roughly proportional to ion charge if ion charge is less than the $Z$ of the atoms in the medium. (2) Elastic collisions with nuclei of atoms in the medium. This component $(-dE/dx)_n$ is generally dominant at velocities below 300 km/sec for low-$A$ atoms in the medium and varies relatively slowly with velocity.

The substantial specific energy loss to ionization and excitation $(dE/dx)_e$ for charged particles at these velocities means that a proportional counter should be a good detector of them. Ionization per unit path length in the counter should be $(dE/dx)_e/W^1$, where $W^1$ is the average energy loss *in atomic electrons* to produce one ion pair. Investigation of $W^1$ shows it to be constant within $\pm 20\%$ down to an ion velocity of 250 km/sec for Ar ions in many gases (including Ar),[7] while the ionization per unit path length is found to remain proportional to velocity down to 60 km/sec for K ions in Si.[8] For this experiment it is conservatively assumed that $W^1$ does not change enough in Ar to preclude detection of a slow unit-charge particle down to 100 km/sec velocity. The measurements used to obtain $W^1$ are stopping measurements collecting ionization produced all the way down to zero velocity, and the threshold used in this experiment is a factor of 7 below the expected ionization at 100 km/sec. It is hard to see how $W^1$ could drop by a factor 7 between 250 and 100 km/sec without any visible effect on measurements at 250 km/sec initial velocity. In calculating expected proportional counter pulse heights it is assumed that $W^1$ has its measured value for minimum-ionizing muons.

While the total specific energy loss (including elastic nuclear scattering) is substantial, Planck-mass particles at 200 km/sec would lose only about $10^{-3}$ of their kinetic energy in passing through Earth, and particles of mass $10^{16}$ GeV would just be stopped.

For magnetic monopoles, although little attention has been given their energy-loss characteristics at velocities below $\beta = \frac{1}{137}$,[9] it can be argued that they would probably ionize enough to be detected in a proportional counter. With decreasing velocity, the very large $dE/dx$ of a monopole becomes velocity dependent, meeting the rising $dE/dx$ curve of a unit-electric-charge particle near $\beta = \frac{1}{137}$. Below this velocity, the $(dE/dx)_{\rm ion}$ curve of the electrically charged particle falls to zero in linear relation with $\beta$. Because of the velocity dependence of the interaction between a monopole and an electron, one might expect the monopole $dE/dx$ to decrease as $\beta^2$. However, at atomic distances, the magnetostatic interaction between a monopole and the electron's magnetic moment is of the same order as the electrostatic interaction between a unit charge and the electron's charge. The monopole $dE/dx$ would therefore be expected, at low velocities, to be of the same order as that of a unit electrostatic charge.

Unlike relativistic particles, these slowly moving particles would not eject electrons with enough velocity to create further ionization ($\delta$ rays). The density of ionization along their tracks would therefore be very high, all of it appearing on the track itself. This should make them tend to saturate organic scintillators, which would respond to them with an unknown and probably very reduced efficiency. It would also make their tracks in emulsions show no increase in density as specific ionization rises with increasing velocity: Only the grains along the path would be sensitized and these would be saturated at a moderate $dE/dx$. Such tracks could easily be overlooked in the ever-present background of straight tracks from penetrating muons of near minimum ionization.

To set some limit on the flux of slowly moving charged particles passing through Earth and learn something about the background of false events in experiments of this kind, a small proportional counter array was set up at Brookhaven National Laboratory just above sea level with no passive shielding from cosmic rays other than that provided by the building itself. It is shown schematically in Fig. 1. Three layers of thirteen 5.1-cm-diam$\times$160-cm-long proportional counter tubes filled with 90% Ar–10% $CH_4$ were stacked under a 160-cm$\times$160-cm$\times$6-cm-thick NE-235A liquid scintillation counter used as a cosmic-ray anticoincidence shield. The three proportional counter trays were spaced 35 cm apart with the scintillation counter 30 cm above the top tray.

The thirteen counters in a tray were operated with a common 2500-V high-voltage supply. All were tested with a $\gamma$ source. Each tray gave a cosmic-ray muon pulse-height spectrum with a broad peak whose maximum was taken as the average minimum-ionizing muon signal. For pulse heights above the peak, the number of events dropped roughly exponentially with increasing pulse height. Time resolution of the counter trays, tested on cosmic-ray muons in coincidence with the scintillation counter, was 0.37 $\mu$sec full width at half maximum.

The electronic logic is shown in Fig. 1. Timing signals were taken from separate discriminators set at $\frac{1}{5}$ the level of the energy discriminators. The logic accepted triple coincidences between the three proportional counters within a 14-$\mu$sec resolving time where all three exceeded their en-

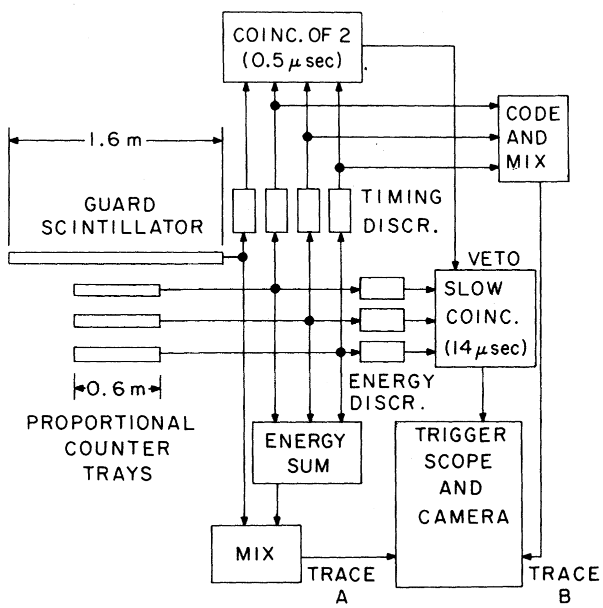


FIG. 1. Schematic diagram of apparatus.

ergy discriminators, rejecting events if any two (including the scintillation counter) were in prompt coincidence, that is, within 0.5 $\mu$sec.

If an event met these requirements, an oscilloscope was triggered and the three timing pulses from the proportional counters (stored on a delay line) were recorded by an automatic camera with the counter identified by the polarity and amplitude of the recorded pulse. In addition, the sum of the amplitudes of the three proportional pulses was recorded as well as the time when the event occurred. The output of the guard scintillation counter was also recorded.

The logic was tested before each run by a sequence of pulses, fed to the proportional counters and to a light-emitting diode above the scintillation counter, simulating a slowly moving particle passing up or down through the array. Amplitudes up to 100 times the energy discriminator setting and delays from counter to counter between 0.5 and 11 $\mu$sec were used to be sure a real event would be recorded correctly.

For all runs the pulse height discriminators on the proportional counters were set at twice the muon through peak, with use of a 2.5-$\mu$sec integration time.

The apparatus was run for 52.9 d. Films were scanned for events in which all intervals between timing pulses were greater than 1 $\mu$sec and the delay between the top and middle counters was equal to the delay between the middle and bottom counters within 1 $\mu$sec. This restricted the vertical component of the velocity of a detected particle to values below 350 km/sec. One down-going event met the scanning criteria, which is consistent with the expected number of accidental coincidences calculated from the measured rates in each counter tray of pulses exceeding threshold and not in prompt coincidence with any other counter.

The area–solid-angle product for the counter array was 0.95 $m^2$ sr: This value is doubled for Planck-mass particles which should penetrate Earth. Taking the number of observed and background counts to be 1, the flux of particles with charge of order unity or greater reaching Earth with vertical component of velocity between 100 and 350 km/sec must be less than 0.03 $m^{-2}$ $sr^{-1}$ $d^{-1}$ for Planck-mass particles or 0.06 $m^{-2}$ $sr^{-1}$ $d^{-1}$ for particles of mass $10^{16}$ GeV or less, at the 90% confidence level.

This work has shown that even the simplest proportional counter array (three planes) can achieve a low accidental background rate in this kind of experiment with no shielding from cosmic rays. A limit two orders of magnitude lower could be achieved with a proportional chamber of the size used in many high-energy physics experiments. However, the most promising way of improving the sensitivity of a search for slowly moving massive particles would be by using one of the proton-lifetime experiments now being planned.[10] Some of these experiments will use proportional counters either as primary counters or as active shielding. These will be arrays with areas of the order of 100 $m^2$ which could be made sensitive to slow particles coming from any direction. They are to be operated for years underground where the cosmic-ray background will be (for the purposes of this experiment) negligible. A factor $10^4$ improvement on the limits quoted here seems entirely possible with minor modifications whose cost would be only a tiny fraction of the total cost of the experiment.

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