First Results from a Sea-Level Search for Supermassive Magnetic Monopoles

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The authors describe a search for supermassive, slowly moving magnetic monopoles, employing a single thick slab of naphthalene-doped acrylic scintillator. Slow, massive particles produce scintillation pulses of unusually long duration in the thick slab and can thus be distinguished from the large flux of relativistic muons that penetrate the detector at sea level. The current limit on the flux of monopoles is 4.1×10^{-13} cm^{-2} sr^{-1} s^{-1} (1σ) for velocities $6\times10^{-4}c \lesssim V < 2.1\times10^{-3}c$.

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In recent years there has been a renewed interest in the search for magnetic monopoles stemming from the prediction of certain grand unified theories (GUTs) that monopoles exist with astoundingly large masses $M\sim10^{16}$ GeV/c^2. Monopoles with such masses are expected to move at velocities of $V\sim10^{-3}c$.[1] At these velocities, ionization energy loss is so feeble[2] that GUT monopoles would pass right through astronomical bodies such as the moon, Earth, and sun and may have evaded conventional detection schemes based on ionization or trapping in ferromagnetic materials. As a result, considerable enthusiasm was generated when Cabrera[3] announced the detection of a signal characteristic of a monopole with the Dirac charge ($g=e/2\alpha$) in a small superconductive loop detector which was sensitive to monopoles of arbitrary velocity.

It is difficult to reconcile Cabrera's enormous flux ($\boldsymbol{F}=6\times10^{-10}$ cm^{-2} sr^{-1} s^{-1}) with several indirect astrophysical constraints. If monopoles are uniformly distributed throughout the universe and moving relative to the earth at $V\sim10^{-3}c$ then a flux greater than $(10^{-15}$ cm^{-2} sr^{-1} s$^{-1})/M_{16}$ (M_{16} is the monopole mass in units of 10^{16} GeV/c^2) would provide more than the critical density needed to close the universe. If monopoles cluster with galaxies, then this flux limit can be raised by the five orders of magnitude needed to be consistent with Cabrera's observation. A somewhat more direct astrophysical constraint is the so-called Parker limit which results from the dissipation of the large-scale galactic magnetic field (GMF) in the presence of a monopole flux. Recent calculations[1] result in a flux limit of $F\leq5\times10^{-16}$ cm^{-2} sr^{-1} s^{-1} for $M_{16}<10$ and $\boldsymbol{F}\leq5\times10^{-15}$ cm^{-2} sr^{-1} s^{-1} for $M_{16}\sim100$. Several solutions have been advanced that circumvent the Parker limit and allow for a much larger flux of monopoles. Salpeter, Shapiro, and Wasserman[4] have argued that for $M_{16}>10$ a flux of monopoles and antimonopoles as large as 1.7×10^{-11} cm^{-2} sr^{-1} s^{-1} could be accommodated as a disk-stabilizing galactic halo with magnetic-charge-density fluctuations providing the source of the GMF. Arons and Blandford[5] have found that the observed GMF can be maintained in a flux of monopoles $\boldsymbol{F}=3\times10^{-12}$ cm^{-2} sr^{-1} s^{-1} with $M_{16}=100$ which resonantly transfer energy to and from the field and provide sufficient matter to stabilize the galactic disk. In these models monopoles would still be expected to have velocities near $10^{-3}c$. Dimopoulos *et al.*[6] have suggested a mechanism whereby the sun traps galactic monopoles into semistable orbits which decay sufficiently slowly to enhance the local flux of monopoles by many orders of magnitude over the galactic flux. In this model, monopoles would have velocities near $10^{-4}c$, typical of meteorites. Such a solution could conceivably reconcile Cabrera's event with the astrophysical limits. However, Freese and Turner[7] have shown that for $M_{16}\sim1$, the orbits are shortlived and the maximum low-velocity enhancement is about 50.

Cabrera has operated an improved superconductive detector[8] for an area-time factor more than ten times that of his original report[3] and has seen no additional monopole candidates. It now seems likely that the original Cabrera event resulted from some instrumental problem. In view of this and the continued expectation that monopoles should be rare and moving at velocities of $V \sim 10^{-3}c$, the obvious course of action is to follow up Cabrera's observation with experiments of vastly increased collecting power. Several searches for GUT monopoles have been reported recently which achieve large collecting power but rely on indirect detection techniques.[9-11] The problem with all the indirect searches is that so many loopholes exist that it is unlikely that any will ever be strong enough to provide compelling evidence against monopoles. In view of these difficulties it seems preferable to search directly for moving monopoles with a detector which relies on as few assumptions as possible. Such experiments should be sensitive to GUT monopoles over a reasonable range of expected velocity and magnetic and electric charge.

Ahlen and Tarlé[12] have examined the response of NE110, a polyvinyltoluene (PVT)-based organic scintillator, to low-velocity electric and magnetic particles. They conclude that in the absence of significant level-mixing enhancements,[13] detectors having a minimum excitation energy ϵ_m are characterized by a velocity threshold $V_{\rm th}$ given by $\epsilon_m = 2mV_{\rm th}(V_{\rm th} + V_{\rm F})$ below which no excitation will occur. Here m is the electron mass and $V_{\rm F}$ is the Fermi velocity appropriate to the given system. Their conclusion is supported by available evidence from the scintillation yield of low-energy recoil protons. For PVT scintillators, $\epsilon_m = 5.0$ eV (the first excited state of the benzene ring system) and $V_{\rm th} \approx 6.5 \times 10^{-4}c$. For comparison, Ar gas proportional counters should exhibit a threshold at $V_{\rm th} = 2 \times 10^{-3}c$ as a result of the 15.8-eV first ionization potential of Ar. Above threshold, the *integrated* scintillation signal rises rapidly until at $V \approx 7 \times 10^{-4}c$ it exceeds that for a relativistic singly charged particle. The analysis of Ahlen and Tarlé relied only on binary collisions between electrons and monopoles for which the cross section scales in a known way relative to that for electron-nucleus scattering. As a result, there is no controversy in comparing results from electric projectiles with those expected for monopoles. There is a chance that monopoles having velocities below the binary collision threshold may excite scintillator levels through Zeeman mixing.[13] This effect has been calculated only for H and He and, at present, there is no justification for relying on this mechanism for more complicated systems.

Since April 1983, we have employed a novel scheme to search for GUT monopoles at sea level with a single thick (7.6 cm) slab of PS-10 acrylic scintillator (10% naphthalene, 1% PPO, 0.01% POPOP) of surface area 2.8 m^2 and geometry factor a full 17.5 m^2 sr. The scintillator is viewed on the edge of 52 RCA 4900 photomultiplier tubes which collect approximately 5000 photoelectrons from a minimum-ionizing muon. The detector response is uniform to 10% over its entire area. Relativistic charged particles traverse the detector in a time much shorter than the response time of the detector system. The full width at half maximum (FWHM) of the anode signal from such fast particles is a characteristic 40 ns. A GUT monopole traveling at $V = 10^{-3}c$ takes a minimum of 250 ns to traverse the thick slab and the anode pulse width from such an event will be a measure of this traversal time. The signature of a monopole in this detector is an anomalously wide anode pulse with a pulse height constant in time.

In Fig. 1 we show the response of PS-10 to monopoles, dyons, and monopoles with bound Al nuclei. There are several differences between PS-10 and NE110 that result in slight modifications to the curves presented in Ref. 12. In PS-10, naphthalene ($\epsilon_m = 4.0$ eV) and perhaps acrylic ($\epsilon_m \approx 4.1$ eV) are the primary energy-absorbing molecules resulting in a lower threshold velocity $V_{\rm th} \approx 5.1 \times 10^{-4}c$. We have measured and incorporated into our calculation the α/β ratio[14] (a

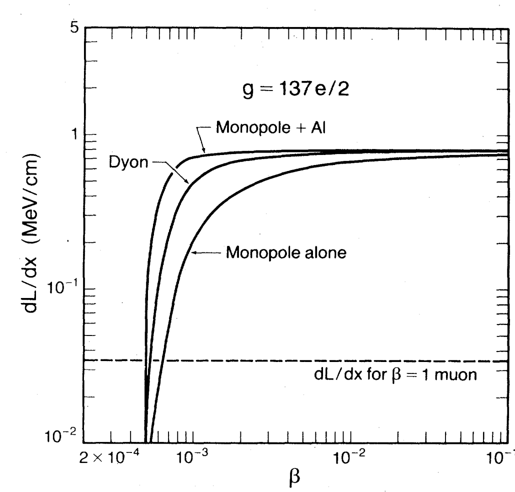

FIG. 1. Scintillation yield for monopoles in PS-10 acrylic scintillator as a function of velocity $V = \beta c$.

measure of saturation) and the conversion efficiency of PS-10. The conversion efficiency for PS-10 is 50% of that for NE110 and the α/β ratio is 6% compared to 7.5% for NE110. It is clear from Fig. 1 that a negligible improvement in dynamic range is achieved by triggering on signals with extremely low integrated light levels. As a result we have chosen to examine all events with an integrated ($\tau = 50$ μs) signal greater than $0.6I_{\min}$, where $I_{\min}$ is the integrated light output for a minimum-ionizing muon. The anode pulse width from each event is measured electronically and a veto is provided if the pulse width falls within the window associated with muons (FWHM $\lesssim$120 ns). Another veto is provided by a pileup inspector which looks for cleanly separated multiple pulses. When an event is not accompanied by a veto, the anode pulse and a shaped integrated pulse are digitized to 8 bits every 10 ns and then stored on a floppy disk for later examination. Two separate gain modes and digitization channels cover the range $(0.6-70)I_{\min}$ in integrated light output. Only about two of the more than 10^6 events per hour are unaccompanied by a veto. These events fall into two categories: ~90% are multiple pulses (accidentals, μ^+ decays, etc.) which, because of the overlap between pulses, appear wide to the electronics. Because of the huge number of photoelectrons per event, multiple pulses are easily identified as such. The remaining ~10% of triggers are events far out in the Landau tail or showers with total light outputs $\geq 70I_{\min}$ which saturate the amplifiers and are again easily identified as such.

As of October 1983 we have accumulated a total live time of 3852 h. During this time over 4×10^9 fast particles penetrated the detector and were rejected as such, whereas only 7137 events resulted in a trigger. Visual examination of the latter revealed that 6150 were double pulses, 107 were triples, 7 were quadruples, and 820 were pulses that had saturated the amplifiers. Only two pulses were of sufficiently small amplitude that noise prevented rejection by visual inspection alone. The duration of these pulses were 140 and 110 ns and they both had integrated light outputs of $0.7I_{\min}$. If these events were monopoles, their minimum velocities (normal incidence) would be $1.7\times10^{-3}c$. At these velocities and with the measured light levels, they would fall more than an order of magnitude below the curve in Fig. 1. We consider this to be well outside the uncertainties of the calculation. Having seen no events with signals characteristic of slow monopoles we can set a limit of $F \leq 4.1 \times10^{-13}$ cm^{-2} sr^{-1} s^{-1} (1σ) on the flux of monopoles with $6\times10^{-4}c \lesssim V < 2.1\times10^{-3}c$. The upper limit is the velocity of a normally incident monopole having the minimum detectable transit time of 120 ns. For velocities in excess of $2.1\times10^{-3}c$ the geometry factor for particles with transit times > 120 ns gradually decreases from the full 17.5 m^2 sr. In Fig. 2 we compare the current limit set by this experiment with other experiments[3,8,15-21] which require no assumptions such as binding nuclei[22,23] or monopole catalysis of nucleon decay,[24] and with theoretical limits.[1,4,5,7] We have truncated the lower velocity limits for several of the experimental results at the point that we calculate they would become insensitive to monopoles. The experiment of Alexeyev *et al.*[15] at Baksan uses a trigger set at $0.25I_{\min}$ for a signal integrated for only 50 ns. The signal from a slow monopole moving through the 30-cm-thick Baksan detector modules will be stretched out in time and the amplitude reduced accordingly. Using the results of Ref. 12 we calculate that the velocity threshold for bare monopoles in the Baksan instrument should be raised to $V_{\text{th}} = 9.8 \times10^{-4}c$. Several experimenters have used the unpublished calculations of Ritson[25] to extend their quoted monopole flux limits to velocities below

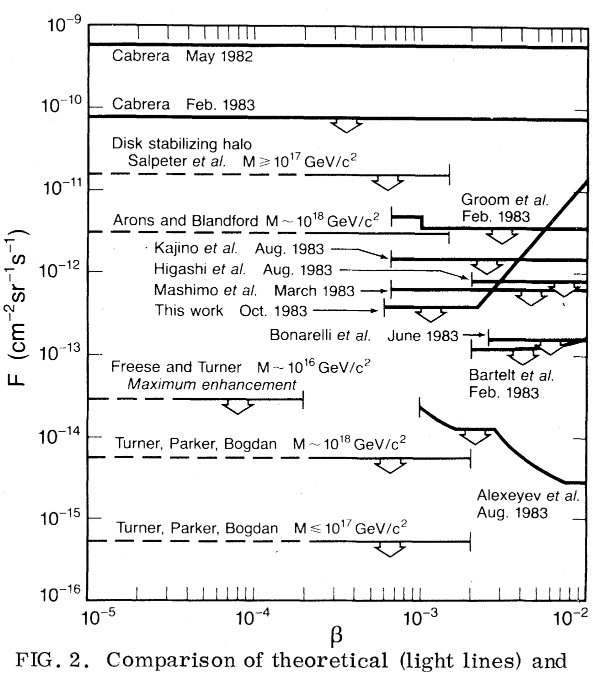

FIG. 2. Comparison of theoretical (light lines) and experimental (bold lines) limits for monopole flux. Solid lines for theoretical limits indicate the most probable velocity window.

the binary collision threshold. We believe that there are serious difficulties with Ritson's calculations and that such extensions cannot be justified.[26] One of the most serious problems with this calculation is that inner-shell electrons are employed to obtain the large velocities needed to excite 3-eV transitions. Such low transition energies are clearly not available to inner-shell electrons and in any case the 3-eV energy levels referred to by Ritson apply only to secondary and tertiary solute molecules. Because of experimental limitations, velocity thresholds for electronic stopping power have not been observed. The lowest proton velocity thus far used in such experiments has been $6\times10^{-4}c$, for which no deviation from a linear dependence of stopping power on velocity was observed for vapor-deposited carbon films.[27] However, this is easily understood by noting that such films are amorphous semiconductors[28] with gaps of the order 0.8 eV.

The limits we present here have direct bearing on models such as that of Arons and Blandford.[5] In their model, monopoles form a halo about the galaxy with a velocity dispersion of ~ 200 km/s. The motion of the sun about the galactic center (V~250 km/s) would result in an anisotropic flux centered about the apex of the solar motion (l_A). The velocity distribution would fall off for $V \gtrsim 1.5\times10^{-3}c$ for monopoles arriving from l_A and at a smaller velocity in any other direction. Our flux limit is almost a factor of 8 below the flux predicted by Arons and Blandford. It should be noted, however, that Arons and Blandford have not properly taken into account the directionality or the distribution in velocity of monopoles associated with the model, so that the correct flux prediction will be smaller. Of the experiments shown in Fig. 2, ours provides the best combination of large area and low-velocity sensitivity necessary to address models in which monopoles cluster with the galaxy. In addition, our flat detector is more suitable than telescopic detectors for detection of a directional flux which will exist in any such model.

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