VOLUME 52, NUMBER 15 PHYSICAL REVIEW LETTERS 9 APRIL 1984

Search for Grand-Unified-Theory Magnetic Monopoles at a Flux Level below the Parker Limit

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(Received 1 November 1983)

We report the results of the first direct search for grand-unified-theory magnetic monopoles with adequate sensitivity to detect a flux as small as the Parker flux limit. If stable monopole-nucleus bound states exist then the observed absence of monopole tracks in our 4.6×10^8-yr-old mica detector places an upper limit of 10^{-17} to 10^{-16} cm^{-2} sr^{-1} s^{-1} on the flux of grand-unified-theory monopoles having velocity $3 \times 10^{-4}c$ to $1.5 \times 10^{-3}c$.

PACS numbers: 14.80.Hv, 12.10.En

Grand unified theories (GUT's)[1] require the existence of supermassive ($\gtrsim 10^{16}$ GeV/c^2) magnetic monopoles,[2] which could have been made in the early universe and would likely have velocities less than $10^{-2}c$ relative to the Earth. Figure 1 displays Cabrera's latest flux limit,[3] the experimental flux limits[4] from other groups (with their lower velocity limits updated[5]), indirect limits[6] based on survival of the large-scale galactic magnetic field in the presence of monopoles (the "Parker limit"), and the new limit we report here, based on a search for stored monopole tracks in an old mica sample.

Our technique relies on the following scenario: (1) Monopoles enter the Earth's atmosphere with a net electric charge less than or equal to zero; (2) as they pass through the Earth they eventually capture nuclei in bound states through magnetic dipole–magnetic monopole interaction; (3) the nucleus-monopole composite passes through a naturally occurring underground sample of muscovite mica, undergoing elastic nuclear collisions which result in the formation of a trail of lattice defects in the mica; (4) the track survives as long as the mica remains unheated, and may be enlarged to macroscopic dimensions by retrieving the mica and etching it in hydrofluoric acid.

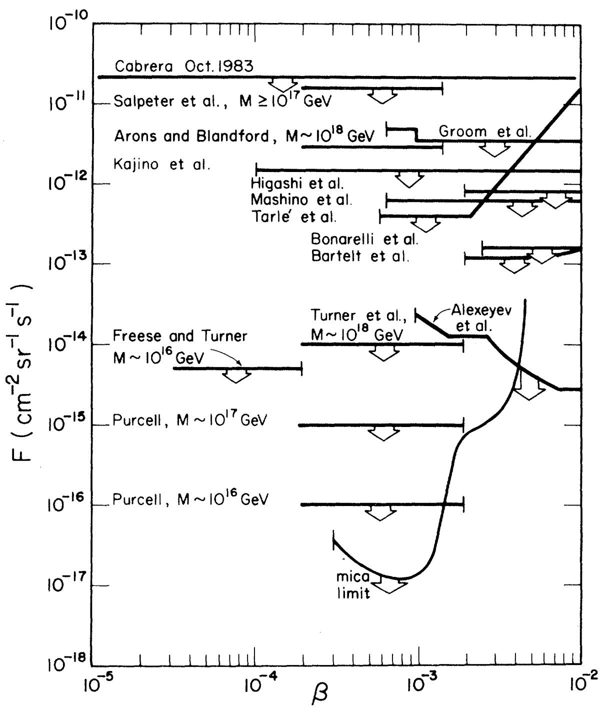

FIG. 1. Flux limits (single-event significance) from past searches and this work. All authors are referenced.

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The formation of etchable tracks in mica is due to the production of lattice defects.[7] Detailed studies have shown[8] that etchable tracks are produced in mica irradiated with very low-energy (0.1 to 3 keV/u) ions ranging from Ne to Th,[8] and that the track-etching rate is proportional to the nuclear component of stopping power, S_n, in the velocity regime where electronic stopping power, S_e, is negligible (e.g., for Fe at $\beta = 10^{-3}$ in mica, $S_n = 5S_e$).[9] It is clear from these studies that at $\beta < 10^{-2}$, elastic nuclear recoils are more efficient at inducing lattice defects than is electronic excitation. For supermassive projectiles, the production of such defects is allowed by kinematics for $\beta > 2\times10^{-5}$.

From Ref. 9 and the calibration data in Ref. 8, we conclude that the track etch rate, V_e, for low-velocity ions in mica etched in 40% HF at 25 °C is given by $V_e = (0.012\ \mu\mathrm{m/h}) \times [S_n/1(\mathrm{GeV\ cm^2/g}]$. Two other types of etch rate are also important: $V_\perp$ and $V_\parallel$ are etch rates perpendicular and parallel to the cleavage plane. For the etch conditions given above, $V_\perp = 0.027\ \mu\mathrm{m/h}$ and $V_\parallel = 1.36\ \mu\mathrm{m/h}$. The difference between $V_\perp$ and $V_\parallel$ is due to the highly anisotropic structure of mica. In order for a penetrating particle to leave a detectable track, it is necessary that $V_e \cos\theta > V_\perp$; otherwise, the surface recedes more rapidly than etching proceeds. In our search we have etched for a time t such that $V_e t \times \cos\theta - V_\perp t > 0.5\ \mu\mathrm{m}$, or $S_n \cos\theta > 2.49$ GeV cm^2/g, so that a monopole track would be delineated by an etch pit at least 0.5 μm deep on each surface of mica exposed to HF. We have also required that any candidate track must show etch pits on surfaces separated by at least 100 μm, so as to discriminate against the background of naturally occurring tracks due to spontaneous fission of ^{238}U (maximum length $= 21\ \mu$m).

A number of workers[10-14] have argued that nuclei with sufficiently large nuclear magnetic moments can be bound to monopoles. Such a bound system will have S_n large enough to record a track. Rather simple arguments[11] yield the following expression for the binding energy of a nucleus to an infinitely massive Dirac monopole: $E_b = (A|\mu| - Z)/4Ar_0^2$, where A, Z, and μ are atomic mass, atomic number, and nuclear magnetic moment in nuclear magnetons of the bound species, and r_0 is a hard-core cutoff taken to be the rms radius of the nucleus (using units where $\hbar = c = m_p = 1$). Using a more rigorous treatment, other authors[10,12] have evaluated binding energies for spin-$\frac{1}{2}$ nuclei and obtained results which differ by little from the above simple expression.

We have estimated cross sections for the radiative capture of a nucleus by a monopole by first calculating the rate for the inverse process and then using the principle of detailed balance. We assumed spherically symmetric ground-state wave functions having an asymptotic form similar to that of the radial functions obtained by Sivers,[10] $\psi \propto (r - r_0)\exp(-kr)$, where $k = (2AE_b)^{1/2}$. Typical values for E_b of nuclei having $|\mu| > 1$ are 0.1 to 1 MeV and typical capture cross sections at $\beta = 10^{-3}$ are 10 to 100 μb. These capture cross sections are too small for monopoles to bind nuclei in the Earth's atmosphere. However, if monopoles enter the Earth with nonpositive electric charge, they are likely to capture nuclei in the Earth. We have evaluated binding energies, radiative capture cross sections, and capture mean paths for all nuclear species in the Earth's crust.[15] We find that four groups of elements dominate the nuclear capture process in the Earth. Relevant data pertaining to these four groups are given in Table I. The nuclear stopping power, S_n, has been evaluated at several velocities according to Ref. 9, assuming the projectile mass to be infinite and the projectile charge to be that of the bound nucleus. We concluded from Table I that every incident monopole is likely to capture a nucleus and to penetrate hundreds of kilometers, more than enough to reach the underground sample of mica. From Table I we see that the Al and Mn groups are best suited for a monopole search.

We looked for nucleus-monopole etched tracks in

TABLE I. Major groups of monopole-nucleus composites.

		Av. E_b		λ (km)			S_n(GeV cm^2/g)	
Group	Z	(MeV)	$\beta = 10^{-4}$	$\beta = 3\times10^{-4}$	$\beta = 10^{-3}$	10^{-4}	3×10^{-4}	10^{-3}
Al	11 to 14	1.9	147	51	20	1.6	3.2	3.4
Mn	22 to 25	1.1	7700	2800	2700	1.8	4.3	6.2
Rb-Sr	36 to 40	0.6	9.6×10^4	4.4×10^4	3.3×10^6	2.0	5.1	8.2
Ba-La	56 to 59	0.4	9.5×10^4	1.0×10^5	1.2×10^6	2.1	5.7	11.0

a sample of mica from Minas Gerais, Brazil, with an Rb-Sr age of 490 ± 20 Myr. From a count of the number of etchable tracks due to spontaneous fission of ^{238}U impurities in the mica and a determination of the uranium concentration, we measured a fission-track age of 441 ± 43 Myr. Study of recoil tracks in mica due to alpha decay of U and Th has shown that the ratio of density of recoil tracks to density of fission tracks is the same within 30% in samples of widely different fission-track ages, implying comparable resistance of the two types of tracks to thermal fading at ambient temperatures typical for mica. Because the track produced by a monopole-nucleus system would have a damage distribution similar to that of an alpha-decay recoil track, we can use the fission-track age as a measure of the monopole collection time. We assume a mean burial depth for the mica to be 5 km over the monopole collection time. A mean depth half as large as this is excluded by estimates of erosion rates of igneous rocks while a mean depth twice as large is excluded by a knowledge of annealing properties of mica and of the geothermal gradient.[16]

We etched a transparent, 125-μm-thick mica sheet for 169 h in HF, then cleaved it into two new sheets each about 60 μm thick and etched them for an additional 60 h. To facilitate realignment the two split halves were kept joined along one edge during etching. We then scanned an area of 13.5 cm^2 in reflected light at 250×, looking for cases in which four etch pits lay along a straight-line trajectory. The combination of etching and viewing conditions was such that we would have been able to see a quadruplet of etch pits along a trajectory at a zenith angle as large as 85° and with the outer etch pits having a depth as small as 0.5 μm. We encountered $\sim 10^3$ large etch pits on each of the four surfaces, with diameters and depths consistent with their being fission tracks, and additional etch pits of smaller diameter quantitatively consistent with their being due to fission tracks that became exposed as etching exposed new surface. We observed that all fission tracks on the inner surfaces occurred in coincident pairs, which established that the realignment of the mica sheets after etching was precise.

We found two cases in which etch pits from each of the four surfaces were aligned along a trajectory that was a straight line within about 10 μm in which the sizes of the etch pits were consistent with a particle with a constant S_n. However, in both cases the magnitude of S_n necessary to account for the etch pit shapes was about twice as large as the maximum value calculated for a monopole bound to the heaviest nucleus with large moment. We would expect about one accidental, nearly aligned quadruplet. Thus, the two quadruplets were probably due to accidental alignments.

Based on this null result we obtain the velocity-dependent limit shown in Fig. 1. This limit is by far the most stringent ever placed on monopole flux. The reduction of sensitivity at large velocities is due primarily to the decrease in S_n. The cutoff velocity at $3\times10^{-4}c$ is due to a threshold associated with overcoming the diamagnetic repulsion of inner-shell electrons.[17] We have taken into account the calculated mean free capture paths for Al and Mn in evaluating the limit in Fig. 1.

Although there is general agreement that monopoles would capture nuclei in the Earth's crust, there are two potential ways in which our experimental limit might be vitiated: (1) For GUT's that predict proton decay, Rubakov and Callan[18] argue that GUT monopoles strongly catalyze baryon decay, making it likely that monopole-nucleus bound states would be short lived. Note, however, that there is no proof yet that baryon-number–nonconserving reactions occur,[19] that it has been argued that SU(5) GUT monopoles would not catalyze baryon decay,[20] and that in some GUT's baryon-number–nonconserving proton decay does not occur. Nevertheless, limits on monopole flux derived under the assumption of catalyzed proton decay[21] or neutron decay[22] form a useful complement to our experiment. (2) If monopoles were to occur predominantly as positively charged dyons or were to enter the Earth with an attached proton,[12] it is likely that Coulomb repulsion would prevent capture of an Al or other heavy nucleus. Detailed theoretical studies of the binding of monopoles to extraterrestrial protons will be extremely important in evaluating the likelihood of this scenario. It will also be desirable to extend calculations of monopole energy loss to evaluate the possibility that bare monopoles or monopoles bound to protons could form etchable tracks through diamagnetic scattering of atoms in the detector.

We thank M. Solarz for experimental assistance, Y. Langevin, S. Parke, N. Kroll, and G. Fiorentini for useful discussions, and the National Science Foundation for partial support through Grant No. PHY-8024128. One of us (P.B.P.) thanks G. Baroni for hospitality at Rome while part of this work was done.

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