Search for Supermassive Magnetic Monopoles Using Mica Crystals

P. B. Price and M. H. Salamon
Department of Physics, University of California, Berkeley, California 94720
(Received 18 November 1985)

The observed absence of monopole tracks in large, ancient mica crystals enables us to set an upper limit of less than $\sim 10^{-18}$ cm^{-2} sr^{-1} s^{-1} on the flux of supermassive monopoles with $0.0004c < V < 0.0015c$ that are stably attached to nuclei. This limit takes into account the fraction of monopoles not initially bound to protons, the fraction that attach with nuclei on their way to the mica, and the measured storage times for tracks with thermal stability similar to that of monopole tracks.

PACS numbers: 14.80.Hv

Magnetic monopoles with mass $\sim 10^{16}$ to $\sim 10^{19}$ GeV/c^2 and a present-day velocity $\sim 10^{-4}c$ to $\sim 10^{-3}c$ are a natural consequence of both grand unified theories and Kaluza-Klein theories.[1] However, the survival of the galactic magnetic field almost certainly sets an astrophysical upper bound of $\sim 10^{-5}$ cm^{-2} sr^{-1} s^{-1} on the flux of monopoles. To improve significantly upon this "Parker limit" with direct, real-time searches would require a detector area $\sim 10^4$ m^2 and a collection time of years. Several such real-time searches are being proposed. In an alternative direct search, Price *et al.*[2] have reported a null result that is a factor 10 to 100 below the Parker limit, based on the absence of tracks of slow monopoles in a 4.6×10^8-yr-old mica crystal. In the present work, using much larger mica crystals, we have obtained a monopole flux limit $\sim 10^2$ times lower than in the first mica search. The new limit includes a correction for the fraction of monopoles initially bound to protons and exploits a new technique[3] for the measurement of the collection and retention time for monopole tracks.

The mica technique relies on the following scenario: A monopole with zero or negative net electric charge enters the Earth and captures a ^{27}Al or other nucleus in a bound state through a magnetic-dipole–magnetic-monopole interaction; the bound pair passes through a naturally occurring underground sample of muscovite mica, undergoing elastic nuclear collisions that result in the formation of a trail of lattice defects in the mica; the track survives as long as the mica remains unheated, and is later enlarged to macroscopic dimensions by retrieval of the mica and etching of it in hydrofluoric acid.

To explain the formation of an etchable track in mica, we refer to Fig. 1. At $v \gtrsim 10^{-2}c$ a heavy ion deposits energy mainly by electronic excitation and ionization at a rate S_e; some fraction of this energy is converted into displaced atoms. If the linear density of displaced atoms in the solid is sufficiently high, a track can be revealed by chemical etching. At $v \lesssim 10^{-2}c$ most of the energy lost by a heavy ion goes into elastic collisions with nuclei, producing displaced atoms directly. This "nuclear" component of energy loss, S_n, has its peak value for ion velocities $\sim 10^{-3}c$. For a bare monopole, S_n is far too small to form a track[4] and S_e is also too small except at velocities $v \sim c$. However, at low velocity a monopole bound to a nucleus with $Z > 10$ can produce an etchable track by virtue of the stopping power S_n of the nucleus being pushed along by the monopole. The curves for S_n for monopole-nucleus bound pairs in Fig. 1 were calculated from an expression S_n that has a sound theoretical basis and fits experimental data for low-velocity ions well.[5] One simply takes the projectile mass to be infinite and the projectile charge to be that of the bound nucleus.

Muscovite mica is the most thoroughly studied of all track-recording solids.[3,6,7] Etchable tracks have been

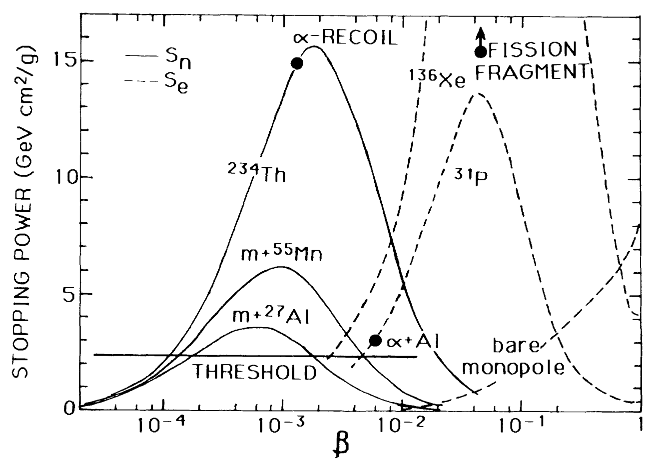

FIG. 1. Stopping power for elastic nuclear collisions, S_n, of monopole-^{27}Al and monopole-^{55}Mn bound pairs (labeled $m+^{27}$Al and $m+^{55}$Mn). Also shown are S_e for a bare monopole and S for three particles that produce natural tracks in mica: a fission fragment ($\approx {}^{136}$Xe), a recoil daughter nucleus from α decay ($\approx {}^{234}$Th), and a compound nucleus from capture of an α particle by an Al nucleus ($\approx {}^{31}$P). The line labeled "threshold" is for a trajectory at $\theta = 0°$.

shown to be produced in mica that is irradiated with very-low-energy ions ($0.0005c < v < 0.0025c$) having $8 \leqslant Z \leqslant 90$.[7] In this regime, where S_e is negligible, the rate of etching along a particle track is given empirically by $v_T = (0.012\ \mu\text{m/h})[S_n\ (\text{GeV cm}^2/\text{g})]$, for muscovite etched in 40% HF at 25 °C. As Fig. 2 shows, in evaluating visibility of an etched track one must consider not only v_T but also $v_\perp$, the rate of etching perpendicular to the cleavage surface in the absence of a track, and $v_\parallel$, the etch rate parallel to the cleavage plane. For the above etching conditions, $v_\perp = 0.027\ \mu\text{m/h}$ and $v_\parallel = 1.36\ \mu\text{m/h}$. In order for a penetrating particle at zenith angle θ to leave a track detectable after an etch time t, it is necessary that

$$v_T t \cos\theta - v_\perp t > H_{\text{crit}}, \tag{1}$$

where H_{crit}, the minimum detectable depth of the etched track under normal scanning conditions, has been determined by us to be $\sim 0.1\ \mu\text{m}$, using a Tolansky interferometric attachment to an optical microscope. For $t = 48$ h (used by us) it follows that $S_n \cos\theta$ must exceed ~ 2.42 GeV cm^2/g to produce a detectable track. Portions of the curves that lie above the horizontal line in Fig. 1 satisfy this inequality for $\theta = 0°$. For a monopole bound to ^{27}Al, the most abundant nucleus in the Earth's crust with a large nuclear moment, a track at $\theta = 0°$ would be revealed by chemical etching for velocities from $0.0002c$ to $0.002c$; at larger zenith angles a track would be etchable over a velocity interval that decreases with θ, becoming vanishingly small for $\theta \gtrsim 48°$. For a monopole bound to ^{55}Mn, a track at $\theta = 0°$ would be etchable for a wider velocity interval, $0.00014c$ to $0.005c$, and at larger angles a track would be etchable over an interval that shrinks to zero at $\theta \gtrsim 66°$.

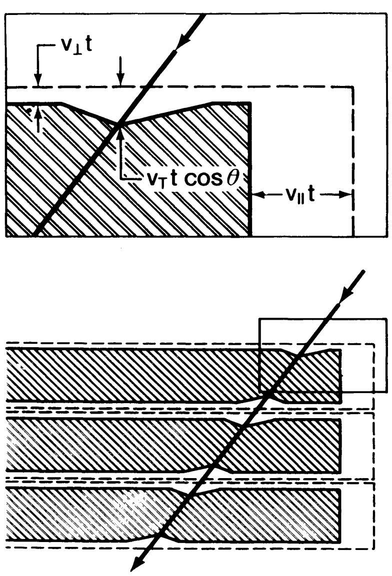

FIG. 2. Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.

Only those monopoles that capture a nucleus before reaching the mica sample will produce a detectable track. The mean burial depth of large, undeformed mica crystals is ~ 3 km. A number of authors[2,8-13] have estimated radiative capture cross sections. We have adopted the results obtained in Ref. 2, where the rate for the inverse process was calculated and then the principle of detailed balance was used. Spherically symmetric ground-state wave functions having an asymptotic form $\psi \propto (r - r_0)\exp(-kr)$ were used, with $k = (2AE_0)^{1/2}$, E_0 the binding energy, and A the mass number of the nucleus. Taking 8.1% and 0.1% for the weight percentages of ^{27}Al and ^{55}Mn in the Earth's crust yields mean paths that vary weakly with velocity in the region of interest and at $\beta = 10^{-3}$ are ~ 20 km for ^{27}Al capture and ~ 2700 km for ^{55}Mn capture. The fraction of monopoles that have captured nuclei before reaching the mica at a depth of 3 km, though substantial, is less than unity and is taken into account in calculation of the flux limit in our experiment.

We selected large, transparent muscovite mica crystals from the British Museum, the Smithsonian Institution, and the Stanford University collection. Application of the following three criteria eliminated all but three crystals with total area ~ 1200 cm^2: (1) absence of any mechanical deformation; (2) $< 100/\text{cm}^2$ background tracks (due to spontaneous fission of random ^{238}U atoms); (3) monopole track-retention age $\gtrsim 5 \times 10^8$ yr.

We digress to explain how the monopole track-retention age is determined. The stopping power and track etch rate for a monopole-nucleus track are much lower than for a fission track (Fig. 1), and its resistance to thermal fading should also be lower.[14] It is not sufficient to establish the fission track-retention age of a mica sample; one needs to establish the monopole track-retention age. Fortunately, early in this study we discovered a new class of naturally occurring tracks produced by particles with stopping power closely similar to that of a monopole-nucleus pair.[3] Thus, a measurement of the retention age of these tracks gives the retention age for monopole tracks. We found that alpha particles emitted from certain daughters in the U and Th decay chains have a high enough energy to initiate nuclear reactions with nuclei in the mica structure, producing what we call α-interaction tracks. From He-ion calibrations we showed that most of these tracks come from reactions of 8.8-MeV alpha particles from ^{212}Po with aluminum and silicon nuclei, leading to silicon (Si) and phosphorus (P) recoil nuclei with $\beta \approx 0.006$, stopping power ≈ 3 GeV cm^2/g (see Fig. 1), and length ~ 0.5 to ~ 1 μm, compared with a length ~ 20 μm for fission tracks. From our He-ion calibrations we calculated that the ratio of surface density of α-interaction tracks to surface density of fission tracks should be ~ 0.15 in micas maintained at normal ambient temperature.[3] A smaller ratio would indicate loss of some of the α-interaction tracks. In our monopole search we used only crystals with a ratio > 0.14, for which the monopole-nucleus track-retention age should be about the same as the fission-track age, and measured the fission-track age in the standard way using a neutron reactor to determine the U concentration.[6]

We laser cut three crystals with track-retention ages of 0.9, 0.6, and 0.6×10^9 years into ~ 150-cm^2 squares, cleaved them into several ~ 100-μm-thick sheets, etched them for 48 h in HF, reassembled a pair of sheets at a time, and scanned them in transmitted light at $\sim 100\times$ with the microscope focused on the common surfaces and with the condenser aperture stopped down to increase contrast. All fission tracks and all α-interaction tracks that crossed the common surface showed up as pairs of superimposed etch pits. As indicated in Fig. 2, the signature of a monopole-nucleus track would be a set of shallow etch pits, one on the top and bottom of each sheet, which in projection would lie in a straight line. A survey with a Tolansky attachment indicated that α-interaction etch pits as shallow as 0.1 μm were readily visible. In a total of 595 cm^2 scanned, we found four cases that satisfied our criterion for approximate quadrupole alignment, consistent with the calculated accidental rate of seven cases. Superimposing a third sheet in its correct position on the others (as in Fig. 2), we found that all four events failed the requirement of sextuple coincidence.

On the basis of this null result, we calculated for two different scenarios (to be discussed in the next paragraph) the curves in Fig. 3 labeled "mica limits" (90% confidence limits). The calculation took into account the areas scanned, the monopole track-retention ages, the velocity-dependent solid angle for satisfaction of the inequality in Eq. (1), the mean free paths for capture of ^{27}Al and ^{55}Mn nuclei in the Earth's crust, the fraction of monopoles that picked up Al or Mn nuclei before reaching the mica as a function of their direction of travel, and the velocity-dependent ranges of monopole-nucleus bound pairs. We assumed that the mica crystals were oriented in a horizontal plane. Since the range of a monopole with mass 10^{16} GeV and velocity $10^{-3}c$ bound to a nucleus is only a few thousand kilometers, upward-moving monopoles were not included. The maxima in the curves of stopping power as a function of velocity in Fig. 1 correspond to minima in the curves of flux limit as a function of velocity in Fig. 3, because at this velocity the solid angle over which a track can be revealed by etching is a

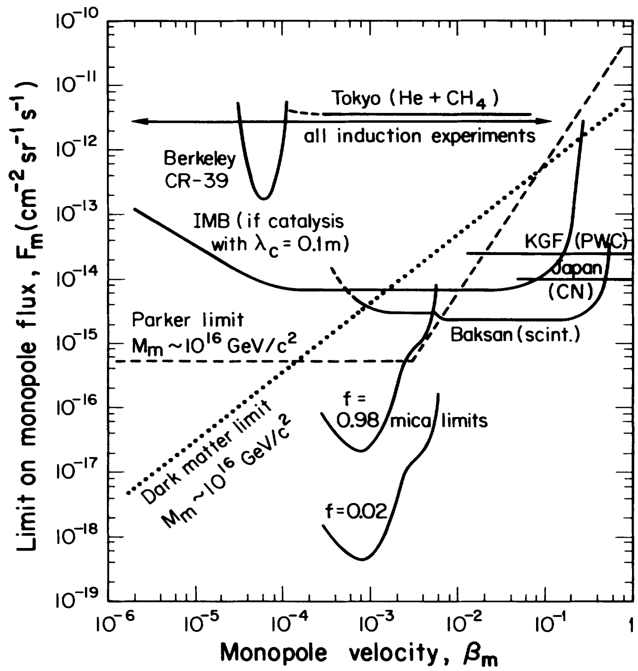

FIG. 3. Monopole flux upper limits (90% C.L.) for several direct searches (solid curves) and indirect astrophysical arguments (dashed curves). Mica limits are calculated for the extreme cases of 2% of monopoles initially bound to protons and for 98% bound to protons.

maximum, consistent with the inequality in Eq. (1). The reduction of sensitivity at large velocities is primarily due to the decrease in S_n. The cutoff velocity at $3 \times 10^{-4}c$ is due to a threshold associated with the monopole overcoming the diamagnetic repulsion of inner-shell electrons and penetrating to the nuclear surface. Disruption of a monopole-nucleus pair in a collision with a nucleus in the Earth above the mica is kinematically impossible for monopole velocities smaller than $\sim 0.003c$, since available c.m. energies in such collisions even with massive nuclei are less than ~ 1 MeV, the typical monopole-nucleus binding energy.

A monopole that reaches the Earth already bound to a proton will, because of Coulomb repulsion, be unable to capture a ^{27}Al or ^{55}Mn nucleus. Bracci *et al.*[15] have calculated the fraction, f, of monopoles that reach the Earth bound to protons that they captured at an epoch between the time of light-element formation and the matter-radiation decoupling time. They showed that f is an increasing function of the monopole-proton binding energy, E_0, and of the baryon-to-photon ratio, η. Values of E_0 from 10 to 200 keV have been calculated,[8–13] depending on the assumed separation of the monopole-nucleus bound pair; the value of η is believed to lie within the range $(3–7) \times 10^{-10}$.[16] When a factor of 2π overlooked by Bracci *et al.* in the exponent of their expressions for bound-state formation and dissociation is taken into account,[17] the value for f is bounded by the values 0.02 (for smallest E_0 and η) and 0.98 (for largest E_0 and η). Division of the mica limit by the factor $1-f$ corrects for the fraction of monopoles that cannot capture nuclei in the Earth. The lower "mica" curve in Fig. 3 corresponds to $f=0.02$; the upper curve corresponds to $f=0.98$. Fortunately, the physics of the epoch at which f is frozen in ($kT \sim E_0/42 < 5$ keV, according to Ref. 15) is not controversial, so that the two curves in Fig. 3 should represent extreme bounds on the mica flux limit.

Each of the remaining solid curves in Fig. 3 represents the most stringent published monopole flux limit based on a particular technique, as given in a recent review.[18]

There is one potential way in which our experimental flux limit would be invalid. Rubakov[19] and Callan[20] have argued that for grand unified theories (GUT's) that predict proton decay, GUT monopoles strongly catalyze baryon decay, making it likely that monopole-nucleus bound states would be short-lived. However, there is no evidence yet that baryon-number–nonconserving processes occur. Moreover, it has been argued that SU(5) GUT monopoles might not catalyze baryon decay,[21] that monopoles in some other GUT's would not catalyze baryon decay,[22] that the rate of baryon decay from a monopole-nucleus bound state may be strongly suppressed,[23] and that in some GUT's baryon-number–nonconserving proton decay does not occur. *The mica result places a limit between three and four orders of magnitude below the Parker limit on the flux of monopoles that do not strongly catalyze nucleon decay.*

If strongly catalyzed nucleon decay does occur, there exist astrophysical limits even more stringent than ours, based on the assumption of catalyzed decays inside neutron stars or white dwarfs.[24] These indirect limits may, however, have loopholes. Thus, direct searches sensitive to bare monopoles or to monopole-catalyzed proton decays are an essential complement to the mica search, even though they probably can never be as sensitive as the mica.

This work was supported in part by National Science Foundation Grant No. PHY-8403710. We thank M. Solarz for experimental assistance.

[1]See papers in *Monopole '83,* edited by J. L. Stone (Plenum, New York, 1984).

[2]P. B. Price, Shi-Lun Guo, S. P. Ahlen, and R. L. Fleischer, Phys. Rev. Lett. **52**, 1265 (1984).

[3]P. B. Price and M. H. Salamon, to be published.

[4]S. P. Ahlen and K. Kinoshita, Phys. Rev. D **26**, 2347 (1982).

[5]W. D. Wilson, L. G. Haggmark, and J. P. Biersack, Phys. Rev. B **15**, 2458 (1977).

[6]R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids* (California Press, Berkeley, 1975).

[7]J. Borg, J. C. Dran, Y. Langevin, M. Maurette, and J. C. Petit, Radiat. Eff. **65**, 133 (1982); J. Borg, Ph.D. thesis, University of Paris, 1980 (unpublished).

[8]D. Sivers, Phys. Rev. D **2**, 2048 (1970).

[9]C. J. Goebel, in *Monopole '83,* edited by J. L. Stone (Plenum, New York, 1984), p. 333.

[10]L. Bracci and G. Fiorentini, Phys. Lett. **123B**, 493 (1983).

[11]J. Makino, M. Maruyama, and O. Miyamura, Prog. Theor. Phys. Jpn. **69**, 1042 (1983).

[12]K. Olaussen, H. A. Olsen, P. Osland, and I. Overbo, Phys. Rev. Lett. **52**, 325 (1984).

[13]J. S. Trefil, H. P. Kelly, and R. T. Rood, Nature **302**, 111 (1983).

[14]E. Dartyge, J. P. Duraud, Y. Langevin, and M. Maurette, Phys. Rev. B **23**, 5213 (1981); J.-C. Dran, Y. Langevin, J. C. Petit, J. Chaumont, and B. Vassent, Nucl. Instrum. Methods Phys. Res., Sect. B **1**, 402 (1984).

[15]L. Bracci, G. Fiorentini, G. Mezzorani, and P. Quarati, Phys. Lett. **143B**, 357 (1984).

[16]J. Yang, M. S. Turner, G. Steigman, D. N. Schramm, and K. A. Olive, Astrophys. J. **281**, 493 (1984).

[17]L. Bracci, G. Fiorentini, G. Mezzorani, and P. Quarati, Phys. Lett. **155B**, 468(E) (1985).

[18]D. E. Groom, to be published.

[19]V. Rubakov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 658 (1981) [JETP Lett. **33**, 644 (1981)].

[20]C. Callan, Phys. Rev. D **26**, 2058 (1982).

[21]T. F. Walsh, P. Weisz, and T. T. Wu, Nucl. Phys. **B232**, 349 (1984); M. Hortacsu, J. Kalayci, and N. K. Pak, Phys. Lett. **145B**, 411 (1984).

[22]D. P. Bennett, Phys. Rev. D **31**, 2323 (1985); S. Dawson and A. N. Schellekens, Phys. Rev. D **27**, 2119 (1983); E. Weinberg, D. London, and J. L. Rosner, Nucl. Phys. **B236**, 90 (1984).

[23]A. S. Goldhaber, in *Magnetic Monopoles,* edited by R. A. Carrigan, Jr., and W. P. Trower (Plenum, New York, 1983).

[24]E. W. Kolb and M. S. Turner, Astrophys. J. **286**, 702 (1984); K. Freese, Astrophys. J. **286**, 216 (1984).