SEARCH FOR SUPERMASSIVE MAGNETIC MONOPOLES USING MICA CRYSTALS

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1. Introduction. The survival of the Galactic magnetic field almost certainly sets an astrophysical upper bound of $\sim 10^{-15}$ 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 searches are being contemplated. We have pursued a novel alternative scheme using large mica crystals capable of recording and storing tracks of slow monopoles over a time scale of $\sim 10^9$ years.

2. Mica as a Detector of GUT Monopoles. At $v > 10^{-2}c$ heavy ions deposit energy mainly by electonic 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 a solid is sufficiently high, a track can be revealed by chemical etching. At $v < 10^{-2}c$ the energy lost by ions goes directly into displacing atoms. This "nuclear" component of energy loss, S_n, has its peak value for ion velocities $\sim 10^{-3}c$, the region of interest for GUT monopole detection.

Muscovite mica, available in large, transparent, sheet-like crystals, is the most thoroughly studied of all track-recording solids [1,2]. Etchable tracks have been shown to be produced in mica which is irradiated with very low-energy ions ($5 \times 10^{-4}c < v < 0.0025c$) having $8 \leq Z \leq 90$ [2]. In this regime, where S_e is negligible, the rate of etching along a particle track is given by $v_T = 0.012(\mu m/hr) \cdot S_n(GeV\ cm^2/g)$, for muscovite etched in 40% HF at 25° C. As Fig. 1 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, $v_\perp = 0.027$ µm/hr and $v_\parallel = 1.36$ µm/hr. In order for a penetrating particle at zenith angle θ to leave a track detectable after an etch time t, it is necessary that $v_T t \cos\theta - v_\perp t > H_{crit}$, where H_{crit}, the minimum detectable depth of the etched track under normal scanning conditions, has been determined by us, using Tolansky multiple beam interferometry, to be ~ 0.1 µm. For t = 48 hr (used by us) it follows that $S_n \cos\theta$ must exceed ~ 2.42 GeV cm^2/g to produce a detectable track. S_n for a slow, bare monopole is far too small to form a track [3]. However, many authors have concluded that monopoles will form bound states with nuclei through magnetic dipole-magnetic monopole interactions [see refs. in 4]. An estimate of S_n of such a composite system in mica is given by evaluating S_n for the nucleus, replacing its mass with the huge mass of the monopole, using an expression for S_n which has a sound theoretical basis and has been well fit to experimental data [5]. One finds that for a monopole bound to ^{27}Al (the most abundant nucleus in the earth's crust with a large nuclear moment), $S_n > 2.42$ GeV cm^2/g for velocities from 2×10^{-4}c to 0.002c. Thus, if monopoles capture nuclei in the earth's crust, they will record tracks in mica located beneath the capture point. Estimates of radiative capture cross sections [4] and of nuclear abundances in the crust yield capture mean free paths of ~10 km. The mean burial depth over the lifetime of mica crystals now in collections is ~3 km. Thus, a substantial fraction of monopoles penetrating a mica detector would be detected.

3. Status of the Search. Price et al. [4] searched for monopole tracks in a 13.5 cm^2 sample of mica with a fission-track-retention age of 4.5×10^8 yr. To eliminate backgrounds due to the accidental alignment of spontaneous fission tracks and other etchable defects, they demanded the linear alignment of etch pits on four cleavage surfaces separated by ~200 μm, about 20 times the range of a single fission track. The curve labeled "old mica limit" in Fig. 2 shows the flux upper limit resulting from that search, in which they found no quadruply aligned etch pits.

We report here the status of a new search which, when complete, will have an area X time factor ~100 times greater than that of the previous mica search. We collected micas from Museum d'Histoire Naturelle (Paris), the British Museum (London), the Smithsonian, and the Stanford collection. Application of four criteria eliminated all but three crystals with total area ~1200 cm^2: (i) absence of any mechanical deformation; (ii) <100/cm^2 background tracks (due to spontaneous fission of random ^{238}U atoms); (iii) fission track retention age >5×10^8 yr; (iv) >3000 alpha recoil tracks from U + Th atoms per ^{238}U fission track. The last criterion assures that, on the assumption that its radiation damage distribution is similar to that of the recoiling daughter of a U or Th α-decay, any track of a monopole-nucleus bound state would survive for the full fission-track retention age.

We laser-cut three crystals with track-retention ages of 0.9, 0.6, and 0.6 billion years into ~150 cm^2 squares, cleaved them into several ~100 μm-thick sheets, etched them for 48 hours in HF, reassembled a pair of sheets at a time and scanned them in transmitted light at ~100 X with the microscope focussed on the common surfaces. Each fission track that crossed the common surface produced a pair of superimposed etch pits. In a total of 470 cm^2 scanned to date, we found three cases that satisfied our criterion for approximate quadruple alignment. Superimposing a third sheet in its correct position on the two others (as in Fig. 1), we found that all three events failed the requirement of sextuple coincidence.

Based on this null result we calculateo the curve labeled "new mica limit" on Fig. 2, taking into account the mean free capture paths of ^{27}Al and

^{55}Mn, the most abundance nuclides with large magnetic moments, and assuming that monopoles are not bound to protons when they hit the earth. The reduction of sensitivity at large velocities is due primarily to the decrease in S_n. The cutoff velocity at 3×10^{-4}c is due to a threshold associated with overcoming the diamagnetic repulsion of inner-shell electrons [6].

4. Critique of the Mica Limit

a) Reduction of nucleus capture cross section? Arafune and Fukugita [6] showed that the long-range force between a monopole and a nucleus due to extra angular momentum carried by a monopole-electric charge system would result in an enhanced or a reduced capture cross section, depending on the sign of the anomalous magnetic moment of the nucleus. For the cases of ^{27}Al and ^{55}Mn, which have a positive anomalous moment, the cross section would be enhanced, so that the limit of Fig. 2 would be even lower if this effect were taken into account.

b) Monopole already bound to a proton. Bracci et al. [7] calculated the fraction of monopoles bound to protons that they captured in the early universe. For all reasonable values of the monopole-proton binding energy (40 to 200 keV) and of the baryon to photon ratio (4 to 7×10^{-10}), they concluded that essentially all monopoles are now bound to protons, and therefore, because of Coulomb repulsion, cannot become bound to an Al nucleus. However, they overlooked a factor 2π in the exponent of their expressions for formation and dissociation. When the correct expressions are used, the fraction, f, of monopoles bound to protons drops to values in the range $f = 0.15$ to 0.98, which raises the mica limit by the rather small factor 1/f.

c) Catalysis of baryon decay. Rubakov [8] and Callan [9] argue that for GUTs 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 proof yet that baryon-number violating processes occur. Moreover, it has been argued that SU(5) GUT monopoles might not catalyze baryon decay [10,11], that monopoles in some other GUTs would not catalyze baryon decay [11,12], and that in some GUTs baryon number violating proton decay does not occur. The mica result places a very stringent limit on the flux of monopoles that do not strongly catalyze nucleon decay. 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 nor are they as sensitive as indirect limits based on the assumption of catalyzed decays inside neutron stars or white dwarfs [13]. The indirect limits may, however, have loopholes.

Final results of the mica search, including data on etching and thermal stability of very low-energy heavy-ion tracks, will be reported elsewhere. This work was supported by NSF Grant PHY-8403710. We thank A.M. Clark (British Museum) for supplying mica samples B.M. 1982, 274a, b, and c.

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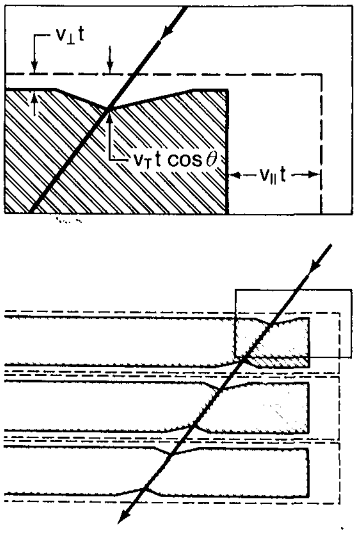

Fig. 1. Collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed again.

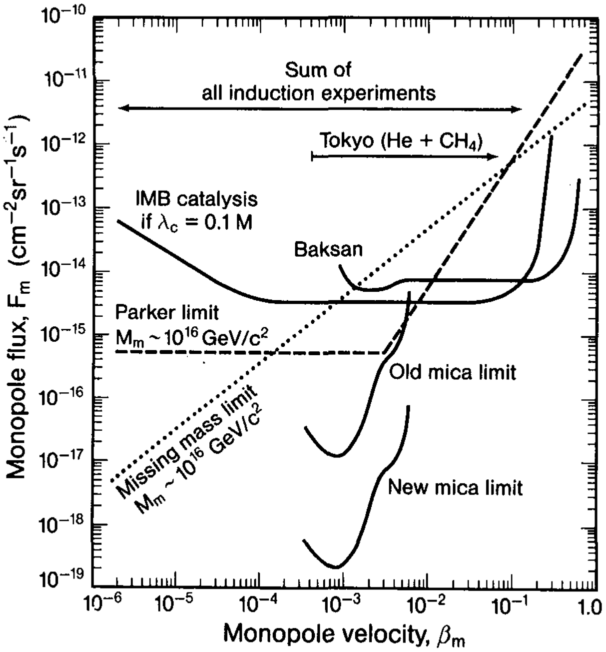

Fig. 2. Monopole flux limits vs monopole velocity for several direct searches (solid curves) and indirect astrophysical arguments (dashed curves).