CERN-EP/84-28

March 9th, 1984

LIMIT ON FLUX OF SUPERMASSIVE MONOPOLES AND CHARGED RELIC PARTICLES
USING PLASTIC TRACK DETECTORS

P.B. Price*

CERN, Geneva, Switzerland

ABSTRACT

It is shown that, at velocities as low as $10^{-4}c$, free monopoles can produce detectable tracks in CR-39 plastic track detectors via diamagnetic repulsion of C and O atoms, and monopoles bound to protons can produce tracks via screened Coulomb collisions in the plastic. A new flux limit of $\sim 1 \times 10^{-13} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ is reported for bare monopoles with $v \sim 10^4 c$ or $> 0.007c$, for dyons and monopole-proton bound states with $v > 3 \times 10^{-5} c$, and for supermassive singly-charged particles with $3 \times 10^{-5} c < v < 0.05c$.

Submitted to Physics Letters

* Permanent address: Physics Dept., University of California, Berkeley, CA 94720.

Grand Unified Theories (GUTs) [1] require the existence of supermassive ($>10^{16}$ GeV) magnetic monopoles [2], which could have been made in the early universe. Numerous searches, summarized in Fig. 1, have been stimulated by Cabrera's [3] report of a possible monopole candidate and by the importance of directly testing GUTs. The current thrust of many groups is to build arrays with collecting power capable of detecting monopoles at a flux below the so-called Parker limit of $\sim 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$, and to make them sensitive to monopoles with velocity below $\sim 10^{-3} c$. The Parker limit - the maximum monopole flux consistent with the survival of the large-scale Galactic magnetic field - is indirect, but attempts to circumvent it [4] require special assumptions about monopole mass and about the nature of the Galactic halo. GUT monopoles either gravitationally trapped within our Galaxy or passing through it should have velocities $\sim 10^{-3} c$, comparable to the Galactic virial velocity and to the relative velocities of galaxies. GUT monopoles gravitationally trapped in semistable solar orbits and with a possibly enhanced local flux [5] would have velocities $\sim 4 \times 10^{-5} c$ to $\sim 1.5 \times 10^{-4} c$ characteristic of meteorites. (Escape velocity for the earth is $3.7 \times 10^{-5} c$).

Recently a track-etching technique [6] has been used to look in a 4.6×10^8 year-old subterranean mica crystal (average depth ~ 5 km) for tracks of GUT monopoles [7]. The resulting flux limit of $\sim 10^{-17} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$, much lower than the Parker limit or any other experimental limits, is valid provided that most monopoles are electrically neutral or negatively charged when they reach the earth and that they capture and retain nuclei such as ^{27}Al in passing through ≥ 1 km of earth on their way to the mica. (A free, very slow monopole would not produce a detectable track in mica.) For mica there exist detailed measurements of the shapes of etched tracks of ions with $10 \leq Z \leq 90$ at very low velocities where track formation results from ejection of atoms from their lattice sites in screened Coulomb collisions rather than by electronic processes. One can easily relate the damage rate of a bound monopole-nucleus system to that of the nucleus alone by regarding the nucleus as infinitely massive and neglecting the small magnetic interaction of the monopole with the crystal. Thus, an attractive feature of the mica detector is that the appearance of a track of a monopole-nucleus system can be directly computed from experimental data. Fig. 1 shows the mica flux limit as a function of velocity.

Although the existence of bound states [8,9] of a monopole and a nucleus with a large magnetic moment is not in question, two scenarios have been discussed that might invalidate the mica search: (a) Bracci et al. [10] have estimated that most monopoles may have radiatively captured free protons in the early universe; those entering the earth would be positively charged, and the resulting Coulomb barrier would inhibit their binding to nuclei. (b) Rubakov [11] and Callan [12] have calculated that in GUTs for which baryon-number is violated by lepto-quark interactions, a GUT monopole will induce baryon decay with a strong cross section (for an opposing view, see ref. [13]). If such is the case, monopole-nucleus bound states would be disrupted on a short timescale.

The CR-39 plastic track detector (composition $H_{18}C_{12}O_7$) is known [14] to be far more sensitive than mica, and several groups are using very large arrays of this inexpensive material in monopole searches, despite the fact that only above a velocity of ~ 0.007 is it sensitive to the electronic component of stopping power of a free monopole [15,16]. I shall now show that, when screened Coulomb collisions and diamagnetic repulsion of atoms in the plastic are taken into account, CR-39 is also sensitive to monopoles, either free or bound to protons, at velocities down to $\sim 3 \times 10^{-5} c$.

Fig. 2 shows my calculated energy deposition rates as a function of velocity, summed over the H, C and O atoms of CR-39, for $(M+^{27}Al)$, $(M+p)$, and M alone (M = monopole). The scale on the left gives the quantity relevant to track formation, $(dE/dx)_{\text{restricted}}$, defined as the energy per unit length deposited within a radial distance of $100 \text{ \AA}$ of the trajectory. For nuclear and diamagnetic stopping, $(dE/dx)_{\text{restricted}} = (dE/dx)_{\text{total}}$; for electronic stopping $(dE/dx)_{\text{restricted}} = \beta (dE/dx)_{\text{total}}$ for β up to $\sim 10^{-2}$. The scale on the right gives reduced etch rate, $s \equiv v_T/v_G - 1$, where v_T and v_G are track etch rate and general etch rate, related to etch pit cone angle by $\theta = \arcsin(v_G/v_T)$. Tracks with $s \geq 0.4$ are detectable with rapid-scan techniques [16]. The relationship between s and dE/dx comes from calibrations with heavy ions [14,17]. The dashed curves with unit slope $(dE/dx \propto \beta)$ give $(dE/dx)_{\text{elec}}$, the electronic contribution for ions [18] and for monopoles [19]. (These quantities are additive when there is a bound system.) The dashed curves with maxima at low velocity

for $(M^{27}\text{Al})$ and $(M+p)$ give $(dE/dx)_{\text{nuc}}$, the contribution due to screened Coulomb collisions with nuclei calculated from the expression of Wilson et al., [20] which fits experimental data for low-velocity ions. The effect of the monopole is to increase (dE/dx) of Al and p by endowing them with essentially infinite mass. The $(dE/dx)_{\text{nuc}}$ for M+p also applies to singly charged supermassive relic particles in the cosmic rays [21]. At higher velocities such particles would follow the $(dE/dx)_{\text{elec}}$ for a proton.

A free, very slow monopole moving through matter exerts forces on atoms due to its magnetic interactions with the atomic electrons. For CR-39 we will neglect energy transfers to H atoms compared with transfers to C and O atoms, and we need consider only the repulsive diamagnetic interaction, since there are no unpaired electrons. The maximum repulsive potential - the energy shift between the ground state of a free atom and the atom with a monopole at its center - has been calculated for hydrogen [22,23] (6.8 eV), helium [22,23] (16 eV), and aluminum [24] (~ 1300 eV). One can estimate the magnitude of the energy shift for the C and O atoms in CR-39 in several ways:

(1) A first-order perturbation calculation [25] of the diamagnetic energy of an atom in the magnetic field of a Dirac monopole ($g=1/2e$) at its centre gives an energy shift of $Ze^2 g^2 \langle r^{-2} \rangle / 2m$ where $\langle r^{-2} \rangle$ is a mean value for the Z electrons at distances r_i from the nucleus. Using the Hartree-Fock electronic charge distributions for C and O atoms [26] gives energy shifts of 450 and 600 eV. These should be viewed as upper limits, because the charge distributions will be forced outward in response to the monopole's intense field.

(2) For the two ground-state 1s energy levels of the hydrogenic atom characterized by the eigenvalue m_j of J_z (total angular momentum projection on the monopole-nucleus axis), the effect of a monopole at the centre is to leave the level with $m_j=0$ unchanged and to increase the energy of the level with $m_j=-1$ by $Z^2 e^4 m / 4$ [27]. Ignoring the 2s and 2p electrons, we get total shifts of 245 and 435 eV for C and O.

(3) Following the approach of Parke [24], I used Malkus' table [22] of eigenvalues and degeneracies for a monopole at the centre of a hydrogenic atom to estimate the total energy, using an effective Z for each

shell to represent the shielding. Comparing these results with the total electronic energies of isolated C and O atoms, I get energy shifts of 200 and 360 eV. For the mix of C and O atoms in CR-39 I adopt the value $V(0) = 300$ eV for the energy shift at a monopole-nucleus distance $R = 0$. An error of 100 eV will not seriously affect the conclusions of this paper.

At large values of R it is safe to use the standard expression for the diamagnetic energy increase for a spherically symmetric atom in a magnetic field, B ,

$$V(R) = Ze^2 B^2 \langle r^2 \rangle / 12m = Ze^2 g^2 \langle r^2 \rangle / 12mR^4 = 0.64 \text{ eV}/R^4 \quad (1)$$

where I take $B=g/R^2$, $Z=6.6$, the average charge for the C and O in CR-39, and $\langle r^2 \rangle = 0.6 \text{ \AA}^2$, a value that can be inferred from experimental measurements of diamagnetic susceptibilities of a large number of elemental substances. I adopt the empirical expression

$$V(R) = (300 \text{ eV}) \exp(-4.45R), \quad (R \text{ in } \text{\AA}) \quad (2)$$

to interpolate between an energy shift of 300 eV at $R = 0$ and values of V at $R > 0.3 \text{ \AA}$ given by eq. (1). The exponential dependence fits the shape of the calculation of $V(R)$ for a monopole near a hydrogenic atom [27] over the region of interest, $0 < R < 0.3 \text{ \AA}$.

To calculate the diamagnetic contribution to (dE/dx) I used the standard procedure [28] of finding the force due to the repulsive potential, calculating the momentum transferred from the monopole to the entire atom as a function of impact parameter b in the impulse approximation, then summing the energy transfers to atoms in the path of the monopole, integrating from $b_{\min}$, given by the kinematic maximum energy transfer $T_{\max} = 2M\beta^2$, to $b_{\max}$, given by the minimum energy transfer to break the chemical bonds holding the atom in a polymer chain. Here M is the mass of the struck atom, and I took $T_{\min} = 12$ eV for the C and O atoms, which leads to a minimum detectable velocity given by $T_{\min} = 2M\beta_{\min}^2$. (For metals and semiconductors ~ 25 eV is required to remove an atom from its lattice site and force it into an interstitial position. For polymers considerably less energy is required, as evidenced by the ejection of very

heavy nuclei such as ^{128}I from molecules via the Szilard-Chalmers (n, γ) process. The result is shown in Fig. 1 as the dashed curve for the free monopole, for which $(dE/dx)_{\text{diamag}}$ reaches a peak value of $\sim 400 \text{ MeV cm}^2\text{g}^{-1}$ at $\beta \sim 10^{-4}$.

Bracci et al. [29] have calculated peak values of $dE/dx \sim 400 \text{ MeV cm}^2\text{g}^{-1}$ for paramagnetic collisions of monopoles in liquid hydrogen and $\sim 75 \text{ MeV cm}^2\text{g}^{-1}$ for diamagnetic collisions of monopoles in liquid helium. For H and He atoms bound in a solid their peak values would be much smaller and at a different velocity when one takes into account the minimum energy transfer to break chemical bonds.

Measurements of etched tracks in plastic detectors show that reduced etch rate s depends on the magnitude of $(dE/dx)_{\text{nuc}}$ in the same way as it depends on the magnitude of $(dE/dx)_{\text{elec}}$. For example, in Ref. [30] a Lexan plastic detector was exposed to Fe ions with $\beta = 10^{-3}$ and etched. At this velocity $(dE/dx)_{\text{nuc}}$ is $3.4 \text{ GeV cm}^2\text{g}^{-1}$, whereas $(dE/dx)_{\text{elec}}$ is only $0.3 \text{ GeV cm}^2\text{g}^{-1}$. The value of s was found to be the same for these tracks as for 70 MeV/u Fe ions, for which restricted $(dE/dx)_{\text{elec}} = 3.4 \text{ cm}^2\text{g}^{-1}$ and $(dE/dx)_{\text{nuc}} = 0$. Because for plastic detectors s appears to depend only on the magnitude of $(dE/dx)_{\text{restricted}}$, whether it is predominantly due to nuclear or electronic collisions, we can use the calculations in Fig. 2 to predict s for a free monopole and for M+Al and M+p.

Kinoshita and Price [15] and Barwick et al. [16] exposed large arrays of CR-39 at an altitude of $\sim 640 \text{ g cm}^{-2}$ in searches for slow monopoles. They reported null results, which they interpreted as flux limits for monopoles with $v \geq 0.007c$. We can now reinterpret their combined results as a flux limit for monopoles down to much lower velocity, using the calculations just discussed. Fig. 1 shows the flux upper limits from CR-39 for free monopoles and for M+p; for $v < 10^{-3}c$ these limits are lower than those from any other detector sensitive to M or M+p; for $v < 6 \times 10^{-4}c$ the limits are a factor ~ 200 lower than Cabrera's best limit. For comparison Fig. 1 shows as a dotted line an estimate [31] of the Parker limit for monopoles of mass $< 10^{17} \text{ GeV}$. The fifty-fold increase in the Parker limit at $v < 2 \times 10^{-4}c$ is the maximum enhancement that could be

allowed by a solar trapping mechanism [5]. To reach the Parker limit for monopoles either free or bound to protons would require a two-year exposure of a 2000 m^2 array of CR-39. Such experiments have begun in Japan.

I note in closing that supermassive singly-charged particles, X^+ and X^- , whose production in the early universe is suggested by some GUTs [21], would produce etchable damage in CR-39 if their velocities were between $\sim 3 \times 10^5 c$ and $\sim 0.05c$. The null result from CR-39 implies that in that velocity interval the flux of relic $X^\pm$ particles is less than $\sim 10^{-13} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$.

I thank S.P. Ahlen, L. Bracci, G. Fiorentini, N.M. Kroll, and S.J. Parke for useful conversations, and CERN and NSF (Grant No. PHY-8024128) for partial support.

REFERENCES

- [1] H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 438 (1974);
H. Georgi, H.R. Quinn and S. Weinberg, Phys. Rev. Lett. 33, 451 (1974).
- [2] G. t'Hooft, Nucl. Phys. B79, 276 (1974);
A. Polyakov, JETP Lett. 20, 194 (1974).
- [3] B. Cabrera, Phys. Rev. Lett. 48, 1378 (1982); Proceedings Monopole 83 Workshop, Ann Arbor (1984).
- [4] E.E. Salpeter, S.L. Shapiro and I. Wassermann, Phys. Rev. Lett. 49, 1114 (1982); J. Arons and R.D. Blandford, Phys. Rev. Lett. 50, 544 (1983).
- [5] S. Dimopoulos, S.L. Glashow, E.M. Purcell and F. Wilczek, Nature 298, 824 (1982); K. Freese and M.S. Turner, Phys. Lett. 123B, 293 (1983).
- [6] R.L. Fleischer, P.B. Price and R.M. Walker, "Nuclear Tracks in Solids: Principles and Applications", Univ. of California Press, Berkeley (1975).
- [7] P.B. Price, Shi-Lun Guo, S.P. Ahlen and R.L. Fleischer, Phys. Rev. Lett., in press (1984).
- [8] D. Sivers, Phys. Rev. D2, 2048 (1970);
C. Goebel, Proceedings Monopole 83 Workshop, Ann Arbor (1984);
J. Makino, M. Maruyama and O. Miyamura, Prog. Theor. Phys. (Japan) 69, 1042 (1983);
K. Olaussen, H.A. Olsen, P. Osland and I. Øverbø, Phys. Rev. Lett. 52, 325 (1984).
- [9] L. Bracci and G. Fiorentini, Phys. Lett. 124B, 493 (1983).
- [10] L. Bracci, G. Fiorentini, G. Mezzorani and P. Quarati, Univ. of Pisa preprint IFUP TH-84-3.
- [11] V. Rubakov, JETP lett. 33, 644 (1981).
- [12] C. Callan, Phys. Rev. D26, 2058 (1982).
- [13] T.F. Walsh, P. Weisz and T.T. Wu, Nucl. Phys. B232, 349 (1984).
- [14] S.P. Ahlen, P.B. Price and G. Tarle, Phys. Today 34 (No.9) 2 (1981).
- [15] K. Kinoshita and P.B. Price, Phys. Rev. D24, 707 (1981).
- [16] S.W. Barwick, K. Kinoshita and P.B. Price, Phys. Rev. D28, 2338 (1983).
- [17] D. Henshaw et al., Proc. 11th Inter. Conf. on Solid State Nuclear Track Detectors, ed. P.H. Fowler and V.M. Clapham, Pergamon Press, New York, (1982) p.115.
- [18] L.C. Northcliffe and R.F. Schilling, Nucl. Data Tables A7, 233 (1970).
- [19] S.P. Ahlen and K. Kinoshita, Phys. Rev. D26, 2347 (1982).
- [20] W.D. Wilson, L.G. Haggmark and J.P. Biersack, Phys. Rev. B15, 2458 (1977).

- [21] P.M. Frampton and S.L. Glashow, Phys. Rev. Lett. 44, 1481 (1980);
J. Ellis, T.K. Gaisser and G. Steigman, Nucl. Phys. B177, 427 (1981);
R.N. Cahn and S.L. Glashow, Science 213, 607 (1981).
- [22] W.V.R. Malkus, Phys. Rev. 83, 899 (1951).
- [23] S.D. Drell, N.M. Kroll, M.T. Mueller, S.J. Parke and M.A. Ruderman, Phys. Rev. Lett. 50, 644 (1983).
- [24] S.J. Parke, private communication.
- [25] J.H. Van Vleck, "The Theory of Electric and Magnetic Susceptibilities", Oxford, Clarendon Press, (1932).
- [26] F. Herman and S. Skillman, "Atomic Structure Calculation", Prentice-Hall, Englewood Cliffs, NJ (1963).
- [27] G. Tiktopoulos, Phys. Lett. 125B, 156 (1983).
- [28] S.P. Ahlen, Rev. Mod. Phys. 52, 121 (1980).
- [29] L. Bracci, G. Fiorentini and R. Tripiccone, preprint IFUP TH-83/26, University of Pisa.
- [30] P.B. Price, in Magnetic Monopoles, ed. R.A. Carrigan and W.P. Trower, Plenum, New York (1983) p. 307.
- [31] M.S. Turner, E.N. Parker and T.J. Bogdan, Phys. Rev. D26, 1296 (1982).

FIGURE CAPTIONS

- Fig. 1 Monopole flux limits (single event significance) labelled M (free monopole) and $M+p$ (dyon or monopole-proton bound state), obtained in this work with CR-39 detectors, compared with limits obtained by others (labelled by authors referred to in Ref. [7]) and with the Parker limit [31] based on the survival of the Galactic magnetic field.
- Fig. 2 Calculated values of restricted energy loss and reduced etch rate for free and bound monopoles in CR-39 detectors.

Fig. 1

Fig. 2