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Summary

Catalysis of proton decay by GUT magnetic monopoles (the Rubakov-Callan effect) is discussed. Combining a short-distance cross section calculation by Bernreuther and Craigie with the long-distance velocity dependent distortion factors of Arafune and Fukugita, catalysis rate predictions which can be compared with experiment are obtained. At present, hydrogen rich detectors such as water (H_2O) and methane (CH_4) appear to be particularly well suited for observing catalysis by very slow monopoles.

Perhaps the two most spectacular predictions of grand unified theories (GUTS) are that the proton decays[1] (baryon number is not conserved) and that super-heavy magnetic monopoles can exist.[2] Even more remarkable, Rubakov[3] and Callan[4] have convincingly argued that GUT magnetic monopoles would efficiently catalyze proton decay, $p + M \rightarrow e^+ + X + M$, with large cross sections. So, if monopoles were ever detected, baryon number violation might tag along as an added bonus. Two fantastic discoveries for the price of one!

Before discussing catalysis, let us briefly survey some other anticipated properties of GUT magnetic monopoles. The lightest monopole generally carries a Dirac unit of ordinary magnetic charge $\pm 2\pi/e$ (where $\alpha = e^2/4\pi \simeq 1/137$) as well as screened color magnetic charge. Its ordinary magnetic field is pointlike in origin down to distances of $O(1/m_{\rm GUT})$, where super heavy $X^{\pm 4/3}$ and $Y^{\pm 1/3}$ boson structure effects are manifested. Those bosons are responsible for baryon number violation and the Rubakov-Callan effect.

In the simplest symmetry breaking scenarios, the monopole mass, m_M, is well determined[5]

$$\frac{m_{\rm GUT}}{\alpha_{\rm GUT}} \leq m_M \leq 1.8\frac{m_{\rm GUT}}{\alpha_{\rm GUT}} \tag{1}$$

where typically, $m_{\rm GUT}$ is in the range $10^{15} \sim 10^{19}$GeV and the unification coupling $\alpha_{\rm GUT} \simeq 1/42 \sim 1$. Therefore, the monopole mass is expected to be very large, $10^{16} \sim 10^{20}$GeV. Currently fashionable supersymmetry and superstring scenarios[6] favor the high mass region around $m_M \simeq 10^{18}$GeV.

Their extremely large masses imply that GUT magnetic monopoles cannot be made in the laboratory or in any known astrophysical environment. Therefore, they should only exist as left-over remnants of the big bang. The predicted flux of those relic monopoles is, however, very uncertain. It ranges from 0 in some inflation models[7] to an unrealistically large value of 1 monopole/cm-sr-s in more standard early cosmologies.[8] The latter possibility is ruled out by many orders of magnitude from lab experiments as well as astrophysical and cosmological arguments.[9] Nevertheless, given the possibility of circumventing many of the existing constraints, it seems prudent to consider the flux (particularly the local flux) as an unknown quantity to be constrained or determined by direct experiments. In that regard, induction experiments presently give[10]

$$F_{\rm monopole} \leq 10^{-12}\ {\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1} \tag{2}$$

That bound depends only on the magnetic charge; hence, it is the least model dependent. During the coming decade, proposed induction experiments may push that bound to $10^{-15}{\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}$. That would take them to the famous Parker bound[11]

$$\begin{gathered} F_{\rm monopole} \leq 10^{-15}{\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}, \\ (m_M \leq 10^{17}{\rm GeV}) \\ F_{\rm monopole} \leq 10^{-15}(m_m/10^{17}{\rm GeV}){\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}, \\ (m_M \geq 10^{17}{\rm GeV}) \end{gathered} \tag{3}$$

which is based on survival of galactic magnetic fields. Note, that the Parker bound is not so stringent for magnetic monopoles with $m_M \simeq 10^{18}$GeV, the presently preferred value in supersymmetry and superstring scenarios. However, bounds on the total mass of the universe[9] then limit the average flux to $\leq 3 \times 10^{-15}(10^{16}{\rm GeV}/m_M){\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}$, a severe constraint. Of course, the local flux could be larger.

Scintillator detectors are already approaching the $10^{-15}{\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}$ Parker bound benchmark. The MACRO detector[10] presently under construction may push that bound to $10^{-16}{\rm cm}^{-2}\ {\rm sr}^{-1}\ {\rm s}^{-1}$, quite an achievement. Those experiments are, however, sensitive to the ionizing properties of the monopole; so, a very low velocity monopole below some threshold (usually somewhere between $\beta = 10^{-3}$ and 10^{-4}) could escape detection. Super-heavy GUT monopoles are expected to have an average $\beta \simeq 10^{-3}$ relative to terrestrial detectors; however, that could go down to as low as 10^{-4} if they are concentrated in local monopole "clouds."

There are many other ideas about how to detect monopoles and clever astrophysical and cosmological constraints which complement the above bounds. For a comprehensive description of those bounds, see the recent excellent review by D. Groom.[10]

The property of GUT monopoles that concerns us here is their ability to catalyze proton decay. The basic idea is that $J = 0$ fermion-monopole scattering involves electric and color exchange interactions which are accompanied by baryon number violation. At the quark level, they give rise to $d_L + M \rightarrow e_L^+ + \bar{u}_R + \bar{u}_R + M$ amplitudes which are independent of $m_{\rm GUT}$ and hence not suppressed. Therefore, at the nucleon level, one expects

$$p + M \rightarrow e^+ + X + M \quad (X = {\rm pions}) \tag{4}$$

to proceed with $\sigma_{\rm catalysis} \simeq 10^{-26}{\rm cm}^2$; unless there are long distance effects or weak interaction subtleties that reduce the rate.

A recent study of the short-distance catalysis cross section by Bernreuther and Craigie using a soft-pion approximation and bag model calculations found

$$\sigma(p + M \to e^+ + \pi^0 + M) \simeq 3 \times 10^{-30}\mathrm{cm}^2/\beta$$
$$\sigma(p + M \to e^+ + X + M) \simeq 1 \sim 3 \times 10^{-28}\mathrm{cm}^2/\beta \qquad (X = \text{pions}) \qquad (5)$$

where β is the relative proton-monopole velocity (in units with $c = 1$). Those results cannot, however, be directly applied to real experimental situations without accounting for long-distance initial and final state interactions. In many cases, such effects can cause tremendous suppressions.

Although much work remains to be done on long-distance corrections to magnetic monopole catalysis, a nice start has been made by the work of Arafune and Fukugita.[13] Using a non-relativistic Hamiltonian, they estimated the distortion of the monopole-nucleus wavefunction due to the long range magnetic field interaction with the electric charge and magnetic moment of the nucleus. That effect gives rise to a velocity dependent cross section suppression or enhancement factor $F(\beta/\beta_0)$ where

$$\beta_0 \simeq 0.17\ A^{-4/3} \qquad (6)$$

with A the number of nucleons. In the case of free protons (as in hydrogen targets),[13]

$$F(\beta/\beta_0) \simeq \beta_0/\beta \quad (\text{Hydrogen}) \qquad (7)$$

so, the cross sections in Eq. (5) are enhanced by an extra factor of 170 for $\beta \simeq 10^{-3}$. For spin-0 nuclei with charge Z, they found[13]

$$F(\beta/\beta_0) \simeq (\beta/\beta_0)^{\sqrt{1+2Z}-1} \quad (\text{spin}-0\ \text{nuclei}) \qquad (8)$$

which gives rise to a suppression for $\beta \le \beta_0$. In the case of ${}^{16}_{8}O$, that results in a suppression factor $\simeq 0.01$ while for ${}^{56}_{26}Fe$, $F(\beta/\beta_0) \simeq 0.8$ for $\beta \simeq 10^{-3}$. The reader is referred to Ref. 13 for details.

Deep underground proton decay experiments have searched for GUT magnetic monopoles via catalysis.[10] To date, no events have been observed. To translate these findings into flux bounds is not straightforward, however, since one must know the cross section. Given the present state of knowledge, we suggest employing the Bernreuther-Craigie cross sections in Eq. (5) supplemented by the Arafune-Fukugita velocity dependent distortion factors. Before applying that prescription, we should also mention that situation is generally complicated by experimental time cuts made on the data. Those cuts cause the detector efficiency to vary with β, the relative monopole velocity. Usually, there is a marked decrease in efficiency at high β because "quick" events are vetoed and at low β because the electronics go dead before a second interaction can occur. (Experiments generally trigger on 2 or more catalysis events in the detector.) What constitutes "high" and "low" β is strongly dependent on the cross section or alternatively, the interaction length. In general, the shorter the interaction length, the wider is the optimal range between β_{low} and β_{high}.

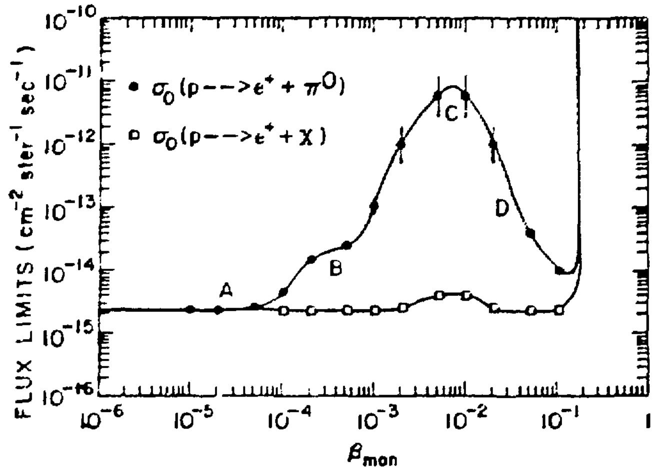

Fig. 1: Magnetic monopole flux bounds from 300 days of IMB running[14] after accounting for long distance initial state interactions. The circles correspond to monopole catalysis of protons into $e^+\pi^0$, while the boxes are for inclusive modes.

As a concrete example, we have applied the above prescription to the results obtained by the IMB Collaboration[14] from 300 days of running with their water Cherenkov detector. In that experiment, a multiple catalysis event had to pass two time gates to be registered. It had to fire in the first gate ($t_1 = 512$n sec) and in the second ($t_2 = 7.2\ \mu$ sec) which followed immediately after the first. After the second gate, the detector goes dead for 3 msec while data is being transferred. We have folded in those requirements and used the cross section estimates in Eq. (5) including a $0.17/\beta$ factor for Hydrogen and a $(\beta/0.00434)^{3.123}$ factor for Oxygen to obtain the flux bounds in fig. 1. A few comments are in order. At the extreme low end of the β scale, the Hydrogen catalysis cross section blows up as $1/\beta^2$; so the flux bound should be simply determined by the detector area and length of the run. However, in the case of extremely large cross sections real catalysis events can be vetoed because too much energy is released or because the catalysis starts outside the fiducial volume of the detector. At point A on the graph, the Hydrogen catalysis cross section drops below the optimal level for the detector, and the flux limit starts to rise (if only the $e^+\pi^0$ final state is counted). At point B, a plateau is created by the balance between Hydrogen's decrasing cross section and the detector's increasing electronic's efficiency. Between B and C, the electronics reach maximum efficiency, but the decreasing catalysis cross section causes an increase in the flux limits. At point C, the Oxygen cross section becomes important and the flux limits decrease. (In the case of $p \to e^+ + X$ events, there is less structure because the cross section is much larger.) At $\beta \gtrsim 0.1$, no flux limits are obtained because at those high velocities monopoles would pass through the entire detector within the first time gates so, the requirement of two distinct events would not be satisfied.

Assuming that the above comparison of theory and experiment is approximately correct, we see from fig. 1 that proton decay detectors are also very good GUT monopole detectors. They already provide flux bounds which are approaching $10^{-15}\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ and one could easily imagine those bounds improving by 1 or even 2 orders of magnitude when the next generation of very large proton decay detectors turn on. Quite an added bonus for experiments designed to search primarily for ordinary proton decay.

It has been argued that neutron stars would capture super-heavy magnetic monopoles.[15] The catalysis reaction should then release enormous amounts of energy which would be radiated in the form of x-rays. Lack of such x-rays has been used to set the bound

$$F_{\text{monopole}} \lesssim 10^{-23} \text{cm}^{-2}\ \text{sr}^{-1}\ \text{s}^{-1} \quad \text{(Neutron Star)} \qquad (9)$$

Of course, if that stringent bound is valid, proton decay detectors have absolutely no chance of observing catalysis. *Objections have been raised regarding the bound in* Eq. (9), usually based on uncertainties in the physics of neutron stars. We are not able to comment on the merits of those arguments. However, we do note that there may be important initial and final-state effects which could severely suppress the catalysis rate in neutron stars. That possibility needs further investigation.

Magnetic monopoles moving through matter appear to be able to capture protons or even some heavier nuclei in $J = 0$ bound states.[16] Such nuclei should eventually undergo catalysis, but that may occur at a much reduced rate.[17] At the same time, their positive electric charges may repel other would be nuclei capture or catalysis candidates. (The coupled monopole-multi nuclei bound state problem is obviously very complicated.) If capture followed by catalysis is the usual reaction, one can well imagine that there could be tremendous differences between effective catalysis cross sections in ordinary matter and neutron stars.

In conclusion, the final verdict on magnetic monopoles is not yet it, both theoretically and experimentally. Much work on proton decay catalysis theory remains to be done, particularly with regard to long distance effects. Experimentally, the flux bounds from neutron stars are somewhat discouraging. However, there is enough uncertainty in the neutron star catalysis rate to warrant further terrestrial searches in proton decay detectors. Such experiments nicely complement induction and ionization detectors. Based on our present understanding of catalysis, it would appear that hydrogen rich targets such as water (H_2O) and methane (CH_4) are particularly good catalysis candidates. In such detectors the free protons can be captured or perhaps directly catalyzed at an enhanced rate for low relative velocities.

Magnetic monopole detection is obviously not easy, but the prize if it is ever found will make the long arduous hunt well worthwhile.

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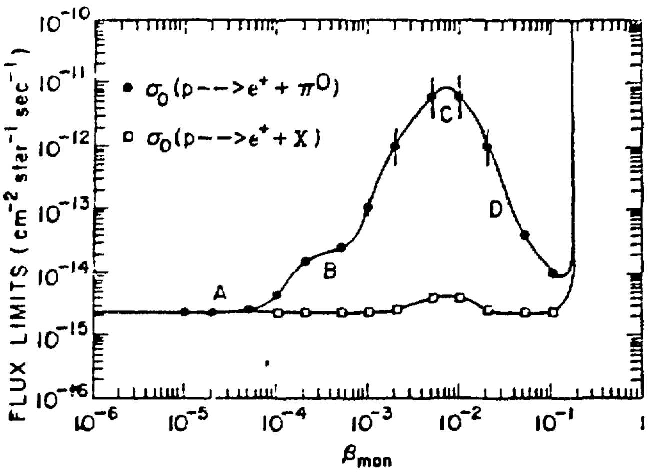

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