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New magnetic monopole flux limits from the IMB proton decay detector

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An improved limit on the flux of magnetic monopoles in the vicinity of the solar system is obtained, assuming that monopoles strongly catalyze nucleon decay (the Rubakov-Callan effect). Flux limits are presented for monopole velocities from $10^{-5}c$ to $10^{-1}c$ and for monopole-nucleon cross sections between 10^{-27} cm^2 and 10^{-21} cm^2. For a representative velocity $\beta \approx 10^{-3}$, and cross section $\sigma \approx 10^{-24}$ cm^2, we obtain a limit $F_m < 2.7 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} and for $\sigma \approx 10^{-25}$ cm^2, $F_m < 1.0 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} at 90% C.L.

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I. INTRODUCTION

If magnetic monopoles exist and if they catalyze proton (or nucleon) decay as suggested by Rubakov [1,2], Callan [3], and others, then proton decay detectors, such as the IMB detector, may be used to set limits on the local flux of monopoles. Monopole-induced nucleon decay is more difficult to detect than spontaneous nucleon decay because the massive monopole can invisibly carry off much of the momentum. This means that the usual searches for proton decay, where events with a significant unbalanced momentum are usually interpreted as neutrino-induced background, are not directly applicable.

The possible modes of a nucleon decay catalyzed by a monopole interaction are not well known. However, there have been predictions [4–6] that, if minimal SU(5) were correct, the modes and branching ratios of monopole catalyzed nucleon decay would be similar to those of noncatalyzed decay (e.g., $p \to e^+\pi^0$). It is expected that a similar situation would exist for theories other than minimal SU(5).

Despite their high stopping power ($dE/dX \sim 100\ \beta$ GeV g^{-1} cm^2 for $\beta < 0.1$ [7]), massive monopoles ($M \sim 10^{16}$ to 10^{17} GeV for SU(5) monopoles [8]) with velocities typical of objects in the solar neighborhood ($\beta = 10^{-4} - 10^{-3}$) can easily reach deep underground detectors such as IMB.

To estimate $\lambda_{\rm cat}$, the mean distance between catalyzed nucleon decay interactions, we use $\lambda_{\rm cat} = 1/(\sigma N_N)$, where N_N is the nucleon density of the target. Estimates of the catalysis cross section σ are unfortunately subject to great uncertainty, ranging from about 10^{-26} cm^2 [9] to about 10^{-19} cm^2 [10] at $\beta = 10^{-4}$. Because of this large range of possible cross sections, summary listings of monopole flux limits such as [11] should be interpreted with care.

II. PREVIOUS RESULTS

The Parker bound $F_m \lesssim 10^{-15}$ cm^{-2}sr^{-1}sec^{-1}, a limit based on the survival of the galactic magnetic field [12], has proven difficult to improve upon by Earth-based detectors. More stringent limits can be obtained from catalyzed nucleon decay in pulsars [13], and from catalyzed nucleon decay in the sun [14–16]. These *indirect* astrophysical measurements may be complemented by more *direct* measurements of the monopole flux incident on the Earth as in the case of large water Čerenkov detectors, if the Rubakov-Callan effect exists.

Recent results from the underwater Čerenkov detector at Lake Baikal [17] put the flux limit at $F_m \lesssim 2 \times 10^{-16}$ cm^{-2}sr^{-1}sec^{-1} for $\beta_m = 10^{-4}$. However, to

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achieve this limit, it was necessary to assume enhanced catalysis cross sections [10], $\sigma = 10^{-21}$ cm^2 at this velocity.

The Kamiokande detector, a 3000 ton water Čerenkov detector located in Kamioka, Japan, has also reported [18] flux limits based on the nonobservation of monopole catalyzed nucleon decay. These limits are $F_m \lesssim 2.5 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} for $\beta_m = 10^{-4}$ and $\sigma = 10^{-25}$ cm^2.

In 1983, the IMB Collaboration published [19] a monopole flux limit $F_m \leq 7.2 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} at velocities $\beta_m = 10^{-4} - 10^{-1}$, assuming a catalysis cross section $\sigma = 10^{-25}$ cm^2. This limit was derived from the nonobservation of *multiple* nucleon decay events in 100 days of live time. In the present paper we extend this analysis, with improvements, to another 623 live days of the IMB detector from 4 May 1986 to its shutdown on 22 March 1991.

III. NEW IMB RESULTS

A. The detector

The IMB detector was a water Čerenkov detector [20,21] located at a depth of 600 m underground [1570 meters of water equivalent (mwe)]. It was a rectangular cavity of 17 m width × 23 m length × 17 m height, filled with 7000 tons of pure water and instrumented with 2048 photomultiplier tubes uniformly distributed over the six cavity walls. A mean effective area of 4×10^6 cm^2 was presented to an isotropic flux of monopoles. The detector trigger required 20 or more photomultipliers detecting one or more photoelectrons each, corresponding to an energy threshold of approximately 20 MeV which allowed detection of many of the anticipated modes of decay including (but not limited to) the modes

$$\begin{aligned} &M + p \to M + e^+\pi^0, \\ &M + p \to M + e^+\eta, \\ &M + p \to M + e^+\rho, \\ &M + p \to M + e^+\omega, \\ &M + p \to M + \mu^+\omega, \\ &M + n \to M + \nu\pi^0, \end{aligned} \tag{1}$$

and

$$M + n \to M + e^+\pi^-.$$

For every event, light deposition and timing for each phototube is recorded. This information is recorded for 512 ns with 1 ns resolution, a period of time called the T_1 scale. Immediately following the T_1 scale is the T_2 scale, wherein hit times and pulse heights are recorded for all the tubes for an additional 7.6 μs with 15 ns resolution. A monopole with $\beta \approx 0.1$ will traverse the average thickness of the detector[1] in one T_1 scale length; a monopole with $\beta \approx 6 \times 10^{-3}$ in one T_2 scale length.

If a monopole traveling through the IMB detector has a sufficently high nucleon decay catalysis cross section, $\sigma \gtrsim 10^{-27}$ cm^2, then there is an appreciable chance that a catalyzed proton decay event will occur as it crosses the the detector while if $\sigma \gg 10^{-27}$ cm^2, then it is likely that several catalysis events will occur for one monopole crossing the detector. In this paper, we discuss searches for both scenarios: the former in the "single-hit" analysis, the latter in the "multihit" analysis.

B. IMB data and live times

The IMB detector has operated in three different configurations known as IMB-1, IMB-2, and IMB-3, distinguished by differing photomultiplier coverage. Data used for this analysis are from the IMB-3 phase, although we include earlier results from IMB-1 [19] in our flux limits. The IMB-3 data are divided into a period when most high light level events were not recorded, and a period when all events were recorded.

In the first period, 629 days, most (but not all) of the events with more than 900 photomultiplier hits on the T_1 scale were not recorded because they were over the maximum light level expected for a single nucleon decay. This limits our sensitivity to multiple catalyzed nucleon decays during this period. The "multihit" analysis that will be discussed in this paper uses 401 days of data from this period. For the "single-hit" analysis, all 629 days of this data were used. In the second period, 222 live days, all events were recorded and all live time was used in the single-hit and multihit analyses. Hence, the total live times are 851 days for the single-hit, and 623 days for the multihit analyses.

C. "Single-hit" nucleon decay analysis

The rate of events detected by IMB can be used to set limits on the flux of monopoles in the detector. The background to a single-hit nucleon decay signal is atmospheric neutrinos that interact in the detector. A flux model for atmospheric neutrinos [22] and a Monte Carlo simulation of neutrino interactions in the detector were used to determine the expected number of contained events which would survive the data analysis process [21]. The rate of events due to atmospheric neutrinos expected in a fiducial volume that is two meters inside the walls of the detector is 1.00 ± 0.20 events/day [21], with the quoted error reflecting the disagreement in the atmospheric neutrino flux models.

The number of events found in 851 live days is 935 [23], which corresponds to a rate of 1.10 ± 0.038 events/day. The 0.10 ± 0.24 events/day excess restricts the maximum nucleon decay rate to $R_m < 0.41$ events/day at 90% C.L. From this we can derive a flux limit using the formula

$$F_m < R_m/(4\pi A \varepsilon_1 \varepsilon_2), \tag{2}$$

where A is the effective cross section of the detector,

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[1] The detector thickness, averaging over all trajectories, is 15 m.

4×10^6 cm^2 and ε_1 is the efficiency for scanners to find a monopole-interaction event, conservatively estimated by trials with Monte Carlo events as being 90%. The quantity ε_2 is the probability for a monopole that enters the detector volume, of producing an event that will pass the analysis selection criteria: an event will be kept by the analysis if it is within the fiducial volume (2 m within the walls) and if the number of tubes hit on the T_1 scale is less than 900. The probability that a monopole will satisfy these requirements was determined by using a simulation of an isotropic flux of monopoles passing through the detector and was found to depend on the velocity of the monopole, the catalysis cross section and, to a lesser extent, the amount of light produced by monopole-induced nucleon decay.

The efficiency of this analysis for monopoles entering the detector reaches a maximum of 76% at low velocities and high cross sections. The resulting flux limits are presented in Fig. 1. Rather than parametrize the results in terms of velocity-dependent cross sections, the curves are presented for different constant values of σ, the catalysis cross section.[2] Sensitivity to high cross-section, high-velocity monopoles is reduced because of the large likelihood of multiple monopole interactions during the T_1 scale[3] which would cause an event to exceed the 900 tube cutoff, while sensitivity to high cross-section, low-velocity monopoles is increased because of repeated detection opportunities on consecutive T_1 scales.

The data examined above include only events that light 70 or more tubes on the T_1 scale. Monte Carlo simulations of the preferred [4] and "standard" SU(5) modes listed in Eq. (1) indicate that these reactions almost always produce events with 70 or more tube hits. However, if other modes that produce less Čerenkov light are favored, these flux limits do not apply.

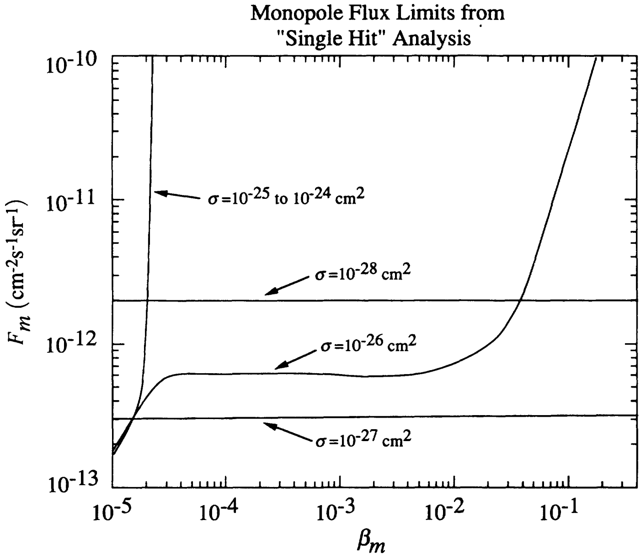

FIG. 1. 90% C.L. monopole flux limits from the "single-hit" analysis for various monopole catalyzed nucleon decay cross sections, plotted as a function of monopole velocity. In this figure, as well as in the next, each curve is for a constant catalysis cross section, assuming all baryons in the detector's water are available for catalysis interactions. The velocity dependence of the curves is due to timing constraints of the detector electronics and software cuts, as explained in the text.

D. "Multihit" nucleon decay analysis

The observation of consecutive interactions of a monopole in the detector can provide a more sensitive technique for detection of monopoles. We have searched for interactions on the T_1 scale followed by an interaction on the T_2 scale (the "T_1T_2 analysis") and for interactions on the T_1 scale followed by another detector trigger within[4] 15 ms the ("T_1T_1 analysis").

1. *The T_1T_2 analysis*

The T_1T_2 analysis looks for events in which the number of tube hits exceeds the background level on both the T_1 and T_2 scales. The background on the T_1 scale is negligible, but it is substantial on the T_2 scale because of phototube after-pulsing, an effect that creates false hits. If the number of tubes hit on the T_2 scale exceeds the after-pulsing level by an empirically determined margin the event is kept. The effect of this criterion, which is small for the preferred nucleon decay modes, and of all other selection criteria are accounted for in the detection efficiency.

The events that pass this criterion are checked to see if they are entering muons. Cosmic ray muons are a significant background to this analysis because a muon event followed by the muon's decay can simulate two monopole interactions.

To reject these muons, events that trigger more than 900 tubes within a 100 ns window on the T_1 scale and trigger fewer than 70 tubes in any 100 ns window on the T_2 scale are eliminated. The 100 ns window is chosen so that all of the light generated by a muon crossing the detector will be included. Monopole catalyzed nucleon decay would produce events that have less than 938 MeV of visible energy which almost always results in fewer than 900 tubes hit in the detector (at least 99% of the time for any mode). Therefore, only monopoles that interact more than once within 100 ns could be lost by this criterion. The second part of this criterion assures that events with more than 70 tubes hit within 100 ns on the T_2 scale will be kept. Monopole catalyzed nucleon decay would almost always result in events with more than 70 tubes hit (as determined by Monte Carlo simulation), so the efficiency of this procedure for keeping monopole events is high [about 94% for the modes listed in Eq. (1) above].

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[2] A strong low-velocity suppression of the catalysis cross section for oxygen nuclei has been predicted [10].

[3] A monopole experiencing multiple catalysis interactions during the T_1 scale would have been treated as a single event by the single-hit analysis software, hence its inclusion in the "single-hit" nucleon decay analysis.

[4] 15 ms is the approximate time of flight across the detector of a $\beta = 10^{-5}$ monopole.

Another procedure for rejecting entering muons relies on the use of an automatic event fitter to determine whether or not the event is fully contained within the detector. If the fitter obtains a position for the event vertex that is within 40 cm of the detector walls and if the fitter returns a high confidence level for that fit then the event *could* be rejected as entering. However, there must again be 70 or fewer tubes hit in 100 ns on the T_2 scale before the event is finally rejected; this retains high cross-section monopoles that might otherwise be missed.

The criteria described above reject all but about one out of every 2000 events. The remaining events were visually scanned by physicists. The events found to originate inside the detector are consistent with neutrino interactions that produce a muon which subsequently decays. They are inconsistent with monopole interactions because the energy deposition on the T_2 scale is too low (70 or fewer tubes hit) and are therefore rejected. No candidate monopole interactions are found by the T_1T_2 analysis.

2. The T_1T_1 analysis

The T_1T_1 analysis looks for multiple monopole interactions inside the detector with at least one hit on each of two successive T_1 scales within 15 ms of each other. Events within 3.5 ms of a previously recorded event will be lost due to data acquisition dead time. A sample of 693 events[5] contained within a fiducial volume that is more than 2 m inside the walls of the detector was examined: the live time before and after each event was searched for other interactions inside the detector within 15 ms. Events thus found were visually scanned by physicists to determine if they were consistent with two consecutive monopole generated interactions. No pair of events was found with both vertices inside the detector.

3. Combining T_1T_1 and T_1T_2 analysis results

From these results the following 90% C.L. upper limit on the monopole flux can be set:

$$F_m < N_0/(4\pi AT\varepsilon_A\varepsilon_B), \qquad (3)$$

where $N_0 = 2.3$ is the upper limit on the number of monopole interactions observed, $A = 4 \times 10^6$ cm^2 is the effective cross section of the detector, $T = 623$ days is the live time searched, and ε_A is the efficiency for the scanners to retain a monopole event, conservatively estimated to be 90%.

The quantity ε_B is the efficiency for a monopole that enters the detector volume of producing an event that will pass the selection criteria outlined above (the T_1T_1 or the T_1T_2 analysis) and was determined by studying a Monte Carlo simulation of an isotropic flux of monopoles incident upon the detector and subjected to the cuts. The efficiency depends on three unknowns: the monopole velocity, the nucleon decay catalysis cross section, and the visible energy produced by the nucleon decay. Although these quantities are not well known, there exist rough predictions of their magnitudes [4,9,10]. Efficiencies for this analysis to detect a monopole that enters the detector reach as high as 97% at low velocities and high cross sections. It should be noted that ε_B is quite insensitive to the visible energy of the nucleon decay modes because all tube cuts are well below the light level expected from the anticipated modes. No significant change in the value of ε_B is observed in Monte Carlo simulations of the modes listed in Eq. (1). Reactions with much less light production might correspond to less stringent flux limits.

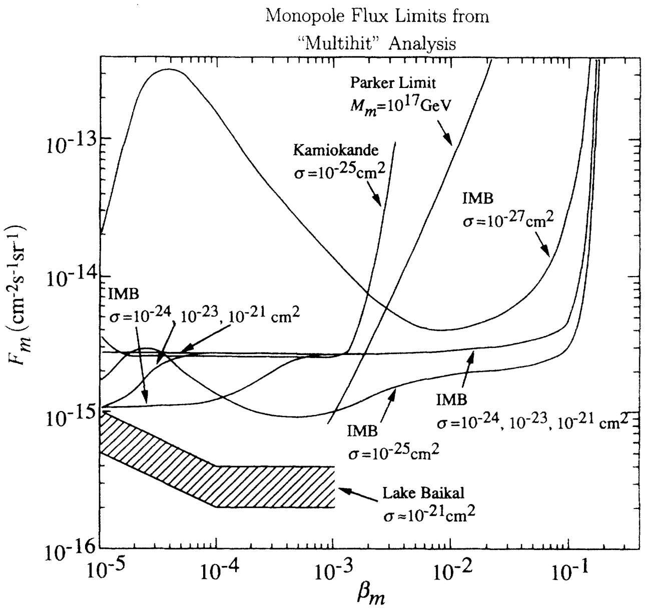

FIG. 2. 90% C.L. monopole flux limits from the combination of the "multihit" analysis and prior IMB results [19] for various monopole catalyzed nucleon decay cross sections. We have also indicated the Parker bound for 10^{17} GeV monopoles [12], and the flux limits from the Kamiokande detector [18] and from the Lake Baikal detector [17]. The lower Lake Baikal curve corresponds to the decay channel $p \to e^+\pi^0$, and the upper curve to the decay channel $p \to \mu^+K^+\pi^-$.

Figure 2 shows the flux limits obtained from this analysis, combined with those of an earlier IMB monopole search [19]. Each curve is for a different catalysis cross section σ.

The loss in sensitivity for low cross sections at around $\beta = 10^{-5}$ is due to a 3.5 ms electronics dead time between a T_2 scale and the following T_1 scale. The highest velocities give poor flux limits because the monopole exits the detector before the T_2 scale is activated, giving no chance for the event to pass the T_1T_2 criterion. High cross sections and high velocities are especially difficult because, for a period of time, most events with more than 900 tubes hit on the T_1 scale were discarded.

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[5] Available from a previous search for spontaneous nucleon decay [23].

IV. CONCLUSIONS

Local monopole flux limits have been obtained for various velocities and catalysis cross sections. For a reasonable monopole velocity, $\beta = 10^{-3}$, the expected catalysis cross section is [17] $\sigma = \frac{2}{18} 0.17\sigma_0/\beta^2 \approx 10^{-24}$ cm^2 taking $\sigma_0 = 10^{-28}$ cm^2. The factor of $\frac{2}{18}$ takes into account the predicted suppression of the decay cross section for oxygen nuclei [10]. The flux limit corresponding to this velocity and cross section is $F_m < 2.7 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} at 90% C.L. For lower cross section $\sigma = 10^{-25}$ cm^2 and $10^{-4} < \beta < 10^{-3}$, the flux limit is $F_m < 1.0 \times 10^{-15}$ cm^{-2}sr^{-1}sec^{-1} at 90% C.L.

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[1] V.A. Rubakov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 658 (1981) [JETP Lett. **33**, 644 (1981)].
[2] V.A. Rubakov and M.S. Serebryakov, Nucl. Phys. **B218**, 240 (1983).
[3] C.G. Callan, Jr., Nucl. Phys. **B212**, 391 (1983).
[4] Zhong-Qi Ma and Ju-Fei Tang, Phys. Lett. **153B**, 59 (1985).
[5] W. Bernreuther and N.S. Craigie, Phys. Rev. Lett. **55**, 2555 (1985).
[6] W.J. Marciano and D. Silvano, in *Physics of the Superconducting Super Collider, Snowmass, 1986*, Proceedings of the Summer Study, Snowmass, Colorado, edited by R. Donaldson and J. Marx (Division of Particles and Fields of the APS, New York, 1987), p. 735.
[7] S.P. Ahlen, Phys. Rev. D **17**, 229 (1978).
[8] V.A. Rubakov, Sov. Sci. Rev. A. Phys. **8**, 1 (1987).
[9] K. Olaussen *et al.*, Phys. Rev. D **52**, 325 (1984).
[10] J. Arafune and M. Fukigita, Phys. Rev. Lett. **50**, 1901 (1983).
[11] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992), p. IX.3.
[12] M.S. Turner, E.N. Parker, and T.J. Bogdan, Phys Rev. D **26**, 1296 (1982).
[13] K. Freese, M.S. Turner, and D.N. Schramm, Phys. Rev. Lett. **51**, 1625 (1983).
[14] J. Arafune and M. Fukigita, Phys. Lett. **133B**, 380 (1983).
[15] L. Bracci and G. Fiorentini, Lett. Nuovo Cimento **42**, 123 (1985).
[16] L. Bracci *et al.*, Nucl. Phys. **B258**, 726 (1985).
[17] L.B. Bezrukov *et al.*, Yad. Fiz. **52**, 86 (1990) [Sov. J. Nucl. Phys. **52**, 54 (1990)].
[18] T. Kajita *et al.*, J. Phys. Soc. Jpn. **54**, 4065 (1985).
[19] S. Errede *et al.*, Phys. Rev. Lett. **51**, 245 (1983).
[20] R. Becker-Szendy *et al.*, Nucl. Instrum. Methods A **324**, 363 (1993).
[21] D. Casper, Ph.D. thesis, University of Michigan, 1990.
[22] H. Lee and Y. Koh, Nuovo Cimento **105B**, 883 (1990).
[23] R. Becker-Szendy *et al.*, Phys. Rev. D **46**, 3720 (1992).