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Upper Limit for Magnetic Monopole Production by Neutrinos*

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ABSTRACT

Existing magnetic monopole searches are re-evaluated in terms of monopole production by cosmic-ray neutrinos. The upper limit for the cross section for monopole production inside the best ocean-bed sample is $\sigma_D \leq 1.0 \times 10^{-39} E_T^2$ cm^2 where E_T is the threshold energy to produce a pair of monopoles expressed in BeV. An even lower limit of $\sigma_C \leq 3.0 \times 10^{-45} E_T^2$ cm^2 is established if the monopoles are collected on the sample from surrounding ocean water.

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I. INTRODUCTION

Recently several speculations have been made concerning a magnetic basis of matter. Carrigan[1] suggested that massive quarks might consist of bound pairs of magnetic monopoles carrying electric charge. Schwinger[2] has proposed a model where quarks are replaced by dyons, particles which also carry both magnetic and electric charge. Dyons are quark-like in that a nucleon consists of three dyons while a meson is made up of two. Magnetic neutrality in normal particles is obtained by introducing two elementary magnetic charge magnitudes, one twice the size of the other. Similar proposals have also been considered by Nambu[3] and Hahn and Biederharn[4] in the framework of the three triplet model. All of these theories contain the interesting feature of the possibility of a large time-reversal violation.[5]

The Schwinger dyon model is able to qualitatively reproduce some of the general features of the meson masses. The theory leads in a natural way to 0^- and 1^- multiplets, introduces hypercharge plausibly, and roughly predicts the magnitude of the K meson electromagnetic mass splitting. However, there are difficulties in detail with the signs of the mass splittings, the magnitude of the electric dipole moment of the neutron, and the smallness of the time-reversal violation that occurs in nature. Schwinger feels that these problems might be alleviated by introducing an exchange mechanism mediated by an intermediate magnetic boson. In turn, this boson could be coupled to the ordinary neutrino field and decay into a magnetic lepton and a neutrino.

Schwinger's suggestion, even aside from the question of dyons, raises an interesting point. No direct search has even been made for magnetic poles produced by neutrinos. Since weak processes and magnetic monopoles have the characteristic of symmetry violation in common this is perhaps a natural process to investigate. A production mechanism analogous to intermediate vector boson production is illustrated in Fig. 1. The magnetic charges are given by the superscripts S and N. The incident neutrino produces a magnetic lepton, L, and a magnetic intermediate boson, S. In turn, the boson decays to a magnetic lepton and a neutrino. An alternate production mechanism might take place by exchanging an S to produce a magnetic baryon at the lower vertex.

Extensive searches have been conducted for magnetic poles and evaluated in terms of strong and electromagnetic production. The most recent terrestrial search for naturally produced poles in ocean-bed ferromagnetic pavement gives a monopole cross-section limit of 2×10^{-34} cm^2 for pole masses of 1000 BeV produced in p-nucleon collisions.[6] Alvarez et al.[7] have recently conducted a search for magnetic monopoles on a lunar sample that sets a comparable strong-interactions limit at 1000 BeV and establishes an upper limit two orders of magnitude smaller at masses of 10 BeV.

These values set stringent bounds on the minimum mass of a pole produced by strong or electromagnetic interactions. It should be noted, however, that there are difficulties in establishing mass limits with any collection technique since the monopole collection and trapping process may be imperfectly understood. As an example, in the ocean-bed search mechanism the monopoles might be trapped on paramagnetic minerals in the ocean water and never arrive at the ocean bottom.

In view of Schwinger's suggestion we have re-evaluated the existing monopole search data to establish an upper limit for neutrino production of monopoles. The most sensitive of the terrestrial monopole searches[6, 8] use ferromagnetic collectors with long collection times such as deep ocean deposits of ferromanganese pavement. The monopoles are extracted from the sample with a powerful magnetic field and identified. In the case of neutrino production, the monopoles can appear in the sample by two processes: direct production in the sample or collection from the surroundings. In the direct production case, the energy of one of the two monopoles from the pair must be low enough so that it does not escape the sample. The cross-section limit will be much higher because only the sample itself is available as a target. On the other hand, the estimate based on collection will be more susceptible to any uncertainties in the molecular binding properties of monopoles or details in the behavior of the sample surface.

II. DIRECT PRODUCTION ESTIMATE

The muon neutrino flux at the surface of the earth has been evaluated by several groups.[9] The spectrum of Osborne et al. can be approximated by an isotropic distribution of the form

$$\frac{dN}{dE_\nu} = \frac{a_\nu}{E_\nu^{\;3}}, \tag{1}$$

where $a_\nu = 0.05\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$ to within 20% in the region from 1.5 to 800 BeV/c and includes both muon neutrinos and anti-neutrinos. There are some disagreements between the groups and some uncertainty concerning the K to π ratio. A conservative value of a_ν at 1000 BeV which takes account of the differences can be taken as $a_\nu = 0.023$. For a flat sample of volume V the number of monopoles produced by this flux in time T is:

$$N_{mono} = 4\pi \frac{N_A \rho}{A} V\, T \int_{E_T}^{E_M} \sigma(E_\nu) \frac{dN}{dE_\nu} dE_\nu \tag{2}$$

where N_A = Avogadro's number, ρ is the density of the material, $\sigma(E_\nu)$ is the monopole production cross section per nucleus as a function of energy, A is the effective mass number for the sample, E_T is the threshold energy, and E_M is the energy at which both monopoles escape the sample. (Note that half of the neutrino flux comes from below the horizon.) The cross section should be averaged over each nucleus, but for coherent production the higher-Z manganese will give the major contribution somewhat above threshold; therefore the cross section is evaluated only per manganese nucleus.

In order to set a limit on the magnitude of the cross section, it is necessary to have some functional cross-section form. Ideally a theoretical cross section such as the intermediate boson prediction of Wu et al.[10] would be employed and the absence of poles used to establish a value for a coupling constant. This is not possible since there is no theoretical prediction for the neutrino-monopole cross section. Instead it has been assumed that the cross section is constant above a threshold energy. This is the assumption that has been used to evaluate the upper limit for strong interactions by Carithers et al.[5] and Goto et al.[11]

A 95% confidence level on the upper limit is established[12] by letting $N_{mono} = \ln 20$. The direct production cross section per manganese nucleus is then

$$\sigma_D \leq A \ln (20) \cdot \left[2\pi \; N_A \; M \; T \; a_\nu \left(\frac{1}{E_T^{\,2}} - \frac{1}{E_M^{\,2}} \right) \right]^{-1} . \qquad (3)$$

For convenience ρV has been replaced by M, the mass of the sample. The maximum energy, E_M, is established by the production mechanism. It is possible for one of the poles to carry off relatively little energy, since the monopoles are produced in pairs. In addition, since the poles will be extremely heavily ionizing, their range will be short. For instance, a Schwinger pole will lose at least 5000 BeV in moving through 1 cm of iron oxide. As a result for reasonable threshold energies, E_M is much larger than E_T and can be neglected. For Fleischer et al.[6] M = 7.7 kG and T = 16 x 10^6 years so that $\sigma_D \leq 1.0 \times 10^{-39} E_T^2$ cm^2, where E_T is in BeV.

Since the electron neutrino flux is an order of magnitude lower, the cross-section limit for electron neutrino production will be about an order of magnitude larger.

To get some feeling for the monopole mass implied by the monopole neutrino cross section, consider $\sigma_D = Z^2 \times 10^{-37}$ cm^2 and let Z = 25. This corresponds to an estimate for coherent production far away from threshold for a conventional intermediate boson.[13] This could very well be an underestimate since the fine structure factor which appears in the cross section would probably be much larger for magnetic monopoles and the neutrino-magnetic boson coupling constant might be much larger. Then $E_T \leq 260$ BeV. The free center-of-mass energy for coherent production off a manganese target at this threshold is 120 BeV. The pole mass corresponding to a 260-BeV threshold is M = 60 BeV.

III. COLLECTION ESTIMATE

A collection limit can be set using the same attack used for the evaluation of the direct production limit. As a good approximation one can assume all of the poles are produced by neutrino interactions on oxygen in the ocean (thus neglecting the atmosphere and the poles coming up from the sea bed). These poles then drift down along the earth's field lines to the collector sample. From a simple argument it follows that

$$\sigma_C = \sigma_D \frac{\rho_D L_D A_C}{\rho_C L_C A_D} , \quad (4)$$

where the subscripts D and C refer to the direct production and collection processes, and ρ, L, and A refer to the density, thickness, and effective atomic number of the media. Effectively the relative cross-section ratio is the equivalent thickness of the ferromanganese target divided by the equivalent thickness of the ocean above the sample, so that $\sigma_C = 0.30 \times 10^{-5} \sigma_D$. Substituting in the direct production cross section, one gets $\sigma_C \leq 3.0 \times 10^{-45} E_T^2 \text{ cm}^2$ (where E_T is in BeV). The threshold energy is found to be 4.7×10^4 BeV for a nominal production cross section of $Z^2 \times 10^{-37} \text{ cm}^2$. This corresponds to a center-of-mass energy of 1200 BeV. This is sufficient to produce poles with mass 600 BeV. Again the electron neutrino cross-section limit will be about a factor of ten larger.

IV. CONCLUSION AND COMMENTS

The cross-section limits determined above for neutrino production of magnetic poles is $\sigma_C < 3.0 \times 10^{-45} E_T^2 \text{ cm}^2$ for the pole-collection interpretation of the data and $\sigma_D < 1.0 \times 10^{-39} E_T^2 \text{ cm}^2$ for the direct-production interpretation. The later limit is more conservative since it depends less on the pole-collection mechanism. The collection limit corresponds to quite high center-of-mass energies. If the intermediate magnetic boson has a cross section of the same order as a "normal" intermediate boson, then the monopole mass might be as high as several hundred BeV. On the other hand the classical magnetic self energy of a Schwinger lepton could be many hundred BeV, so that it is not difficult to conceive of magnetic leptons with masses greater than this limit. Thus it is not possible to say that Schwinger leptons have been ruled out by the present cross-section limits.

It is interesting to compare the direct neutrino flux received by the ocean-bed sample with the neutrino flux available in a bubble-chamber neutrino experiment at an accelerator. In a bubble chamber the two lepton poles would be slowed rapidly by ionization loss and then pulled toward the appropriate magnet pole along a field line. This should give rise to a very characteristic track along a field line with a possibly imperceptible kink at the production vertex. In the CERN propane bubble-chamber exposure,[14] the total neutrino flux through the chamber was approximately 1.9×10^{11} neutrinos/cm^2, while the number of carbon nuclei was 1.7×10^{28}. The accelerator neutrino spectrum is only roughly similar to the cosmic-ray neutrino spectrum and, of course, has a definite upper bound. The integrated neutrino flux through the ocean-bottom sample above 1 BeV was of the order of 1.5×10^{14} neutrinos/cm^2. The mass of the Fleischer et al. sample was 7.7 kG so that the target contained 4.2 x 10^{25} manganese nuclei. Thus, if no monopole events are found in the CERN chamber film it will set a similar cross-section limit to the direct production limit in the terrestrial sample for neutrino energies below about 10 GeV. The CERN neutrino bubble-chamber film has been re-investigated to search for neutrino induced monopole production. These results will be presented in a separate publication.

The recent Alvarez et al. macroscopic search conducted on an 8.35 kG lunar sample using an electromotive force technique gives an effective area-time factor about two orders of magnitude greater than the Fleischer et al. terrestrial sample. For poles produced by strong interactions this essentially reduces the cross-section limit by the same factor. However, the situation is entirely different for neutrino production of poles. By far the dominant source of terrestrial neutrinos is the decay in the atmosphere of mesons that have been produced in strong interactions at the top of the atmosphere. This can occur because of the tenuous nature of the atmosphere. On the moon mesons are produced by cosmic-ray interactions in the lunar surface where the average meson interaction length is about 20 cm. In that distance a 1-BeV pion will have a probability of 0.4% of decaying, thus reducing the neutrino flux correspondingly. The actual situation is somewhat worse because the relevant momentum region of the neutrino spectrum which determines the cross-section limit is produced by higher-energy mesons. Consequently the experiment of Fleischer et al. still sets the limit on neutrino production of poles. In fact, lunar and deep ocean searches are somewhat complementary since one favors strong and electromagnetic interactions while the other includes the effects of weakly interacting particles.

It is interesting to consider less direct tests for a magnetic substructure in elementary particles. As an example, the very high magnetic fields predicted[15] for pulsars (10^{12}-10^{13} gauss) might be sufficient to directly overcome the pole-pole binding if the binding were small enough. In turn the interaction of the poles could result in gamma-ray emission along the lines suggested by Ruderman and Zwanziger.[16] At present, pulsar fields are estimated to be about five orders of magnitude smaller than the field required to overcome the binding of two Dirac poles at a separation of one fermi.

A second test might proceed along the following lines. If the K_L^o and K_S^o each consists of two dyons in different internal states, it might be possible to polarize the dyons in an external magnetic field and produce an effective mass shift. This would be equivalent in some sense to the Zeeman effect in an atom. Note, however, that it does not presuppose the need for spin. The K_L^o-K_S^o interference phenomenon offers a sensitive tool similar to an interferometer for detecting a small change in the mass difference. Some years ago prior to the discovery of time-reversal violation, Good[17] developed a decay distribution for a similar effect by considering neutral kaons with magnetic moments. A search for magnetic effects would consist of K_o^L-K_o^S mass difference measurements in varying magnetic fields. The experiment would be complicated by the time delay for the alignment of the induced polarization axis. Present experiments[18] show no indication of a mass difference that depends on the field in the regenerator region.

To usefully set bounds on the magnetic constituents it would first be necessary to demonstrate theoretically that external polarization can occur in dyon models. The polarization energy of two point monopoles separated by 1 fermi in a field of several kilogauss is somewhat greater than the K_L^o-K_S^o mass difference. However, normal quantum mechanical effects should appreciably diminish the splitting.

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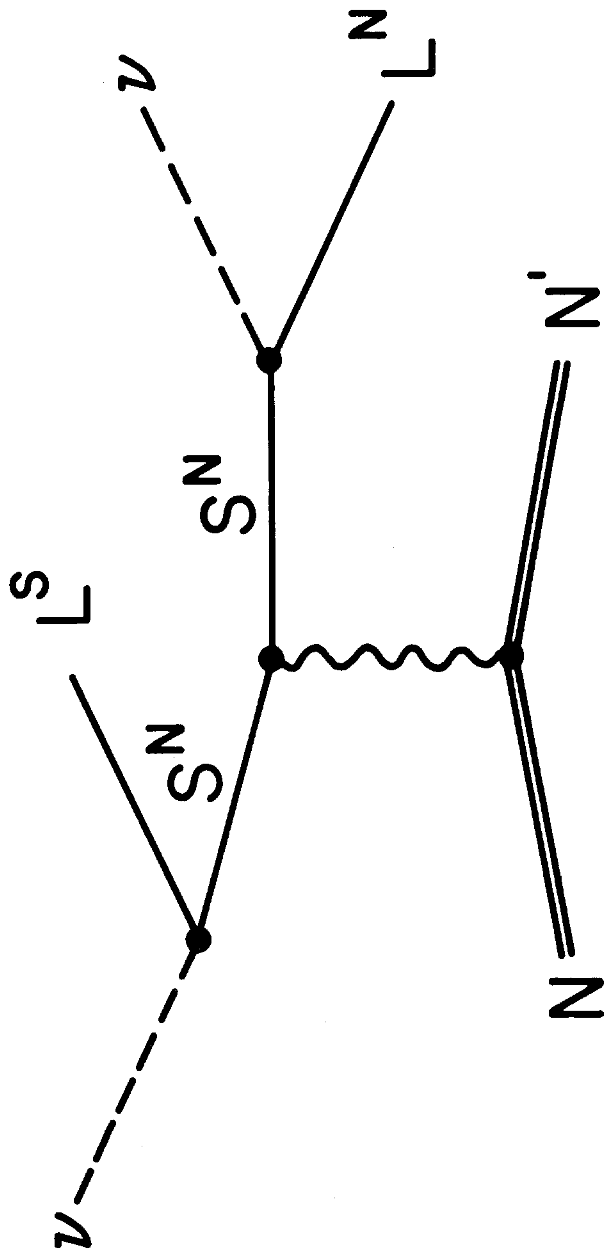

Fig. 1. Intermediate magnetic boson mechanism for production of magnetic lepton pairs.