NAL PROPOSAL NO. 76

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SEARCH FOR MAGNETIC MONOPOLES PRODUCED AT NAL

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ABSTRACT

Following the ideas outlined in our Oct. 29, 1969 letter of intent to E.L.Goldwasser we propose to undertake a three phase program to search for possible magnetic monopole production at NAL. In the first phase we will look for free magnetic monopole production in strong and electromagnetic interactions by using collectors placed in the proton beam dump and an electronic detection technique similar to one previously employed in cosmic ray searches. The second phase will extend the search we have recently carried out for neutrino production of free magnetic monopoles by placing large collectors in the NAL neutrino beam. In the third phase we will search for bound magnetic monopoles by looking for breaks as a function of energy in the production of low energy gamma ray showers by protons.

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I. PHYSICS JUSTIFICATION

"Procul dubio omnes lineae (magneticae) hujusmodi in duo puncta concurrent sicut omnes orbes meridiani in duo concurrunt polos mundi oppositos."

Espistola Petri Peregrini de Maricourt de magnete (1269)

Undoubtedly the elementary particle concept which has the longest history of being proposed but not discovered is the hypothesis of the magnetic monopole. The search for free magnetic poles has continued for a number of centuries. Near the turn of this century the search abated as researchers realized atomic magnetism arose from electric currents. Then in the 1930's Dirac[1] made the striking observation that electric charge quantization could be explained if magnetic poles existed.

A number of theoretical objections have been raised in the past to Dirac's argument and the magnetic monopole hypothesis[2]. Perhaps the most serious is the observation by Hagen[3] that magnetic monopoles are not compatible with the usual assumptions of Lorentz invariance. Schwinger[4] has been able to overcome this difficulty by permitting an apparent asymmetry in the Dirac string, but maintaining rotational and Lorentz invariance.

Thus up to this time no one has discovered an incontrovertable reason why magnetic poles should not exist. Indeed recent "dyon" theories based on magnetic quarks have

aroused considerable interest[5]. In Schwinger's view they offer the possibility of explaining SU_3 while at the same time giving some insight into both the nature of hypercharge and a possible time reversal mechanism.

Many attempts have been made to detect magnetic monopoles in strong and electromagnetic processes both with accelerators and in natural production searches. Monopole searches at the Brookhaven AGS[6] and at CERN[7,8] indicate that monopole masses of less than three BeV are not produced in strong interactions. Deep ocean sediment searches[9] have established cross section limits at even higher masses. Alvarez et al.[10] have used an Apollo-retreived lunar sample with an extremely large area-time factor to lower the cross section limits two more orders of magnitude. Recently we have extended the search for monopoles to weak processes by reevaluating the existing experiments in terms of the natural neutrino flux[11]. No poles have been found in any of these searches although Kolm and co-workers[12] have detected unusual signals that could be interpreted as poles of one-third the Dirac charge.

Two straightforward explanations can be offered for the lack of experimental observations; either the poles are too strongly bound or the mass of the poles is so large that they have not been produced in the experiments. Mass ranges well beyond NAL energies have already been explored with natural production searches. However, the availability of

high intensities at NAL offers a unique opportunity to force the cross section down further in the mass range up to about 15 BeV/c^2.

The ability of the NAL accelerator to lower existing cross section limits can be demonstrated by a comparison to the smallest strong interaction cross section limit, the lunar search of Alvarez et al.[10]. For 15 BeV/c^2 masses (corresponding to incident proton energies of 500 BeV) the Alvarez et al. cross section limit is $2.0*10^{-41} cm^2$. The lunar sample limit is exceeded after about one day's running and lowered by a factor of 100 after several months using an iron target one interaction length long exposed to an intensity of $1.5*10^{13}$ protons/pulse at NAL.

An NAL monopole program should include two possibilities. In early searches free monopoles may be found, in which case measurement of their properties would become of paramount importance. If the poles are not observed in these searches it will be useful to continue to extend the searches to establish even lower limits. On the other hand, it will also be desirable to examine alternate hypotheses such as the Ruderman and Zwanziger[13] suggestion that pole pairs may remain bound but radiate in deexciting.

Characteristically experimental searches for free poles break into two parts, 1) the production and collection of the poles, and 2) the detection and possible storage of

of the poles. At NAL the production will necessarily lead to an extremely radioactive sample with activities of several hundred curies possible. We believe that this constitutes by far the most difficult and important aspect of an experiment at NAL and therefore will determine the character of the detection apparatus. The form of the apparatus is also somewhat conditioned by the magnitude of the magnetic charge one is interested in detecting. The largest charge that has been suggested is $g = 12\ g_D$ ($g_D = e/2\alpha$) in Schwinger's dyon theory[5]. In the past many accelerator searches have been insensitive to such large poles. Our present apparatus design will be sensitive to magnetic charges up to at least $24\ g_D$. The smallest value that has been discussed is the possible experimental signal of Kolm and his co-workers[12] of $g = g_D/3$. Our apparatus will be sensitive to charges well below this value. It should be noted that electromotive techniques, such as the ones suggested and employed by Tassie[14], Vant-Hull[15] and Alvarez et al.[16] become less sensitive at small values of magnetic charge.

We propose to locate monopole collector devices in the beam dumps at NAL. Since the nature of the operation and availability for access of these dumps are not yet clear we will only suggest detection schemes which we feel are compatible with the requirements of the radioactive targets. As the accelerator policy on operations and beam dump usage is refined we may alter the detection arrangements suggested

below.

II. THE EXPERIMENTS

We have mapped out an extensive program for monopole investigations at NAL. At this time we wish to propose a first phase and suggest two other later possibilities that we may propose after we have gained some experience with the accelerator.

Phase I: Beam Dump Search

As we mentioned earlier, the details of the collection process can be tailored to the nature of the beam dump. However, we would like to propose two explicit collection schemes for the sake of definiteness.

The first method would be used if a water-filled dump similar to the one at SLAC is available at NAL. Monopoles will be produced in the water by both strong and electromagnetic processes provided the water comprises a fraction of the material which interacts with the beam. Energy deposition may give rise to some boiling but the monopoles produced by the beam will be thermalized in the surrounding water. If a diamagnetic material such as copper is used for the container then the poles will diffuse through the liquid, acted on by the force of the earth's field and repelled by the diamagnetic container. At the top of the dump an opening to an air-filled solenoid would be provided. In their random paths poles of the proper sign would pass near the entrance

to the solenoid and be attracted by the field. The solenoid would serve as a monopole conduction channel to the outside of the shielding approximately 30 ft away where the monopole detector would be located. Figure 1 illustrates the arrangement schematically. A field of about 75 gauss can easily be achieved in a solenoid with a diameter of 2 cm. For this field poles as low as 1/6 of a Dirac magnetic pole will not be accelerated but instead be dragged along through the air and follow the field lines. Some focusing action against scattering in the air can be provided by lining the inside of the solenoid with a diamagnetic copper pipe.

The important advantages of this technique are: (1) It requires no handling of radioactive material at any point. Discussions with the radiation physics group at NAL indicate that there is no hazard involved in having a small air passage leading from the beam dump. (2) It allows continuous monitoring so that possible limitations of the detection apparatus can be investigated and the search is decoupled from the operational requirements of the beam dump.

If a water dump is not available we propose the following alternate scheme. A paramagnetic solid such as aluminum would be placed in the center of the interaction region of the dump. Monopoles produced in the material would be bound by the paramagnetism. Cooling arrangements might be required to protect against melting. At suitable times the collector would be removed from the dump and placed at the

end of the detector solenoid. The magnetic field of the detector would be strong enough to overcome the paramagnetic binding of the collector. As a precaution it may be desirable to dissolve the collector or vaporize it following the technique of Petukhov and Yakimenko[17].

Access at the beam dump for the alternate scheme is more of a problem. Radioactivity of the collector can be expected to be on the order of 100 R/hr at one meter. Although this is a difficult source strength it can be handled. Typically a lead pig with six to eight inch walls would be required for this. A curved solenoid acting as a monopole conduction channel could be built into the pig, if the radiation emerging from the exit window of the pig presents difficulties in operating the detection apparatus.

The implications for the choices of particular beam dumps are discussed in the apparatus section. Typically samples would remain in the dumps for several months. We see no reason, however, not to continue to renew the collector samples indefinitely to continue to lower the limits.

Figure 2 illustrates the detection scheme we propose to employ. It is similar to an apparatus used by Kolm and collaborators[12], for a search for naturally produced monopoles. Monopoles from the collectors are accelerated by a 1 m long solenoid operating at 25 kgauss. It may be useful to provide some focusing by slightly tapering the solenoid field. Part of the way through the solenoid a very thin

stripper foil (1 micron or less) acts to strip off any oxygen molecules that have become bound to the pole. Three thin plastic scintillation counters are placed at the exit of the solenoid and used to form a coincidence. The magnetic field is sufficiently high so that poles up to 25 times a Dirac charge can penetrate the three detectors. (Note that although the energy gain in the solenoid is proportional to the magnetic charge, the energy loss in the detectors is proportional to magnetic charge squared. Thus, higher charges are more difficult to send through the counters.) The signals in the counters will be at least 130 times minimum ionizing for a charge as low as 1/6 the Dirac charge. This fact will be used to set a threshold high enough so that cosmic ray muons are not detected. A cosmic ray veto may not be employed. This is because the monopole energy loss process may be accompanied by bremsstrahlung which could cause the veto counters to fire and thus eliminate the event. A range telescope consisting of aluminum and scintillants will be placed after the three counter telescope. The range of the monopole in the aluminum should be correlated with the pulse height in the scintillators. Smaller values of the charge will be associated with longer ranges. Poles stopped in the paramagnetic aluminum should be able to be reaccelerated by placing the aluminum plate at the entrance of the solenoid.

It may be necessary to increase the field in the solenoid to something greater than 50 kgauss if ferromagnetic rather than paramagnetic collectors are used. This should not be too difficult. We have also considered the use of two sequential solenoids with a drag medium interposed to introduce a time delay between two counters. This would make the coincidence signal even cleaner.

Phase II: Search for Magnetic Leptons Produced by Neutrinos

A collector for use in a neutrino beam must necessarily have a large volume both because the beam is several meters in diameter and the cross sections are expected to be small. To achieve this condition one form an experiment might take is the following: A large water (diamagnetic) tank intercepting the area of the neutrino beam and as long as feasible is placed directly behind the other experimental apparatus in the neutrino beam. Strips of aluminum foil are placed in the tank perpendicular to the ambient magnetic field (probably the earth's field). Since the aluminum is paramagnetic, it will bind the poles produced in the water. After some length of time, the aluminum foil will be removed from the tank and placed in the detector illustrated in Figure 2 to be searched for monopoles.

Phase III: Search for Bound Poles

If no monopoles are detected in the collection experiments we propose a search for anomalous, low energy gamma ray showers from pole-anti pole deexcitation as suggested by Ruderman and Zwanziger[13]. Low energy shower detectors would be placed downstream from a target located in a proton beam in which the energy was being varied. The shower yield would be monitored as a function of the incident energy. Magnetic excitation of elementary particles would be manifested as a kink in the shower yield spectrum as a function of energy. Of course further evidence would be required to directly associate the kinks with magnetic monopoles. One possibility would be to test the effect of a strong magnetic field on the bound poles near the production point. The field may produce an appreciable change in the gamma ray yield.

IV: Apparatus

In the following we will discuss only the equipment requirements for the first phase of the search. The other two phases will be considered at a later stage after some experience with the accelerator is available.

A. Beam Dumps.

We have considered the relative advantages of three regions in the experimental areas where proton beams interact. Five hundred BeV protons will be dumped in the ex-

ternal beam dump below the Area 1 beam line. This dump will probably receive at most 5% of the maximum beam available in the accelerator. It may be possible to load samples directly into the dump from enclosure C in the primary proton beam, if a 250 ft extension rod system can be fabricated to reach along the beam tunnel. A possible alternative is to add a new penetration from the region over the dump. Use of a monopole conduction channel would eliminate the problem of access.

The Area 2 beam dump will receive a high intensity, 200 BeV proton beam early in the accelerator operation. Access to solid collectors placed in the dump will be possible when the target box cart is removed to the remote handling facility. Use of a partially water-filled dump and a conduction channel might be somewhat more difficult because of the need to couple into the target box cart.

The neutrino target offers one of the best possibilities of a solid collector that operates with a very high intensity, 500 BeV proton beam. The effect of magnetic fields from the nearby focusing elements will have to be considered.

We will continue to investigate the access, total flux and maximum energy expected for all of the areas where an appreciable fraction of the proton beam interacts. We propose to incorporate suitable monopole collector materials in the most logical places for high energy and

high flux experiments.

B. Monopole Conduction Channel.

The channel construction shown in Figure 1 is extremely simple. The solenoid is constructed using a single layer of #14 wire around a 2 cm diameter tube and operates at a current of 10 amps. This provides a field of about 75 gauss and requires only 300 watts of power for a channel 30 ft long. It is possible to curve the channel since the poles are not accelerating but moving at a constant velocity due to the interaction with the air.

C. Detector.

The 25 kgauss solenoid has been designed around an existing cryostat at NAL. The cryostat is presently being used for tests on a 3 ft model of a superconducting quadrupole. It will be available for other applications in about six months. The superconducting group estimates that a suitable solenoid can easily be wound in several months. It appears easy to achieve higher fields if it is necessary to overcome the binding of ferromagnetic collectors.

Although the monopole coincidence counters are thin (15 mils) we anticipate no difficulty in constructing them. Both the required counter materials and associated electronics are now available in the experimental apparatus pool at NAL.

A commercially available film, parylene, can be used for the thin stripper foil shown inside the solenoid.

D. Other Requirements.

We feel that Phase I can be carried out with a small group. It may be desirable to add collaborators with a working knowledge of the beam dumps and some experience with superconducting technology.

Analysis of the search limits should require only a modest effort since very complete and beautiful studies have already been carried out on the earlier accelerator experiments[6,7].

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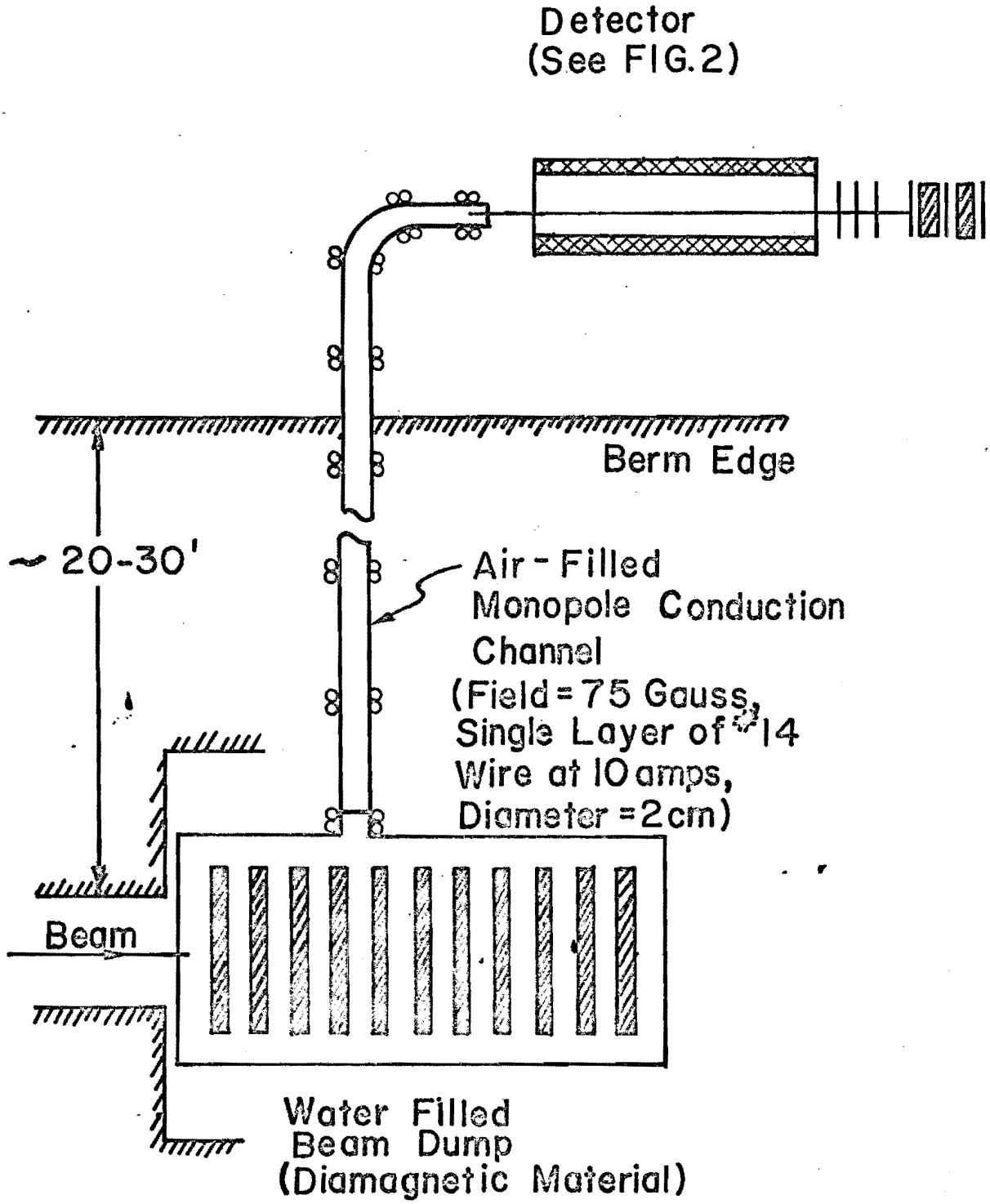
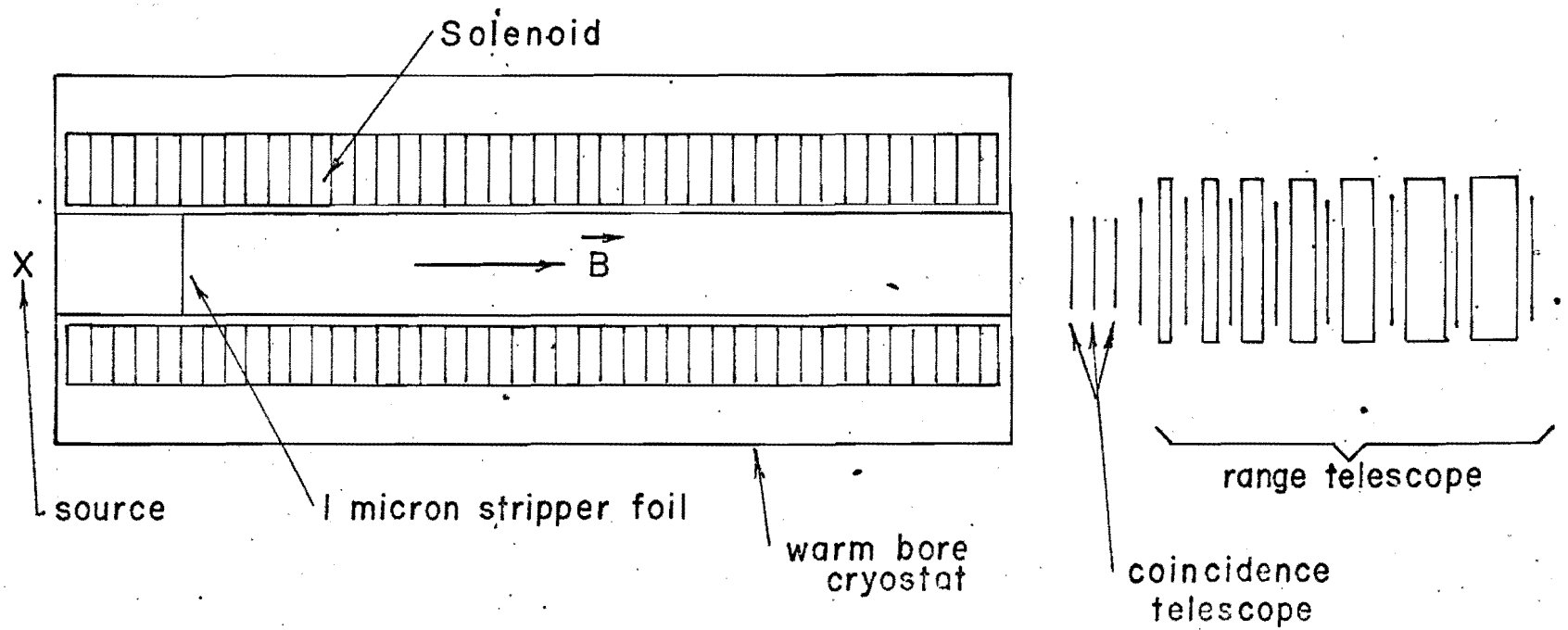


Experimental Arrangement (not to scale)

FIG. 1



25 kG Solenoid in a warm bore cryostat
and monopole detector

FIG. 2

Prop. #76 - Appendix

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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. 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.

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 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.

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. It should be noted, however, that there are several difficulties in establishing mass limits with any production process.

In the first place the effect of pole-pole binding is largely neglected in the calculations of the mass limit. Two classical Dirac charges ($g = e/2\alpha$) one fermi apart are bound with an energy of 6.7 BeV, while two Schwinger leptons ($g_1 = 12g$) have a binding energy of 970 BeV. At least the binding energy plus the mass of the poles must be put into the center-of-mass to produce free poles. The classical binding energy may be modified by a number of effects such as radiation damping[8] and spontaneous breaking of γ_5 symmetry.[9] Ruderman and Zwanziger[10] have proposed that soft photon radiation may be a damping mechanism which diminishes the production of free poles even if sufficient center-of-mass energy is available to create a pole pair.

In the second place, the monopole collection and trapping process may be imperfectly understood since the particle is not observed. 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.

The test of a monopole model must rest on experimental data since the binding, collection, and production processes are not fully understood. To that end we have re-evaluated the existing monopole search data to establish an upper limit for neutrino production of monopoles. The most sensitive terrestrial monopole searches[6,11] use a ferromagnetic collector with a long

collection time 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 susceptible to any uncertainties in the molecular binding properties of monopoles or details in the behavior of the sample surface.

Direct Production Estimate

The muon neutrino flux at the surface of the earth has been evaluated by several groups.[12] 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.[13] 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.[14]

A 95% confidence level on the upper limit is established[15] 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.[17] 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. 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_p = 60 BeV, if the effects of binding are neglected.

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

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

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 if the pole binding is small. Again the electron neutrino cross-section limit will be about a factor of ten larger.

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 binding energy is not too large and 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 binding energy of two Schwinger magnetic leptons is nearly 1000 BeV. In addition, the soft shower mechanism

of Ruderman and Zwanziger would make production even more difficult. 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 Fleischer et al. 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 the field line with a possibly imperceptible kink at the production vertex. In the CERN propane bubble-chamber exposure,[16] 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 4.23×10^{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.

It is interesting to consider less direct tests for a magnetic substructure in elementary particles. As an example, the very high magnetic fields predicted[18] 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. 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[19] 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[20] 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, the normal Zitterbewegung effects should appreciably diminish the splitting.

FOOTNOTE AND REFERENCES

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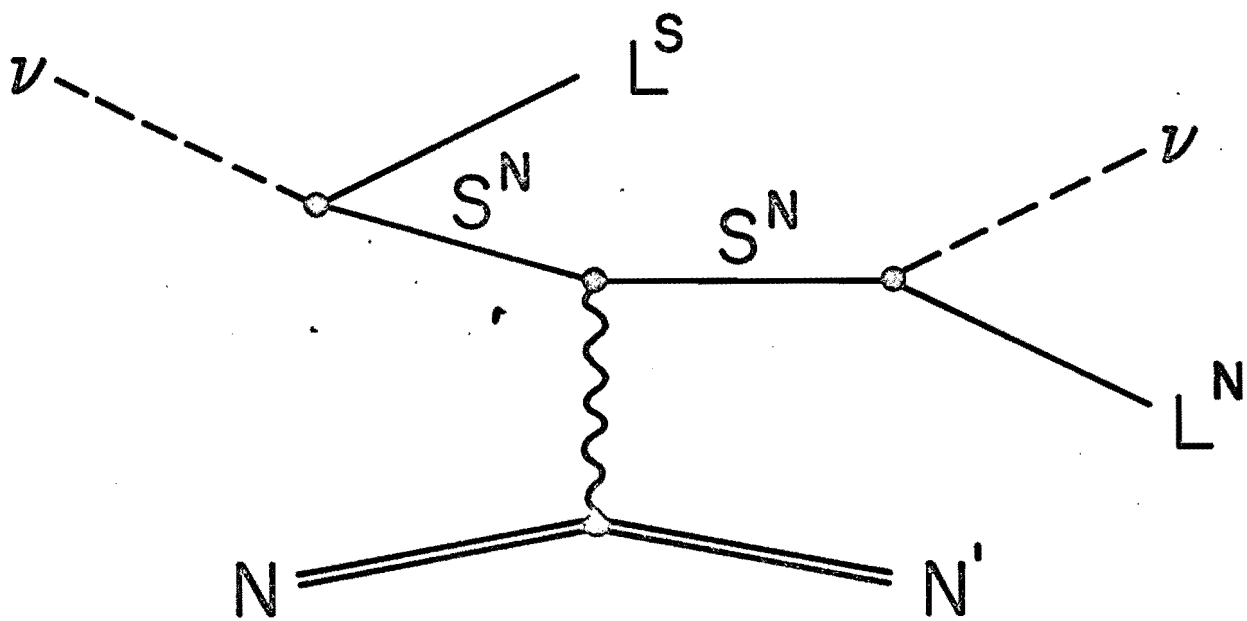
FIGURE CAPTION

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