Search for Magnetic-Monopole Production by 300-GeV Protons

R. A. Carrigan, Jr., F. A. Nezrick, and B. P. Strauss
*National Accelerator Laboratory, Batavia, Illinois 60510**
(Received 20 July 1973)

In a search for magnetic monopoles, a steel beam dump has been exposed to 3.4×10^{16} protons of 300 GeV energy at the National Accelerator Laboratory. The search apparatus employed an 80-kG solenoid 50 cm long capable of extracting a monopole and accelerating it through a series of thin scintillation counters. A monopole would have been identified by its energy loss and range in the scintillators. No monopoles with magnetic charges in the interval from $\frac{1}{6}$ to 24 times the Dirac magnetic charge were found. The upper limit at a 95% confidence level for the cross section per nucleon on iron is 6×10^{-42} cm^2.

There appears to be no compelling reason why an isolated magnetic pole should not exist with magnetic properties analogous to the electrical properties of an electric charge.[1] Dirac's observation[2] that the existence of an isolated magnetic monopole could explain electric-charge quantization added impetus to the interest in magnetic monopoles. This suggestion is certainly one of the most elegant solutions to this problem. An unusual property of the magnetic-monopole–electric-charge system is that it intrinsically violates time-reversal invariance.[3] The discovery of time-reversal violation in 1964 has turned this apparent defect into something of a virtue. Further, Schwinger[4] has suggested that dyons, particles with both magnetic and electric charge, could give rise to an SU_3 algebra. Particle models utilizing dyons have also been developed by Barut.[5]

While there appear to be no overwhelming theoretical reasons to rule out isolated magnetic poles, there are reasonable arguments which suggest that the cross section for production of a pole-antipole pair would be small and require very high center-of-mass energy.[6] For example, to separate a classical Dirac pole pair at an initial separation of 1 F to infinity requires an energy of 7 GeV.

Experimental searches for magnetic poles extend back over many centuries and constitute one of the earliest roots of elementary particle physics.[7] Almost as a matter of tradition, an accelerator on the forefront of development is used to extend the search to the new energy range. Up to this time, the best lower limits on monopole production by protons with energies above 70 GeV have been set by a group of three cosmic-ray experiments.[8-10] The limits from each are roughly comparable while the experiments themselves are somewhat complementary. The previous highest-energy accelerator search[11] has been carried out at Serpukhov with 70-GeV protons.

The experiment described here has not been undertaken with the object of proving or disproving the magnetic monopole conjecture or even attempting to make the most concentrated experimental attack on the problem possible at the National Accelerator Laboratory. Rather, it has been carried out as part of a systematic search for free magnetic monopoles making the fullest possible utilization of the available resources in the early phases of NAL operation.

The basic search strategy has had three assumptions: (1) The range of magnetic charges searched for was between $\frac{1}{6}$ and 24 times the Dirac charge. The lower limit is a factor of 2 lower than the magnetic charge for Kolm's pseudoevent,[9] while the upper limit is two times higher than that allowed for dyons with an electrical charge of $\frac{1}{3}$ in Schwinger's magnetic quantization. (2) The energy-loss properties of magnetic particles in matter obeyed those suggested by Cole, Bauer, Martemianov and Khakimov,[12] and many others, i.e., those of a very heavily ionizing particle with an energy loss approximately $1/\alpha^2$ of a minimum ionizing electrically charged particle. (3) Ferromagnetic binding was assumed as described by Goto, Kolm, and Ford (GKF).[13]

The last two assumptions have been discussed many times. It should be noted that the presence of an additional electric charge (e.g., dyons) would not appreciably affect any of these assumptions since its interaction would be down in electromagnetic strength by a factor of the order of α.

The basic experimental technique consists of bombarding a steel beam dump with 300-GeV protons, then placing pieces of the dump at one end of a high-field solenoid to extract and accelerate any monopoles. Finally, a possible monopole would be detected by high-energy loss and its range in a series of thin scintillators and absorbers. Figure 1 illustrates the apparatus schematically.

The beam dump in this experiment consisted of a stainless steel assembly 127 cm thick along the beam, 1.0 cm high, and 3.7 cm wide. The induced radioactivity in the dump was the major practical problem in carrying out the experiment. For example, the radiation level of the dump was approximately 70 R/h about 30 cm from the dump several days after the irradiation. To ameliorate the problems with radioactivity, the dump was divided into fifty smaller samples (1.0 cm high by 3.7 cm wide by 2.5 cm thick) for ease of handling and insertion into the solenoid. Care was taken that the dump did not accidentally come into contact with any ferromagnetic material or substantial stray magnetic fields. The dump was placed 23 m beyond the 30-cm aluminum production target used for the neutrino and muon beams at NAL. Roughly, one-third of the protons in the external beam pass through the production target without interacting. A magnet downstream deflects these protons onto the monopole dump. Typically, the beam spot size at the dump was 2 mm wide by 3 mm high. The position of the spot and the development of the nuclear cascade in the dump were checked by means of radiography after the exposure.[14] The number of protons incident on the dump was determined by counting the Mn^{54} 303-day half-life activity in the front end of the dump. This technique had been cross-calibrated earlier by comparing to the activity in a copper foil that had been exposed to a known number of protons. The calibration gave $N_p = 3.4\times10^{16}$ protons incident on the dump. Use of the long-lived Mn^{54} activity avoids small corrections having to do with the irradiation history of the dump.

Note that the dump is about seven absorption lengths or fifty radiation lengths thick. Under this circumstance, a full nuclear cascade consisting of pions, kaons, Λ's, neutrons, antiprotons, and γ rays can develop and interact repeatedly. For this reason the monopole production limit established here applies in some sense (after folding in a production model such as that of Hagedorn and Ranft[15]) to all of these particles. This feature is one important reason for employing a dump rather than a production target for a search.

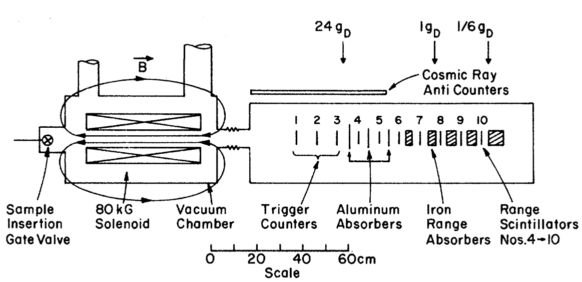

FIG. 1. Schematic diagram of monopole accelerator solenoid and detector system. The arrows indicate stopping positions in the range absorbers of monopoles with 24, 1, $\frac{1}{6}$ Dirac charges. An iron backstop 2.0 cm thick is placed behind the sample to catch any poles of opposite polarity.

After a cooling period to allow for decay of the short-lived radioactivities, the samples from the dump were placed in turn in one end of a 50-cm long, 80-kG superconducting solenoid with a 5-cm-diameter warm bore. The saturation magnetization for the 446 steel used in the dump was 12 kG. For the GKF binding hypothesis, 80 kG is more than three times the field required to extract a pole from the dump sample. The samples were introduced into the evacuated solenoid by means of a gate valve. Care was taken that the entrance path into the gate valve was such that the samples never encountered a field greater than 500 G. The sample was then moved to the center of the solenoid along the solenoid axis by means of a rod attached to a winch. Provision had to be made to overcome the pull of more than 45 kg on the sample at the entrance to the solenoid. Note that the velocity of the pole through the sample is sufficiently fast so that there is no problem concerning the length of time the sample remains in the solenoid.

Any monopoles would have been detected in a series of ten very thin scintillation counters with air light pipes. These counters operated as both dE/dx counters and a range telescope. A series of aluminum and steel range absorbers were interposed between the third and tenth counters. These absorbers were segmented so they could also be inserted in the solenoid. While larger magnetic charges gain energy in the magnetic field in proportion to their charge, they lose energy proportional to their charge squared. Therefore, larger magnetic charges stop earlier than smaller charges, and give correspondingly larger light pulses from scintillators. A monopole with twenty-four times the Dirac charge could just penetrate the first three counters, while one with $\frac{1}{6}$ the Dirac charge would just pass the tenth counter. Note that the entire counter-solenoid system was evacuated to prevent air acting as an energy degrader (or trap for a stopping monopole). Each counter consisted of a 0.25-mm-thick scintillator with an effective area of 5.1 cm by 7.6 cm. A 5.5-MeV Am^{241} source with a shutter mechanism and a light-emitting diode were attached to the end of each counter allowing the counters to be calibrated and their linearities checked. The 5.5-MeV α ray corresponds closely to the energy lost in a counter by a $\frac{1}{6}$-Dirac-charge monopole. Typically, the counter resolution for the 5.5-MeV α was 20% full width at half maximum. In operation, the first two counters had to have their gains readjusted after the magnetic field of the extraction solenoid was activated.

An "event" was triggered by a majority coincidence of the first three counters. This triggered a dual beam scope which displayed the signals from both the anode and a low dynode of the first three counters and the next-to-last dynode of counters four through ten. In addition, a light display was photographed showing which of the anodes of the counters triggered discriminators (thresholds set for $\frac{1}{6}$ Dirac charge), including two larger blanket counters placed above the monopole counters. The appearance of a signal from these blanket counters would have served to flag triggers coupled to cosmic rays. This trigger was very loose. Real "events" would have to satisfy dE/dx and range requirements. In addition it would have been possible to recycle the monopole through the system.

An important feature of the system was the ability to simulate real events with the light pulsers. In view of the expected low signal rate, this was an essential check on the functioning of the apparatus.

With the apparatus set to accelerate north magnetic poles, no events were found which even faintly satisfied the requirement of a monopole signature. From this, the number of protons incident on the dump and the target thickness, a 95% confidence limit can be set on the upper limit of the cross section per nucleon for the production of a monopole by 300-GeV protons using the formula

$$\sigma_N \leq \frac{3\sigma_{pN}}{N_p f} .$$

σ_{pN} is taken as 47.1 mb, the proton-nucleon absorption cross section obtained from the 17.1-cm absorption length in iron determined by Engler *et al.*,[16]; f is an absorption factor which reflects that the proton-monopole cross section is based on the first 20 cm of the dump, i.e., 70% of the protons have been absorbed. This gives $\sigma_N \leq 6\times10^{-42}$ cm^2.

For comparison, the Serpukhov search at 70 GeV established a limit of $\sigma_N \leq 4.2\times10^{-43}$ cm^2. No mention is made of the number of proton traversals of the Serpukhov target but indirect estimates indicate that it was 5×10^{18}. The effective target thickness was somewhat less than the NAL dump. The most recent result from the lunar cosmic-ray search using the entire available lunar sample and a 1000-g/cm^2 mixing depth gives an upper limit for the cross section at 300 GeV ten times higher than this experiment. Figure 2 illustrates the relation of this experimental limit to other recent searches. The abscissa is expressed in monopole mass which is the maximum mass kinematically possible, neglecting pole-antipole binding effects.

This cross-section limit is subject to the following constraints:

(1) Magnetic charge. The magnetic-charge range searched for is between $\frac{1}{6}$ and 24 times the Dirac charge. The limit on the upper charge value was set by the thickness of the first three counters, while the limit on the lower charge was set by the counter thresholds to trigger an event. The transverse dimensions of the solenoid and counters were chosen so that the variation of monopole trajectories with magnetic charge was not a limitation.

(2) Mass. The upper limit for a particle mass produced in pairs on a free proton with 300-GeV protons is 12 GeV, neglecting pole-antipole binding. The apparatus is such that masses below 100 GeV could still be counted, that is, bound states such as a monopole bound to an iron nucleus had trajectories which would still pass through the counters.

(3) Electric charge. This is no constraint on the cross-section limit since it constitutes only a small perturbation on both the orbits and range relations. Monopoles bound to iron nuclei will have different range characteristics but still fall within the detection capabilities of the apparatus.

(4) Monopole lifetime. Since the monopole charge is assumed to be conserved, the daughter product would still be accelerated and detected by the system. If the charge split into less than six products and was initially one Dirac charge or

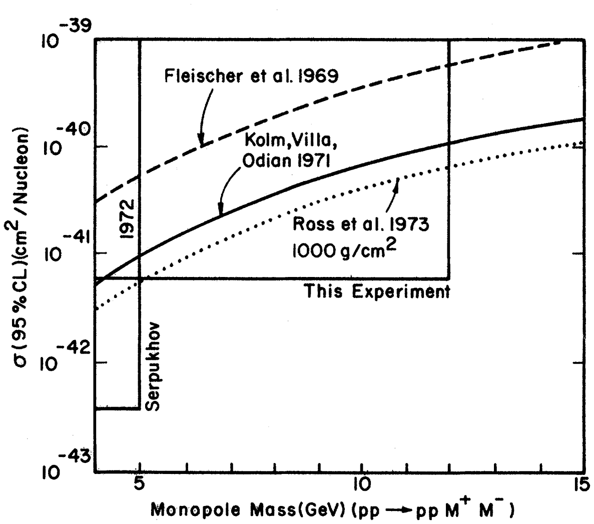

FIG. 2. Upper limit for the cross section of monopole production in p-nucleon collisions. Relevant cross sections based on $A^{2/3}$ are shown. The 12-GeV limit is the result of this experiment. The 5-GeV limit is Serpukhov (Ref.11). The dashed line is Fleischer *et al.* (Ref. 10), the dotted line is Ross *et al.* (Ref. 8), and the solid line is Kolm *et al.* (Ref. 9).

greater, it would still be detected.

The present experimental technique can be extended to proton exposures at least two orders of magnitude larger. The technique is limited primarily by radiation handling difficulties and the length of the exposure.

With few exceptions, there appears to be no real utility in carrying out free-monopole searches in beams of other particles in view of the fact that nearly all particles are produced and interact in profusion in a proton dump. An important exception is a beam of neutrinos. Schwinger has suggested that a magnetic intermediate boson might serve as a medium of exchange in nuclear processes. If so, these magnetic bosons might be produced in neutrino processes along the lines suggested for the normal hypothetical intermediate vector boson. In a previous bubble chamber search and a reevaluation of existing cosmic-ray data,[17] no evidence was found for such a magnetic particle. However, the neutrino beam facilities at NAL offer the possibility of some improvement in the capabilities for such a search.

We wish to acknowledge the help of M. Otavka in carrying out the extraction runs; S. Baker helped perform the radioactivity analyses. R. Stefanski, T. Yamanouchi, R. Orr, and T. Toohig of the Neutrino Laboratory have been most helpful in the execution of the dump exposures.

---

*Operated by Universities Research Association Inc. under contract with the United States Atomic Energy Commission.

[1]R. A. Carrigan, Jr., Nuovo Cimento 38, 638 (1965).

[2]P. A. M. Dirac, Proc. R. Soc. Lond. 133, 60 (1931); Phys. Rev. 74, 817 (1948).

[3]W. C. Carithers, R. Stefanski, and R. K. Adair, Phys. Rev. 149, 1070 (1966).

[4]J. Schwinger, Science 165, 757 (1969).

[5]A. O. Barut, Trieste Report No. IC/73/734, 1973 (unpublished).

[6]J. L. Newmeyer and J. S. Trefil, Phys. Rev. Lett. 26, 1509 (1971).

[7]"*Procul dubio omnes lineae (magneticae) hujusmodi in duo puncta concurrunt sicut omnes orbes meridiani in duo concurrunt polos mundi oppositos*." The quotation is from the *Epistola Petrus Perigrinus de Maricourt De Magnete (1269)*, and may be the earliest recorded observation along these lines.

[8]L. W. Alvarez, P. H. Eberhard, R. R. Ross, and R. D. Watt, Science 167, 701 (1970); R. R. Ross, P. H. Eberhard, L. W. Alvarez, and R. D. Watt, Phys. Rev. D 8, 698 (1973).

[9]H. H. Kolm, F. Villa, and A. Odian, Phys. Rev. D 4, 1285 (1971).

[10]R. L. Fleischer, H. R. Hart, I. S. Jacobs, P. B. Price, W. M. Schwartz, and F. Aumento, Phys. Rev. 184, 1393 (1969).

[11]I. I. Gurevich, S. Kh. Khakimov, V. P. Martemianov, A. P. Mishakova, L. A. Makarina, V. V. Ogurtzov, V. G. Tarasenkov, L. A. Chernishova, L. M. Barkov, M. S. Zolotarev, V C. Okhapkin, and N. M. Tarakanov, Phys. Lett. 38B, 549 (1972); Zh. Eksp. Teor. Fiz. 61, 1721 (1971) [Sov. Phys.—JETP 34, 917 (1972)].

[12]H. J. D. Cole, Proc. Camb. Philos. Soc. 47, 196 (1951); E Bauer, Proc. Camb. Philos. Soc. 47, 777 (1951); V. P. Matemianov and S. Kh. Khakimov, Zh. Eksp. Teor. Fiz. 62, 35 (1972) [Sov. Phys.—JETP 35, 20 (1972)].

[13]E. Goto, H. H. Kolm, and K. W. Ford, Phys. Rev. 132, 387 (1963).

[14]S. Baker, R. Carrigan and F. Nezrick, NAL Report No. NAL-TM 419, 1973 (unpublished).

[15]R. Hagedorn and J. Ranft, Nuovo Cimento Suppl. 6, S1, 169 (1968).

[16]J. Engler, W. Flauger, B. Gibbard, F. Mönning, K. Runge, and H. Schopper, Nucl. Instrum. Meth. 106, 189 (1973).

[17]R. A. Carrigan, Jr., and F. A. Nezrick, Phys. Rev. D 3, 56 (1971).