NEW LIMITS ON THE PRODUCTION OF MAGNETIC MONOPOLES AT FERMILAB

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First results from an experiment (Fermilab E882) searching for magnetically charged particles bound to elements from the CDF and DØ detectors are reported. The experiment is described, and limits on magnetic monopole pair production cross sections for magnetic charges 1, 2, 3, and 6 times the Dirac pole strength are presented. These limits ($\sim$ 1 pb), hundreds of times smaller than those found in previous direct accelerator-based searches, use simple model assumptions for the photonic production of monopoles, as does the extraction of mass limits in the hundreds of GeV range.

1 Introduction

The most obvious reason for introducing magnetic charge into electrodynamic theory is the symmetry thereby imparted to Maxwell's equations. Further, the introduction of fictitious magnetic charge simplifies many calculations, as Bethe and Schwinger realized in their work on waveguides during World War II.[1]

Henri Poincaré first studied the classical dynamics of an electron moving in the field of a magnetic monopole,[2] while J. J. Thomson in lectures at Yale demonstrated that a classical static system consisting of electric (e) and magnetic (g) charges separated by a distance R had an intrinsic angular momentum pointing along the line separating the charges[3]: $\mathbf{J} = \frac{eg}{c}\hat{\mathbf{R}}$. Requiring that the radial component of this angular momentum be a multiple of $\hbar/2$ leads to Dirac's celebrated quantization condition, $eg = \frac{n}{2}\hbar c, \quad n = \pm 1, \pm 2, \pm 3, \ldots$. In fact, Dirac obtained this quantization condition by showing that quantum mechanics with magnetic monopoles was consistent only if this quantization condition held.[4] Thus, the existence of a single monopole in the universe would explain the empirical fact of the quantization of electric charge. Schwinger generalized this quantization condition to dyons, particles carrying both electric and magnetic charge.[5] He further argued that n had to be an even integer (sometimes even 4 times an integer).[5] Thus the smallest positive value of n could be 1 or 2, or 3 or 6 if it is the quark electric charge which quantizes magnetic charge.

2 Experiment Fermilab E882

The concept of the present experiment is that low-mass monopole–anti-monopole pairs could be produced by the proton–anti-proton collisions at the Tevatron. The monopoles produced would travel only a short distance through the elements of the detector surrounding the interaction vertex before they would lose their kinetic energy and become bound to the magnetic moments of the nuclei in the material making up the detector. We have obtained a large portion of the old detector elements (Be, Al, Pb) from the DØ and CDF experiments, and are in the process of searching for monopoles in these materials using an induction detector. A first paper describing our analysis of a large part of the DØ Al and Be samples has appeared.[6]

The model for the production process is that the monopole pairs are produced through a Drell-Yan process, which includes one factor of the velocity β to account for the phase space, and two additional factors of β to simulate the velocity suppression of the magnetic coupling. We use this rather simple model, the best available, because a proper field theoretical description of monopole interactions still does not exist.[7]

Any monopoles produced by the Tevatron are trapped in surrounding detector elements with 100% probability, and will be bound in that material permanently provided it is not melted down or dissolved.[8] Although the theory of binding is also in a crude state, monopole binding energies to nuclei are at least in the keV range, which is of the same order as the energy trapping the nucleus-monopole complex to the material lattice, more than adequate to insure permanent binding (and to preclude the extraction of monopoles from the sample by available magnetic fields).

We can set much better limits than those given by previous direct accelerator-based searches[9] because the integrated luminosity of Fermilab has increased by a factor of about 10^4 to 172 ± 8 pb^{-1} for DØ.

A schematic of the apparatus is available: *www.nhn.ou.edu/%7Egrk/apparatus.pdf.* The Fermilab samples are cut to a size of approximately $(7.5\ \mathrm{cm})^3$ and are repeatedly moved up and down through a warm bore in a magnetically shielded cryogenic detector. The active elements are two superconducting loops connected to SQUIDs, which convert any current in the loops into a voltage signal. In empty space, the persistent current set up in the loop having inductance L by a monopole of charge g passing through it is $LI = 4\pi g/c$. A more exact expression was used in fitting data.

A pseudopole was constructed by making a long solenoid, which could either be physically moved through the detector loop, or turned on and off. It was also attached to an actual sample, so the background due to magnetic dipoles in the sample could be seen. Results of such tests are shown in Fig. 1. This demonstrates that we could easily detect a Dirac monopole.

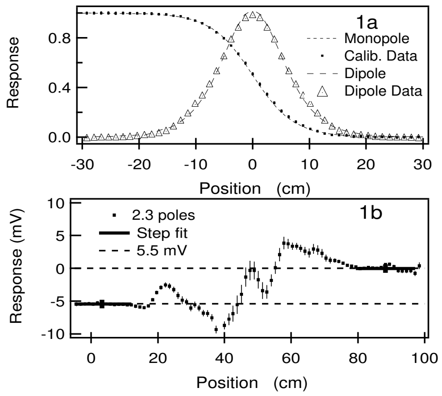

Figure 1. "Pseudopole" curves. a) Comparison of theoretical monopole response to an experimental calibration and of a simple point dipole of one sample with that calculated from the theoretical response curve. b) The observed "step" for a pseudopole current, corresponding to 2.3 minimum Dirac poles, embedded in an Al sample.

The monopole signal is a step in the output of the SQUID after that output has returned from its relatively large excursions resulting from dipoles in the sample. 222 Al and 6 Be samples were analyzed, and the distribution of steps had a mean of 0.16 mV and and rms spread of 0.73 mV, as shown in Fig. 2. We use the Feldman-Cousins analysis[10]: Because 8 samples were found within 1.28 σ of $n = \pm 1$, where 10.4 were expected, we can say at the 90% confidence level that the upper limit to the number of signal events with $n = \pm 1$ is 4.2. We also remeasured those outlying events, and found that all were within 2σ of $n = 0$, so we have no monopole candidates in this set. Similarly, the upper limit to the number of $|n| \geq 2$ events is 2.4.

We use the β^3 modified Drell-Yan production model together with the evolved CTEQ5m parton distribution functions[11] to estimate the acceptance of our experiment, as shown in Table 1. Using the total luminosity delivered to DØ, the number limit of monopoles, the mass acceptance so calculated, and the solid angle coverage of our

Table 1. Acceptances, upper cross section limits, and lower mass limits, as determined in this work (at 90% CL).

Magnetic Charge	$\|n\| = 1$	$\|n\| = 2$	$\|n\| = 3$	$\|n\| = 6$
Sample	Al	Al	Be	Be
$\Delta\Omega/4\pi$ acceptance	0.12	0.12	0.95	0.95
Mass Acceptance	0.23	0.28	0.0065	0.13
Number of Poles	< 4.2	< 2.4	< 2.4	< 2.4
Upper limit on cross section	0.88 pb	0.42 pb	2.3 pb	0.11 pb
Monopole Mass Limit	> 285 GeV	> 355 GeV	> 325 GeV	> 420 GeV

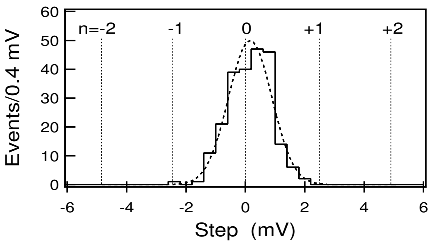

Figure 2. Histogram of steps. Vertical lines define the expected positions of signals for various n.

samples, we can obtain the $p\bar{p}$ cross section limits for the production of monopoles as given in Table 1. These are better by a factor of 200 than the earlier results of Bertani.[9] Using the production model again, we can convert these cross section limits into mass limits, simply by scaling the Drell-Yan cross section by the monopole enhancement factor of $n^2(137/2)^2$. These mass limits, also indicated in Table 1, are some 3 times larger than those of prior searches for accelerator-produced monopoles trapped in matter.[9]

3 Conclusions

This experiment to detect low-mass, accelerator produced magnetic monopoles is continuing. Over the next year, we will analyze the remaining Pb and Al samples from CDF, and extract better limits. In the future, such an experiment carried out using LHC exposures could reach monopole masses of a few TeV.

Acknowledgments

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