Fermi National Accelerator Laboratory

FERMILAB-Pub-77/111-EXP
2000.000

(Submitted to Phys. Rev. D)

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December 1977

Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

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ABSTRACT

In a search for magnetic monopoles produced in high-energy pp collisions, a series of metallic collectors was exposed at an intersection region of the CERN-ISR to an integrated luminosity $Lt \simeq 7.2 \times 10^{37}$ cm^{-2}. The search was sensitive to poles with a mass $m_g \lesssim 30$ GeV. For $m_g < 20$ GeV, the search yielded an upper limit cross section of $\sigma < 1.3 \times 10^{-37}$ cm^2 (95% confidence level) for $0.2 \lesssim g \lesssim 1.2$ Dirac magnetic charges; for $1.2 < g < 24$ the limit is $\sigma \lesssim 4 \times 10^{-37}$ cm^2.

I. INTRODUCTION

Experimental searches for free magnetic monopoles extend back for many years. Since the proposal of Dirac in 1931,[1] searches have been performed at nearly every new accelerator at the frontier of the highest energies. Interest continues in the possibility of finding free magnetic monopoles in spite of negative results from these searches at accelerators and in cosmic rays. Indeed in the last several years there has been wide consideration of a theoretical model suggested independently by 't Hooft and Polyakov.[2] This model contains a very massive magnetic monopole. The mass range suggested by 't Hooft and Polyakov, $M \propto M_W/\alpha$ or 5 to 10 TeV, only seems accessible at a very big accelerator operating as a colliding-beam facility. However, variants of this approach, such as models proposed by Troost and Vinciarelli,[3] have suggested substantially lower masses. These theoreticals models, along with a review of recent searches, have recently been summarized in an extensive magnetic-monopole bibliography covering 1973 to 1976.[4]

Most searches for free poles are based on the hypothesis that they have a relatively large magnetic charge g:

$$g = ng_o = \frac{1}{2}\frac{\hbar c}{e}\, n \simeq \frac{137}{2}\, e\, n, \qquad (1)$$

where e is the elementary electric charge and n is an integer.[1,5] Thus magnetic poles should ionize heavily, should easily be accelerated in magnetic fields, and should be trapped in matter. In "direct" searches magnetic monopoles are searched for immediately after their production, which could possibly occur in high-energy particle collisions.

In "indirect" searches, such as the one described in this paper, the magnetic monopoles produced in high-energy pp collisions are brought to rest in a material, frequently ferromagnetic, where they are assumed to be bound. Later on the pieces are placed in a strong magnetic field, by means of which any pole is extracted and accelerated. Any pole that has been bound in the material is then detected in a series of counters. In the absence of a monopole this type of experiment is capable of yielding stringent upper limits on the pole production cross section since one may integrate the production search over a long time. Note, however, that one has to make some assumptions about the behavior of monopoles in matter.

This paper describes the result of an "indirect" search performed in the Intersecting Storage Rings (ISR) of the European Organization for Nuclear Research (CERN). At present, the ISR provides the largest available center-of-mass energies, thus allowing searches up to very high masses. On the other hand, since the ISR luminosity is considerably smaller than those of conventional accelerators, cross-section upper-limit measurements are several orders of magnitude larger than those determined with fixed-target accelerators.

II. EXPERIMENTAL

The search described in this paper was made in two separate experiments. In the first experiment we used one piece of the I5 vacuum chamber, which was made of 1.8 mm thick stainless steel of the type Avesta-a-SKRN. The piece, about 1 m long, was approximately one-fourth of an intersection region in the direction of beam 2 and covered approximately one-quarter of the solid angle. It had been exposed since the beginning of the ISR operation in 1971 until 1974 to a roughly estimated integrated luminosity of about $Lt \approx 3 \times 10^{37}\ cm^2$.

The second experiment was made under more controlled conditions and when the ISR luminosity had reached and surpassed its design value. The I3 vacuum chamber (1.5 mm thick) was surrounded with segmented pieces of a ferromagnetic steel (446) and sheets of soft iron, covering almost half of the solid angle. The region was free of any strong magnetic fields. The geometry of the collectors in the intersection region is shown in Fig. 1. Near 90° to the direction of the protons, the iron collectors were about 2-cm thick. They were sized in thickness to stop most monopoles with $g \geq 0.3\ g_D$. The segmented pieces were machined at Fermilab to standard sizes of $1 \times 2.5 \times 4\ cm^2$; the sheets were pressed into shape at CERN. (See Fig. 1.) These collectors were left in place around the ISR from March 1975 to May 1976 and received an integrated luminosity $Lt \approx 7.2 \times 10^{37}\ cm^2$ over roughly 2400 hours of machine operation, as illustrated in Table I. For both the vacuum chamber and the iron collector geometries, monopoles could be trapped down to angles of less than 6° relative to the out going proton beam.

After exposure all pieces, sheets, and the vacuum chamber were brought to Fermilab. (All had negligible radioactivity.) In the hot machine shop the soft iron sheets and the vacuum chamber were cut to dimensions smaller than $2 \times 2.5 \times 4\ cm^3$.

The samples were placed in turn inside a copper box, which was then inserted in one end of a 50-cm long, 80-kG, superconducting solenoid, with a 5-cm diameter warm bore.[6] The side of the box facing the solenoid was covered with a soft iron piece 1-mm thick. The iron served as a stopper on any lightly bound monopoles so they would not be accelerated too early in a less desirable field geometry. The saturation magnetization (times 4π) is about 21.6 kG for the soft iron and 12 kG for the 446 steel. In the model of Goto, Kolm and Ford,[7] a field of 80 kG is several times the field required to extract a pole from the sample. For the stainless-steel vacuum chamber a much lower field would have been sufficient for the extraction.

The box was introduced into the solenoid with the help of a rod attached to a winch. Care was taken that the entrance path into the solenoid was such that the samples did not encounter a field greater than 500 G. Provisions had to be made to overcome the pull of more than 50 kG on the sample at the entrance to the solenoid.

A monopole with one unit Dirac charge would be accelerated to an energy of approximately 80 GeV in the magnetic field of the solenoid. It would be detected in a series of twelve scintillation counters, with air light guides. In general these counters were made very thin. The apparatus is shown in Fig. 2. These counters operated both as dE/dx counters and as a range telescope. For this last purpose a series of aluminum and iron range absorbers was interspersed between the third and tenth counters. Magnetic charges should gain energy in the magnetic field in direct proportion to their magnetic charge, while they should lose energy in matter proportional to their charge squared. Therefore larger magnetic charges should stop earlier than smaller ones and give correspondingly larger light pulses from the scintillators. The system was arranged such that monopoles with $24g_D$ could just penetrate the first three counters, while monopoles with 1/15 the Dirac charge would pass the eleventh counter. Further details on the detecting equipment, on its calibration and performance are given in Ref. 6. In this extraction run we added two sheets of plastic detectors (Kodak Nitrocellulose, each of $0.02 \times 9 \times 12$ cm^3) behind counter 3. These foils would be sensitive to monopoles with magnetic charge $g \gtrsim 0.3\ g_D$.[8]

The counter-solenoid layout was set such that we were sensitive to monopoles with magnetic charges in the range $1/15\ g_D < g < 24\ g_D$. A candidate event was triggered by a coincidence of the first three counters for $g > 0.25\ g_D$. For $g < 0.25\ g_D$ the system would have been triggered coincidence between the thicker counters 5, 10, 11. A coincidence triggered a dual beam scope, which displayed the signals from all the counters. In addition a light display was photographed showing which of the anodes of the counters triggered their discriminators (including two large cosmic-ray blanket counters placed above the monopole counters). Some care was taken to preserve the ability of this system to measure energy loss over a wide range of g values. Photographs were taken of fake events using light pulsers to calibrate the system. While the system trigger was very loose, all the counter information was on the scope photograph. Real events would have to satisfy dE/dx and range requirements. In addition it would have been possible to recycle the range absorber in which a pole stopped through the extraction system so that the monopole could be studied further.

The apparatus was set to accelerate north magnetic poles for roughly half of the processed material and south poles for the other half. Roughly 1000 pieces, most weighing eighty grams each, were cycled through the system. The detection device was in operation for event detection for approximately ten hours. In that time the apparatus was triggered five times. This is consistent with the background trigger rate from cosmic rays with the magnet off and no sample in place. None of these five events had even a remote resemblance to a magnetic monopole. Several occurred when no sample was in place. The "least unlikely" candidate had a cosmic-ray anti present, inconsistent pulse height and a very low g value.

III. RESULTS

No monopole candidate was registered. We can thus only estimate an upper limit for the production of monopoles, using the formula

$$\sigma \leq \frac{K}{\frac{\Omega}{4\pi} f \, \Sigma_i L_i t_i \eta_i}, \qquad (2)$$

where we used K=3, to estimate a 95% confidence level. The fraction of the solid angle covered by the collectors, $\Omega/4\pi$, is estimated to be 0.25 for the vacuum chamber case and 0.38 for the iron collectors analyzed. $L_i t_i$ is the integrated luminosity over all runs of the same energy. The fraction of the collector material processed is f, 83% in the case of the iron collectors, and 100% in the case of the vacuum can. The detection efficiency, η_i, was studied using the known geometries and the assumption that magnetic monopoles were produced isotropically in the reaction

$$p + p \rightarrow p + p + G + \overline{G} \qquad (3)$$

and, further, that the available energy was divided among the outgoing particles proportionally to relativistic phase space.[9]

In the first experiment, which analyzed a piece of the vacuum chamber, monopoles with $g \gtrsim 1$ would have been stopped, while those with smaller magnetic charges would have more frequently escaped. The situation was reversed for the collectors of the second run, which were mainly sensitive to low magnetic charges. Table II gives the estimates of the detection efficiencies for the collectors for detecting one of the monopoles in the case of monopoles with 10-GeV mass (the dependence of the efficiency on the monopole mass is rather weak). Note that both a north and south monopole should be produced. This improves the detection efficiency because it offers two opportunities to collect the products of an event.

Figure 3 illustrates, schematically as a function of the magnetic charge the cross-section limits obtained in this experiment compared to previous ones. Figure 4 gives again schematically, the cross-section limits as a function of monopole mass.

We conclude that for masses smaller than 20 GeV we have established an upper limit at the 95% confidence level on the cross section of $\sigma \lesssim 1.3 \times 10^{-37}\ cm^2$ for $0.2 \lesssim g \lesssim 1.2$, and $\sigma \lesssim 4 \times 10^{-37}\ cm^2$ for $1.2 < g \lesssim 24$ for the production of magnetic monopoles in proton-proton collisions at ISR energies.

One observation concerning binding should be made. The stainless-steel vacuum can is not ferromagnetic. Perhaps the magnetic monopoles did not remain embedded in the stainless steel. If they did not, then in the second phase of the experiment poles with similar characteristics would have moved out into the ferromagnetic collectors so that the high g values expected to be stopped in the vacuum chamber would have been collected in the iron collectors during the second phase. Note that the steel vacuum chamber was thinner in the second phase so that both g ranges have been covered with some overlap.

This experiment has improved on the earlier ISR search by an order of magnitude. Nevertheless it still does not set as stringent a limit as cosmic-ray experiments, which on the other hand require further assumptions.

The higher energy storage rings now proposed at several Laboratories, should have larger luminosities than the ISR. Since integrated cosmic-ray cross sections drop roughly as $1/E_{lab}^2$ it should be possible for a future colliding-beam machine to outdistance the cosmic-ray limits.[14]

We would like to thank the ISR staff for the smooth operation of the accelerator and F. Bonaudi, G. Kantardjian, and their crews for providing excellent supporting facilities. F. A. Nezrick's participation in the planning and early phases of the experiment was most helpful.

REFERENCES

[1]P. A. M. Dirac, Proc. Roy. Soc. Lond. 133, 60 (1931).

[2]G. 't Hooft, Nucl. Phys. B79, 276 (1974). A. M. Polyakov, JETP Letters 20, 194 (1974).

[3]W. Troost and P. Vinciarelli, CERN Th. 2195 (1976).

[4]R. A. Carrigan, Jr., Magnetic Monopole Bibliography 1973-76, Fermilab Report FERMILAB-77/42, January 1977.

[5]E. Amaldi and N. Cabibbo, "On the Dirac Magnetic Poles", in Aspects of Quantum Theory, (Cambridge, 1972). Ed. A. Salam.

[6]R. A. Carrigan, Jr., F. A. Nezrick, and B. P. Strauss, Phys. Rev. D8, 3717 (1973) and Phys. Rev. D10, 3867 (1974).

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

[8]G. Giacomelli, A. M. Rossi, G. Vannini, A. Bussiere, G. Baroni, S. Di Liberto, S. Petrera and G. Romano, Nuovo Cimento 28A, 21 (1975).

[9]M. Ageno and E. Amaldi, Statistical Computation of the Momentum Spectra of Monopoles Produced in Paris in Nucleon-Nucleon Collisions, Internal Report Istituto Superiore di Sanita, Roma, DT/60/15 and DT/60/16 (1960).

[10]I. I. Gurevich, S. K. Khakimov, V. P. Martemianov et al., Phys. Lett. 38B, 549 (1972).

[11] R. L. Fleischer, H. R. Hart, I. S. Jacobs, P. B. Price, W. M. Schwarz, and F. Aumento, Phys. Rev. 184, 1393, 1398 (1969)

[12] H. H. Kolm, F. Villa, A. Odian, Phys. Rev. B4, 1285 (1971).

[13] R. R. Ross, P. H. Eberhard, L. W. Alvarez, R. D. Watt, Phys. Rev. D8, 698 (1973).

[14] G. Giacomelli and A. Thorndike, Proc. of the 1975 Isabelle Summer Study, VII, 1975. R. Carrigan, Proc. of the 1977 Fermilab Summer Study, 1977

Table I-Integrated luminosities to which the samples were exposed from March 1975 till May 1976

P_{beam} (GeV/c)	E_{cm} (GeV/c)	Lt^{a} ($\times 10^{35}$ cm^{2})
11.7	23.3	2.4
15.4	30.6	21
22.5	44.6	25
26.7	53.0	579
31.6	62.7	19
asymmetric		1.0
TOTAL		647.4
Including technical runs		720

[a]Note that the segmented collectors were removed a few months earlier than the solid iron collectors. This results in a slightly lower overall average luminosity.

Table II. Estimated detection efficiencies for detecting one of the two monopoles with a mass of 10 GeV produced in reaction (3)

E_{cm} (GeV) / g	45	53	63
0.2	1	1	1
0.6	0.95	0.97	0.98
1.0	0.7	0.84	0.9
1.4	0.2	0.4	0.5

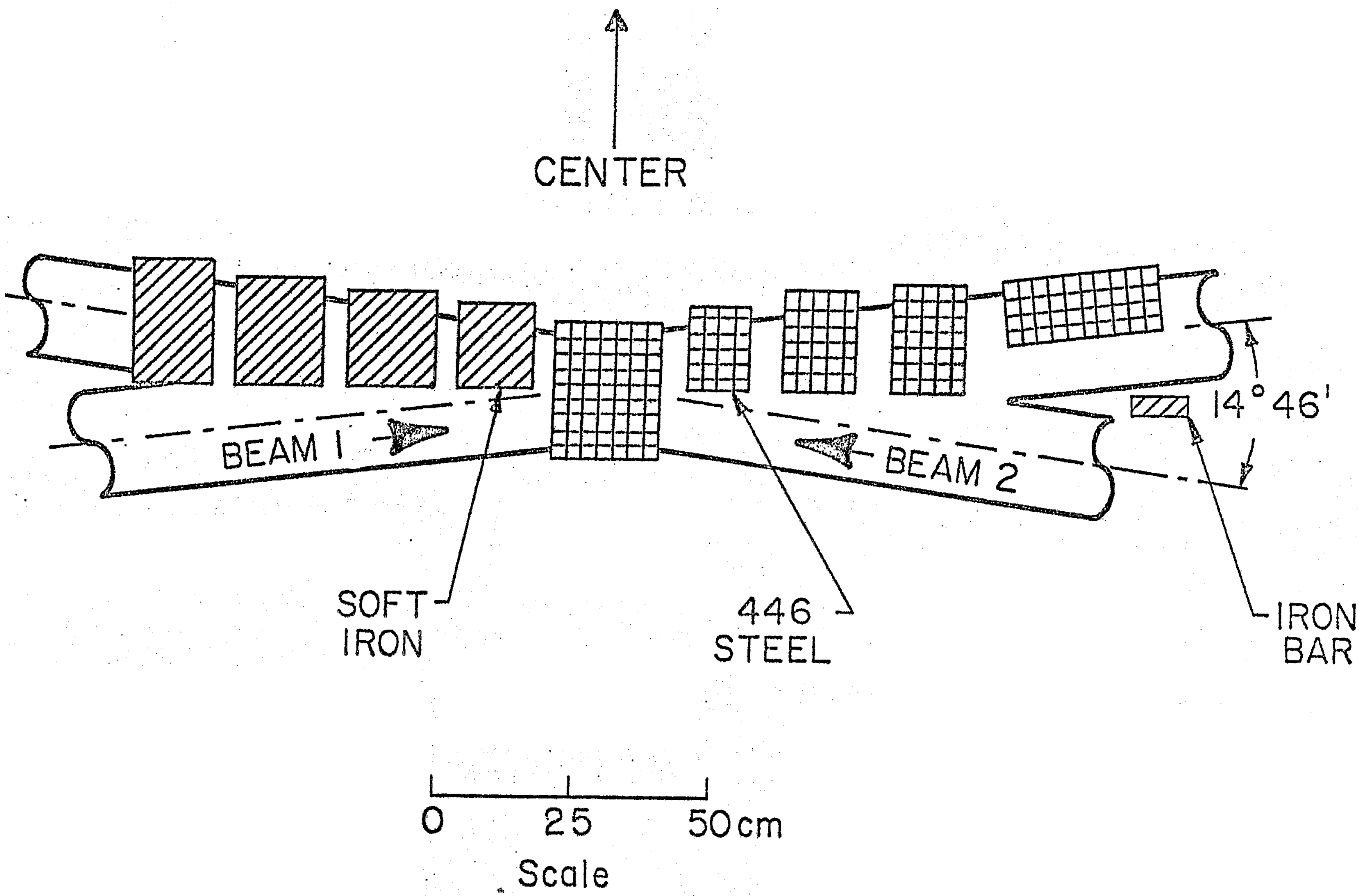

Fig. 1. Configuration of ferromagnetic monopole collectors at the I3 intersection region of the ISR.

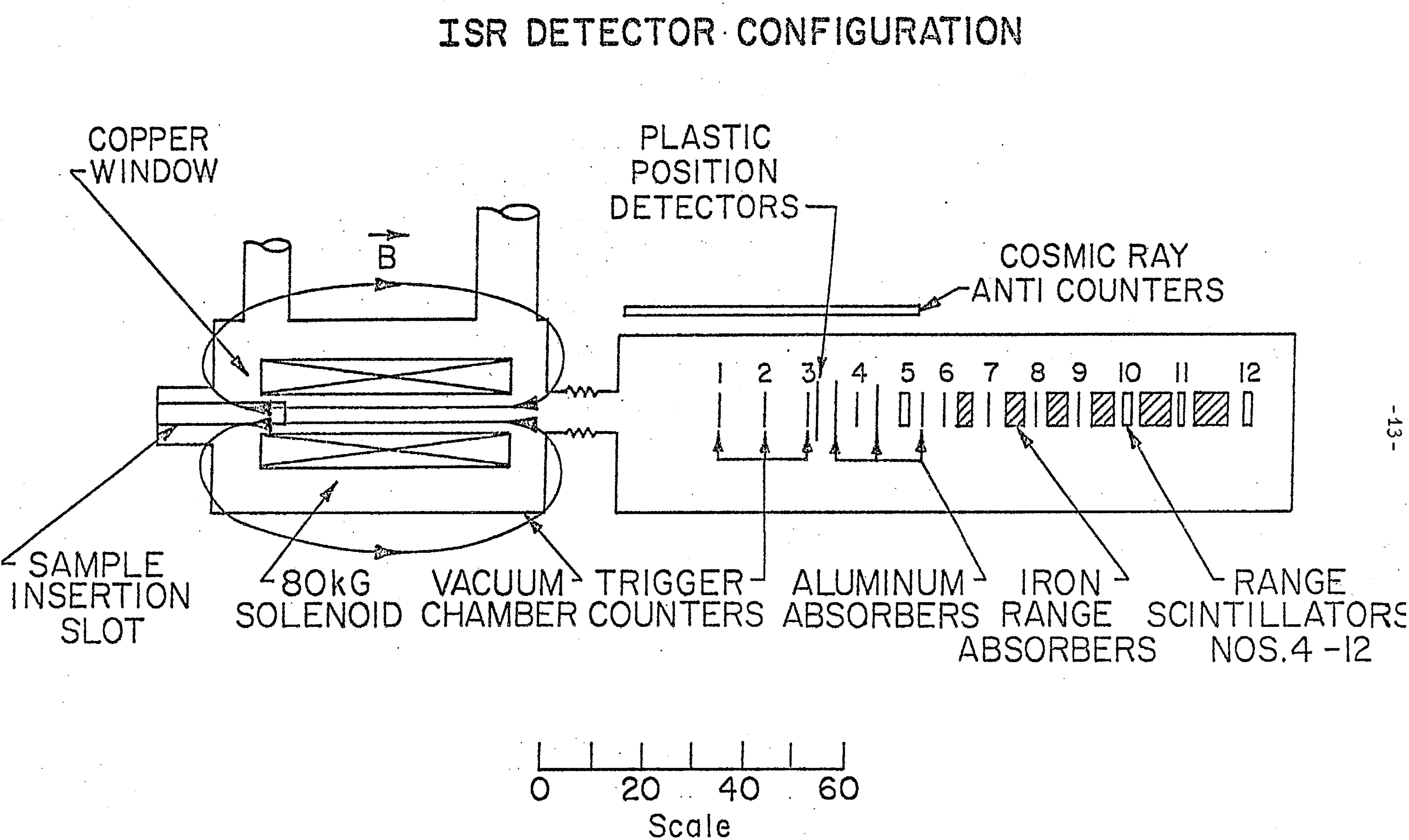

Fig. 2. Monopole detector system. Monopoles with $g = 4g_D$ will stop in 5, $2g_D$ in 6, $0.8g_D$ in 8. The light from 4 is attenuated by 250 to measure ionization for monopoles with $g > 4g_D$.

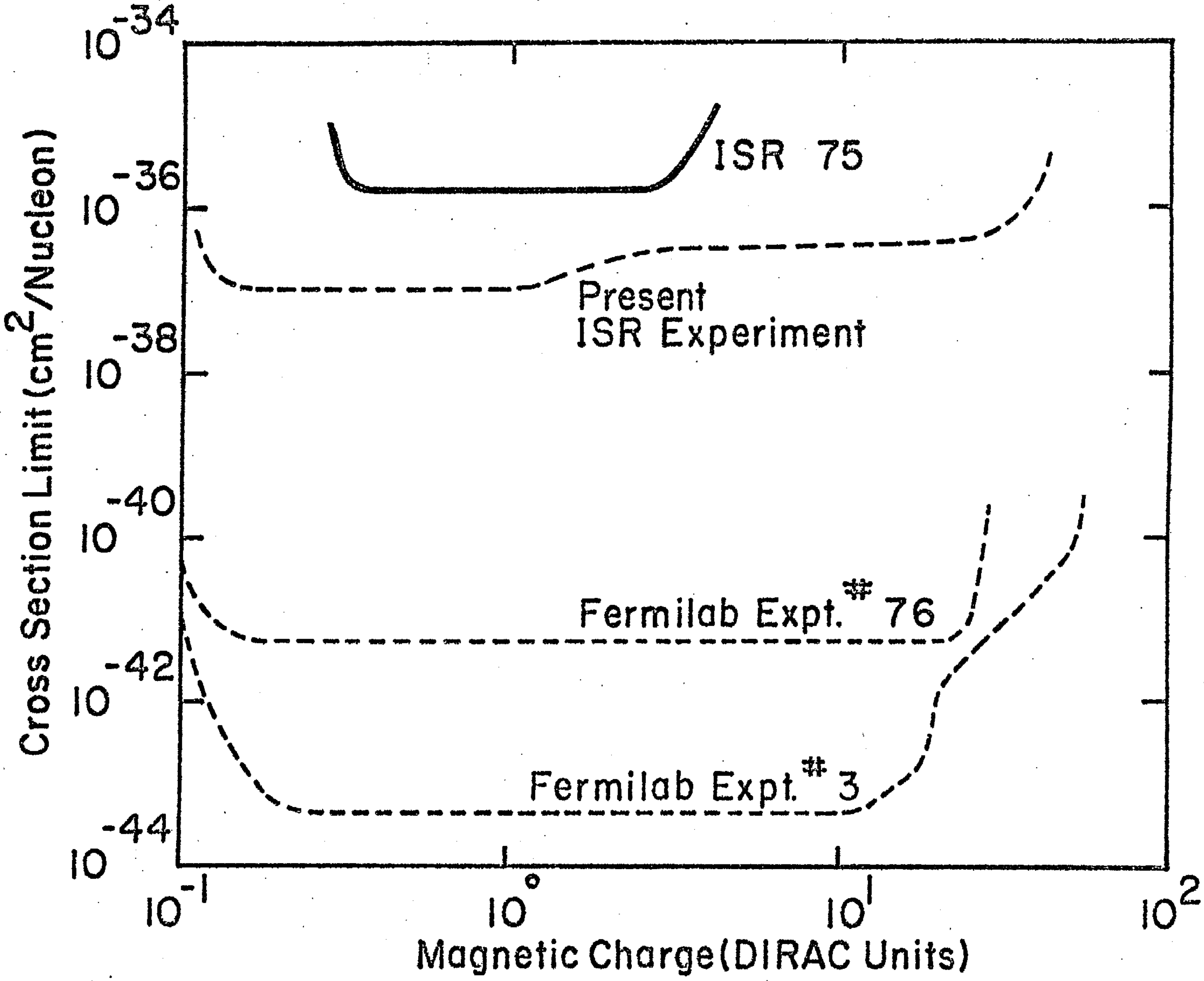

Fig. 3. Compilation of some upper limits for monopole production plotted versus their magnetic charge. Solid and dashed lines refer to "direct" and "indirect" measurements (3, 8, 10-13).

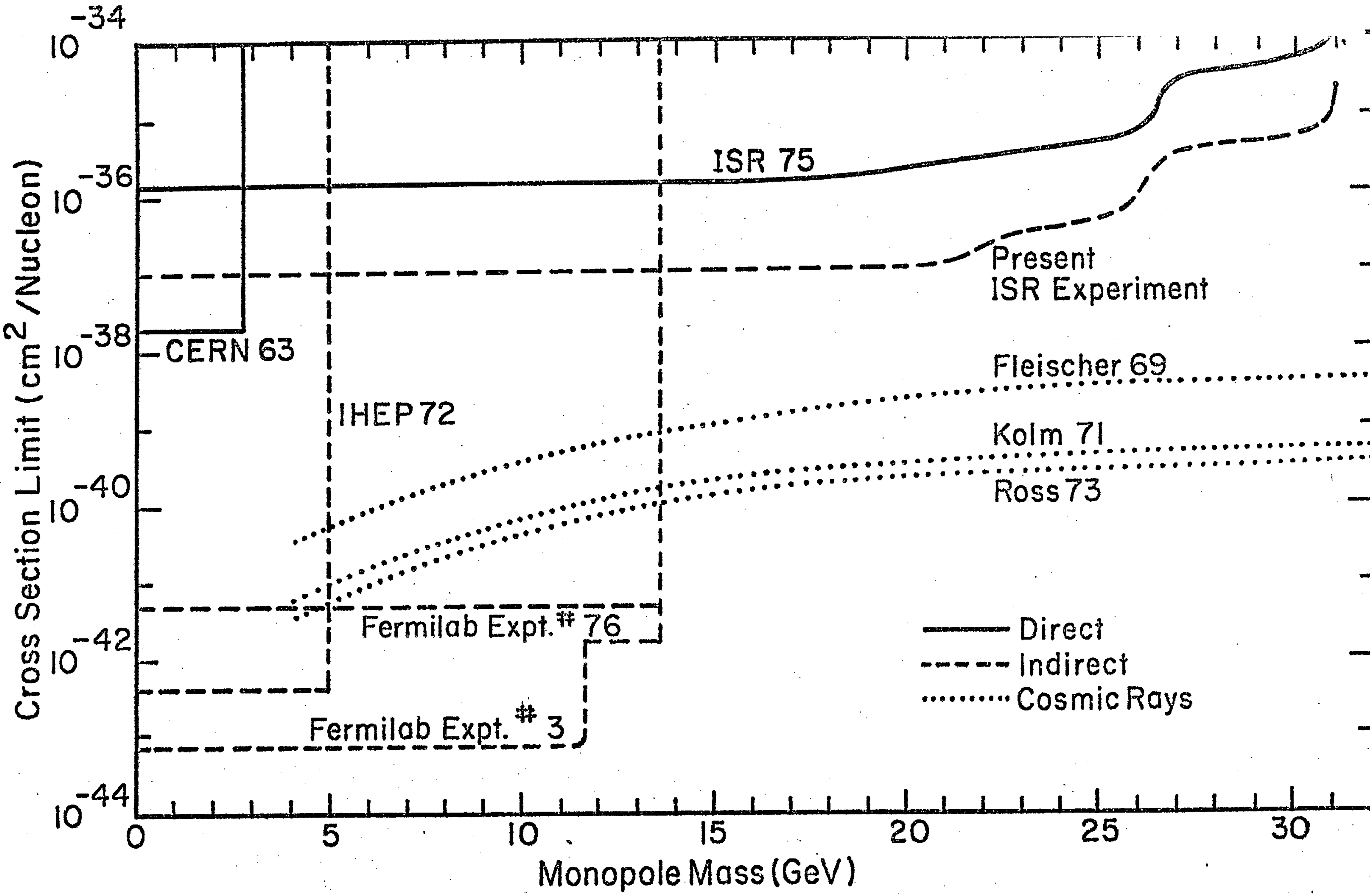

Fig. 4. Compilation of the recent upper limits for magnetic-monopole production (3, 8, 10-13). Solid and dashed lines refer to "direct" and "indirect" measurements respectively at high-energy accelerators; dotted lines refer to cosmic-ray experiments.