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Search for Magnetic Monopoles at the CERN-ISR with Plastic Detectors.

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Summary. — A search for Dirac's magnetic monopoles produced in pp collisions was performed at the CERN-ISR employing plastic detectors. The search was sensitive to poles with a mass $m_g \leqslant 30$ GeV. For $m_g < 20$ GeV and a magnetic charge $0.4g_0 < g < 2.5g_0$ the search yielded an upper limit on the production cross-section of $\sigma < 2 \cdot 10^{-36}$ cm^2 (95% confidence level).

1. – Introduction.

Since the first proposal by Dirac in 1931 [1], many searches for magnetic monopoles have been performed, employing a variety of direct and indirect methods, all of which have yielded negative results.

The searches for free poles are based on the hypothesis that they should

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

have a large magnetic charge g, according to the following relationship:

$$g = ng_0 = \frac{1}{2}\frac{\hbar c}{e} n \simeq n \frac{137}{2} e \,, \tag{1}$$

where e is the elementary electric charge and n is an integer, which in the original proposal could assume the values $n = 1, 2, 3, \ldots$; according to other authors n should be a multiple of 4 [2,3]. If the elementary charge is that of fractional-charge quarks, then g_0 in (1) would be three times larger. There is thus some uncertainty in the minimum allowed value of g; but even $n = 1$ implies a large magnetic charge and thus large effects. Because of the uncertainty in n, it is clear that searches for magnetic monopoles have to be designed in order to be sensitive to as large a range in n as possible, even for noninteger values and for $n < 1$.

Because of the large g value, magnetic poles are expected to have large masses. Theoretical estimates of the cross-section for monopole production are difficult to make because of the large value of g, and thus of the coupling constant of poles to the electromagnetic field, $g^2/\hbar c \simeq 34.2$; this prevents the use of any perturbation calculation.

The methods employed for searches for free magnetic poles may be classified into two groups:

i) direct detection of monopoles immediately after their production in high-energy collisions;

ii) indirect searches, where monopoles are searched for long after their production.

Experiments of the second kind yield considerably better upper limits, since one may integrate the production over a long time; but one is forced to make a number of assumptions about the behaviour of monopoles in matter.

This work describes the results of a direct search for free magnetic monopoles performed at the Intersecting Storage Rings (ISR) of the European Organization for Nuclear Research (CERN). The ISR provides large c.m. energies, thus allowing searches up to very high masses (up to 30 GeV). On the other hand, since its luminosity is considerably smaller than those of conventional accelerators, it only allows cross-section measurements several orders of magnitude larger. Magnetic monopoles, assumed to be produced in high-energy proton-

(2) J. SCHWINGER: *Phys. Rev.*, **144**, 1087 (1966); **151**, 1048 (1966).
(3) E. AMALDI and N. CABIBBO: *On the Dirac magnetic poles*, in *Aspects of Quantum Theory*, edited by A. SALAM (Cambridge, 1972); E. AMALDI: *On the Dirac magnetic poles*, in *Old and New Problems in Elementary Particles*, edited by G. PUPPI (New York, N. Y., 1968).

proton collisions, should have been detected with plastic detectors immediately after their production.

The experimental technique is described in Sect. 2. The results are presented and discussed in Sect. 3.

2. – Experimental.

The present search was made in two runs, the first of which was performed during the period August-December 1973 and the second during the period March-October 1974 (see Table I).

TABLE I. – *Integrated luminosities of the two exposures.* These values correspond to those of «physics» runs. About $(10\div20)\%$ more luminosity was obtained in practice during machine development and «physics preparation» runs.

$E_{c.m.}$ (GeV)		23.6	30.8	45.0	53.2	62.8
Lt (10^{34} cm^{-2})	exposure 1	12	5	153	169	2
	exposure 2	10	47	113	263	30

Twelve stacks of plastic detectors were placed around the intersection region I1 of the ISR. Each stack consisted of 10 plastic sheets, each 200 μm thick, with a surface of (9×12) cm^2. The third and fifth sheets of each stack were of Makrofol-E, and the eight others of nitrocellulose. The 10 sheets of each stack were positioned on a support by means of three pins. This reference made it possible to follow tracks from one sheet to another with an uncertainty of $(20\div30)$ μm. The lay-out of the experimental arrangement is shown in Fig. 1.

The solid angle covered by the detectors was $\Omega\simeq3.5$ sr; the accepted angular range was $30°\leqslant\theta\leqslant90°$. The only material between the crossing region and the first plate was the 0.18 mm stainless steel of the vacuum chamber.

Each plastic detector has its typical detection threshold: particles which ionize less than the threshold value are not detected at all. Nitrocellulose sheets are sensitive to particles which ionize more than 0.8 GeV/g cm^{-2}, while the less well established threshold for Makrofol-E is around 3.5 GeV/g cm^{-2}. The ionization energy loss of a monopole should be

$$(2)\qquad \left(\frac{dE}{dx}\right)_{\text{pole}}=\beta^2n^2\frac{g_0^2}{e^2}\left(\frac{dE}{dx}\right)_{p},$$

where $(dE/dx)_p$ is the ionization energy loss of a proton with the same velocity β. For $\beta\simeq1$, $(dE/dx)_{\text{pole}}\simeq 9n^2$ GeVg^{-1} cm$^2\simeq4700n^2$ times the ionization of minimum ionizing particles. Nitrocellulose sheets are thus sensitive to relativistic monopoles with $n\geqslant0.3$, while Makrofol-E is sensitive to $n\geqslant0.7$. Nonrelativistic monopoles ionize less because of the factor β^2 in eq. (2). The tracks are developed by means of a chemical etching that proceeds preferentially along the particle trajectory with a velocity V_T, larger than the general dissolution velocity V_s of the plastic in bulk. For more details we refer to a technical report (4).

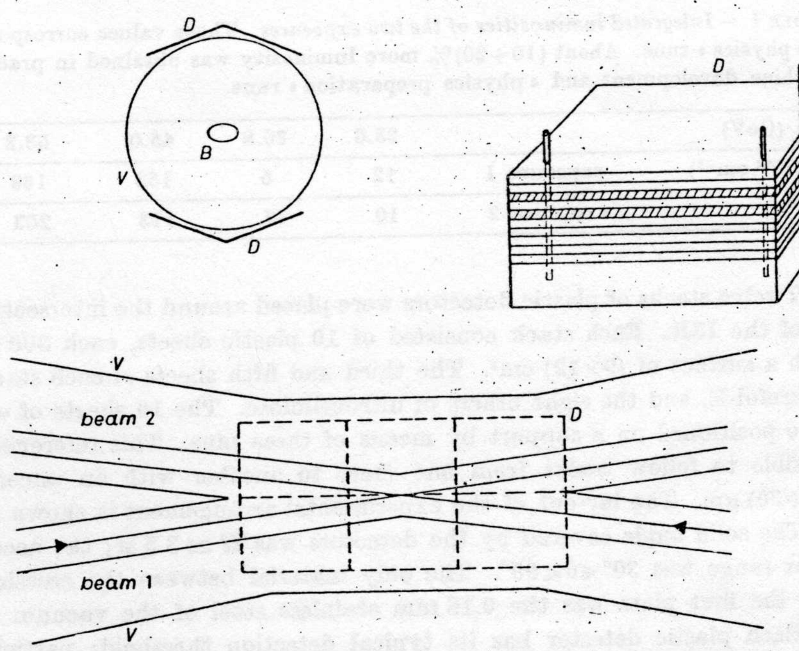

Fig. 1. – **Illustration of the experimental lay-out of the exposures at the ISR and of the structure of each stack:** B **beams,** V **vacuum chamber,** D **detector.**

The nitrocellulose sheets were etched in a NaOH solution 6N at 50 °C for 60 minutes. The etch is long enough to ensure that the track left by a monopole crossing the 0.2 mm thickness of the sheet would be completely visible whatever its angle of incidence within those geometrically possible. Thus we could use as a scanning condition the fact that a monopole candidate corresponds to a track which crosses at least the first nitrocellulose sheet (see Fig. 2).

Because of the high dE/dx threshold values, plastic detectors may be used in a large background of minimum ionizing particles. The background limit is in fact given by nuclear fragments of low energy, with $Z > 2$, produced by interactions of the incoming particles. Measurements have shown that about 10^5 protons were needed to produce one visible track at the surface of the nitro-

(4) G. Baroni, S. Di Liberto, S. Petrera and G. Romano: Nota Interna No. 595, Istituto di Fisica dell'Università, Roma (1974).

cellulose sheets; the corresponding figure in Makrofol-E is about 10^7 protons. In the etched plates these fragments yield a general background which shows up as randomly oriented tracks. The background tracks appear only at the two surfaces of the sheets (in our second stack we had about 10^6 tracks per cm^2

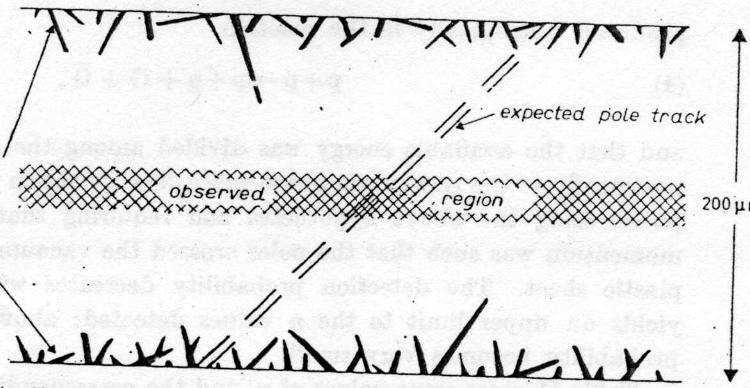

Fig. 2. – Illustration of the scanning procedure of the nitrocellulose sheets. The illustration shows several background tracks, a monopole candidate and the scanning region.

in the nitrocellulose sheets). On the average these tracks do not penetrate farther than 15 μm, with a most a few tracks up to (40÷50) μm. Consequently, the scanning was performed by focusing in a region between the two surfaces of the sheet and looking for tracks crossing the whole thickness (see Fig. 2). This kind of area scanning is very fast, because of the absence of background tracks in this region. Standard optical microscopes using 26×, 10× were used.

3. – Results.

No monopole candidate was found in the scanning of the first nitrocellulose sheets of each of the 24 stacks. We can thus only estimate an upper limit for the production cross-section of monopoles, using the formula

$$\sigma \leqslant \frac{K}{(\Omega/4\pi)\sum_i L_i\, t_i\, \eta_i}\,. \tag{3}$$

We use $K = 3$, which means a confidence level of 95%; $\Omega/4\pi$ is the fraction of solid angle covered by the detectors; $L_i t_i$ is the integrated luminosity over all runs of the same energy; η_i is the detection probability that a monopole will reach the detectors, computed assuming that magnetic monopoles were produced isotropically in the reaction

$$p+p \to p+p+G+\overline{G}, \tag{4}$$

and that the available energy was divided among the outgoing particles proportionally to the relativistic phase-space. The detection probabilities were computed using the above hypotheses and requiring that the lower detectable momentum was such that the poles crossed the vacuum chamber and the first plastic sheet. The detection probability decreases with increasing n. This yields an upper limit to the n values detected: above $n=3$ the detection probability becomes very small.

Table II gives some values of η_i and the corresponding upper limits for the production cross-section of magnetic monopoles as a function of monopole mass and charge ($n=1, 2$).

TABLE II. – *Upper limits for the production cross-section for free monopoles* (95% confidence level). The Table also gives the probability of detection η as a function of monopole mass for two values of n ($n=1$ and $n=2$).

		$E_{c.m.}$ (GeV)			
		45.0	53.2	62.8	σ (10^{-36} cm²)
	m_g/m_p	η (%)			
$n=1$	5	94	96	98	1.5
	10	94	96	98	1.5
	20	56	85	94	1.9
	25	0	57	90	3.9
	30	0	0	61	54
$n=2$	5	76	84	89	1.8
	10	68	79	87	1.9
	20	0	23	68	8.8
	25	0	0	40	83

Figure 3 shows the limits given in the present work together with those of other authors. It appears that our limits in cross-section are poorer, but they extend to a larger mass interval. Furthermore their computation does not require any hypothesis about the behaviour of monopoles in bulk matter. The technique used would allow us to reach better cross-section limits if higher integrated luminosities were available.

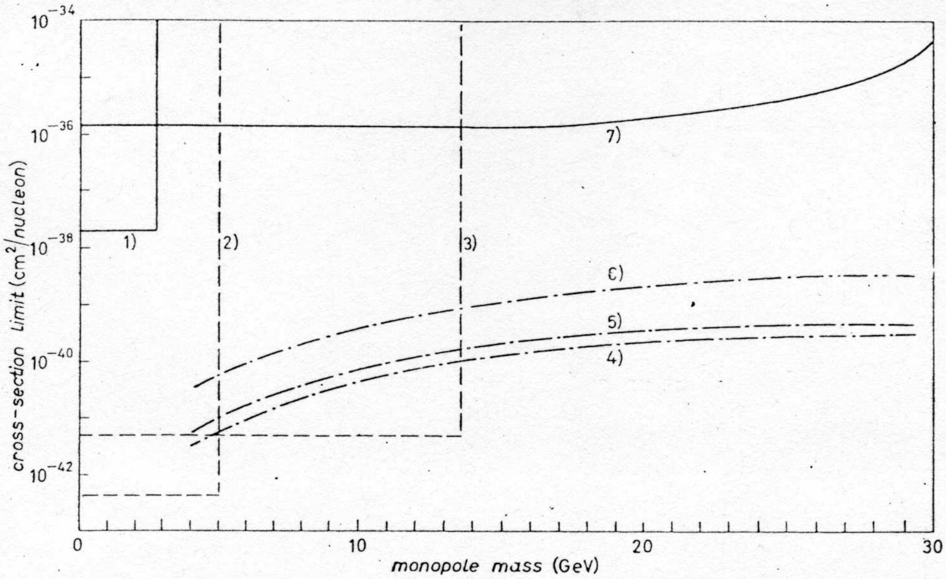

Fig. 3. – Compilation of the recent upper limits for monopole production (ref. (3,5-9)). Solid and long-dashed lines refer to direct and indirect measurements, respectively, at high-energy accelerators; dash-dotted lines refer to cosmic-ray experiments: 1) CERN 63, 2) IHEP 72, 3) FERMILAB 74, 4) ROSS 73, 5) KOLM 71, 6) FLEISCHER 69, 7) present experiment.

We conclude that the cross-section for the production of free magnetic monopoles with i) masses smaller than 20 GeV and ii) n values in the range $0.4 < n < 2.5$ is smaller than $2 \cdot 10^{-36}\ \text{cm}^2$ (95% confidence level).

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