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SEARCH FOR DIRAC MAGNETIC POLES

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In 1931 Dirac(1) showed that one can construct a first quantization theory which contains, as sources of the electromagnetic field, point magnetic poles besides point electric charges. The most peculiar aspect of Dirac's papers is that the value of the magnetic poles does not appear as a new universal constant, introduced in the theory by borrowing its value from the experiments, as we do in all present theories for the value of the elementary charge. The value of Dirac's poles, if they exist, should necessarily be integral multiples n $(n = 0, \pm 1, \pm 2, \ldots)$ of an elementary pole g which is expressed in terms of e, $\hbar$ and c by the relationship

$$\frac{g}{e} = \frac{1}{2} \frac{\hbar c}{e^2} = \frac{137}{2} \tag{1}$$

Dirac theory, although very suggestive from many points of view, is not at all complete; even to-day thirty years after the first Dirac paper, is not clear how one should procede in order to perform the second quantization of the electromagnetic field, when magnetic point sources are present besides electric point charges.

Many rather subtle questions can be debated about the possibility of developing such a theory to its end. Since, however, the possible existence of Dirac magnetic poles does not contradict any well established law of nature, many authors have proposed experiments in order to search for poles either in the cosmic radiation, or among the secondary particles produced in high energy collisions.

The most complete, among all these papers, is that by Bradner and Isbell(2), to which we refer for the quotation of previous works. These authors performed a series of experiments with the Bevatron at the Radiation Laboratory from which they arrive to the conclusion that if Dirac poles of mass smaller or equal to the protonic mass, exist, they are produced with a very small cross section: the upper limit for the cross section for production of pairs of poles in proton-nucleon collision, ranges for three different types of experiments between 10^{-35} and 10^{-40} cm^2.

Since the greatest mass of particle made in pairs by collision of 27 GeV protons on nucleons, is 2.94 proton mass(3), it was felt interesting to extend the search for Dirac poles to the energies provided by the CERN PS.

It may be recalled at this point, that Dirac theory does not make any prediction about the mass of the poles. The value

$$m_g = 2.55\ m_p$$

is however often considered as a kind of reference value, since it corresponds to a classical radius of the poles equal to the classical radius of the electron. Poles of lower mass are expected to have correspondingly larger linear dimensions.

Following these lines of thoughts, two sets of experiments have been set up at CERN; one with counters by Giacomelli et al.(4); the other with nuclear emulsions technique by our group. In both types of experiments one makes use of the very large energy loss undergone by poles moving at high velocity through matter, which follows by simple semiclassical arguments from the value of g given by the Dirac's relation (1).

Here we report on the results we have obtained until now with emulsions. Similar results have been obtained by the Giacomelli group as well as by two groups working at Brookhaven along somewhat similar lines(5).

The details of the experiments can be understood by keeping in mind the main properties of poles:

a) They would have very high energy loss by ionization: at high velocity the ionization of a pole is expected to be 4,700 times the minimum ionization produced by a particle of charge e.

b) They would gain 20.5 MeV per centimeter by the accelerating force of a kiloersted field.

c) They would be repelled by diamagnetic substances and attracted by paramagnetic substances. The work necessary to push a pole into a diamagnetic substance such as graphite is estimated to be slightly less than one tenth of an eV, while the extraction work from a paramagnetic crystal such as chromuim can amount to few tens of eV.

d) As a consequence of the paramagnetism of oxygen a pole in gas would tend to form a globule of oxygen molecules which is expected to involve between 6 and 70 molecules.

Type II experiment

Fig. 1 shows the experimental arrangement used in type II experiment. A graphite target 3.3 g/cm^2 thick (2.06 g/cm^3) was placed in the 27.2 GeV circulating proton beam of the PS. On each accelerator pulse the magnetic field in the 108 cm long solenoid was raised to 2.1 kilooersted in the center of the coil before the target was erected. The field remained on for a flattop of 600 milliseconds, and the target remained erected for approximately 30 milliseconds each pulse. The tip of the target broke off sometime during the bombardment so we do not know whether the solenoid field was 800 or 310 oersted at the surface of the target (Table 1). If the internal potential fluctuations in the graphite (and oxygen in the target) are less than about 0.7 eV(6), poles would be pulled to the surface by the applied magnetic field. They would be removed from the graphite by the field, if their surface binding is so small ($\lesssim 0.8$ eV)(7) that they can diffuse out of the target surface in the time - during the run - that the field was applied in the useful direction ($t < 3\ 10^{-2}$s); otherwise they would stay bound there until experiment I is performed (see below).

Since carbon is a diamagnetic substance we expect that the poles would be repelled from it, apart from the effect of the oxygen molecules adsorbed on the graphite surface; the occlusion binding energy is expected to be between 0.1 and 0.2 eV per molecule.

The poles escaping into the vacuum from the graphite would be accelerated by the applied field. Their velocity upon striking the approximately 0.5 μ thick plastic foil would be sufficient to strip the oxygen and allow the pole to escape from the back side of the foil with a velocity greater than 10^8 cm/sec, if the globule contained less than about 200 molecules. Poles would then gain an energy of 2.2 GeV before passing through the 0.14 mm thick mylar foil and entering the five 200 μ thick Ilford K_o emulsions placed above the foil at 45° with respect to the incident particles. The poles should give a track of length between 1000 μ ($m_g = m_p$) and 1200 μ ($m_g = 2.5\ m_p$). They should have been easily observable also in the third pellicle of the stack where they should ionize more than 1000 times minimum.

The target was exposed for a total of 2.64×10^{14} circulating protons, each making on the average some 10 trasversals(8). The first emulsion could not be used because of the very high background due to soft radiation produced by the 27 GeV protons in the target. For the same reason the second emulsion was only in part usable. The third pellicle was very clear and was scanned very carefully but no track was found that could be attributed to a magnetic pole.

From the data given above one can compute a 5% confidence limit on the production cross section in proton-proton collision for an energy of the incident particles of 27 GeV (Table 2). This result, however, is subject to some reservations arising from the uncertainty in the internal potential fluctuations in graphite and the dimensions of the oxygen globules (see Table 2).

Type I experiments

The graphite target from the type II experiment described above was removed from the PS and exposed to a 60 kilooersted field of pulse duration approximately 2 ms. (Half-maximum to half-maximum). The experimental arrangement is diagrammed in Fig. 2. The D.C. field of the solenoid was turned on first, giving a field of 62 oersted at the target surface. Since this is less than the 310 oersted applied inside the PS machine, poles could not be removed by the D.C. solenoid field. Next, the pulsed magnet was energized to 120 kilooersted central field, to provide a field of 60 kilooersted at the surface of the graphite. The vacuum of 10^{-5} mm gave a mean-free path greater than 47.5 cm for globules of 180 oxygen molecules. Heavier globules would lose little energy in collisions with gas. The stripping foil of approximately 1/20 μ thickness would allow poles to emerge with greater than orbital electron velocity, for globules at least as heavy as 600 oxygen molecules.

Fast poles passing through the 30μ thick mylar exit window would produce heavy ionization in the first four of eleven 200μ Ilford K-5 pellicles placed at 45° with respect to the incident particles. Beyond 1,100 microns the 2 kilooersted D.C. field would pull the poles through the emulsion, and produce tracks of approximately $7 \times I_{min}$ in the remaining 2,000 microns of emulsion.

Hence even if our estimates of monopole binding were grossly wrong, we would nevertheless have been able to see distinctive tracks in the K-5 emulsion for poles bound with as much as 24 eV in graphite, or for poles bound to globules of about 500 occluded oxygen molecules. Since the scanning of the emulsions did not show any track that could be attributed to poles, we confirm our previous conclusions which now holds without reservations arising from the uncertainties involved in the binding properties of poles except for binding of between 8 and 10 oxygen molecules.

Three exposures with paramagnetic targets were also made:

1) Aluminium (Conduction electron paramagnetism) - A 10 mm thick target was exposed to an integrated circulating beam of 1.297×10^{15} protons at 25 GeV, each making 25 trasversals of the target. It was then carried, by a route with magnetic field everywhere less than 2 oersted, to a magnet which was pulsed to 150,000 oersted for 1 millisec. Fig. 3 shows the arrange-

ment of target, coil, and a 600 μ stack of G-5 emulsions. The magnetic field at the target surface was about 75 kilooersted. Monopoles bound in the target, or to occluded oxygen, with as much as 30 eV would be pulled free, and would follow magnetic field lines to the emulsion stack. The ionization produced by the monopoles as they are pulled through the emulsion depends upon the magnetic field required to overcome the binding in target, oxygen, and emulsion. A binding of only 1/4 eV would result in a readily visible track of $2 \times I_{min}$. However, a binding less than about 0.6 eV might permit - under the pull of the earth's magnetic field - the loss of monopoles by diffusion out of the target, during the time between bombardment and application of magnetic field.

2) $Cu_{98\%}$ - $Cr_{2\%}$. (Ionic paramagnetism of Cr and diamagnetism of Cu) - A 6 mm target was exposed to an integrated circulating beam of 1.040×10^{15} protons at 25 GeV, and then was exposed to a pulsed magnetic field, as in the case of Al described above. This time, however, the target was placed 1 cm from the center of the magnet, and the G-5 emulsions were placed in a region of diverging field lines (Fig. 4). The 150 kilooersted magnetic field at the target would remove poles bound by as much as 60 eV. The emulsions would intercept more than half of the poles removed from the target.

3) Al-Polyethylene (Conduction electron paramagnetism of Al, and diamagnetism of polyethylene) - A 10 mm target was exposed to an integrated circulating beam of 0.814×10^{15} protons at 25 GeV, and then was exposed to a pulsed magnetic field, as in the

case of Cr + Cu described above.

The emulsions have been exhaustively scanned. All tracks seen in the emulsions can be attributed to cosmic rays. Hence, one can set for each experiment approximate 5% confidence limit on production of monopoles in proton-proton collision as given in Table 1.

* * *

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(1) P.A.M. Dirac - Proc. Roy. Soc. A. 133, 60 (1931).

(2) H. Bradner and W.M. Isbell - Phys. Rev. 114, 603 (1959).

(3) This value is obtained by neglecting the small contribution of Fermi motion.

(4) M. Fidecaro, G. Finocchiaro and G. Giacomelli (in press).

(5) G. Collins, E.M. Purcell, J. Hornbostel et al. - private communication.

(6) This value is obtained by imposing the condition that the migration rate produced by the magnetic field through the target during the exposure should be short with respect to the time of exposure of the target to the beam; this condition is necessary in order to ensure that the majority of the produced poles is actually collected by the solenoid field.

(7) This value is computed by taking into account: a) the repulsion originating from the diamagnetism of graphite; b) the possible binding of poles to particular locations; c) the attraction of the oxygen molecules occluded to the target surface. It does not include the effect of the magnetic field which reduces it to about 0.7 eV.

(8) The numbers of traversals have been computed for the various targets by taking into account both nuclear collisions and multiple coulomb scattering for a maximum presumible angle of scattering in the vertical direction $\vartheta_c = 2 \times 10^{-3}$ rad. The computation is based on the results of N. M. Blachman and E. D. Courant (Phys. Rev. 74, 140, 1948; 75, 315, 1949) who treated the gas scattering in a proton-synchrotron.

(9) This lower limit originates from the condition that the poles should be removed from the target by the earth's magnetic field in a time much longer than that elapsed between the end of the exposure to the proton beam and the exposure to the magnetic field.

(10) These values represent the work made by the magnetic field (see Table 1) pulling the pole on a lattice dimension (2×10^{-8} cm).

(11) The values of N are computed by imposing that the length of time that a pole remains on the target surface should correspond to the actual condition of the experiment. This time is given by the reciprocal of the "jump rate" computed by taking into account the various binding energies listed in note (10) as well as the action of the magnetic field.

TABLE 1

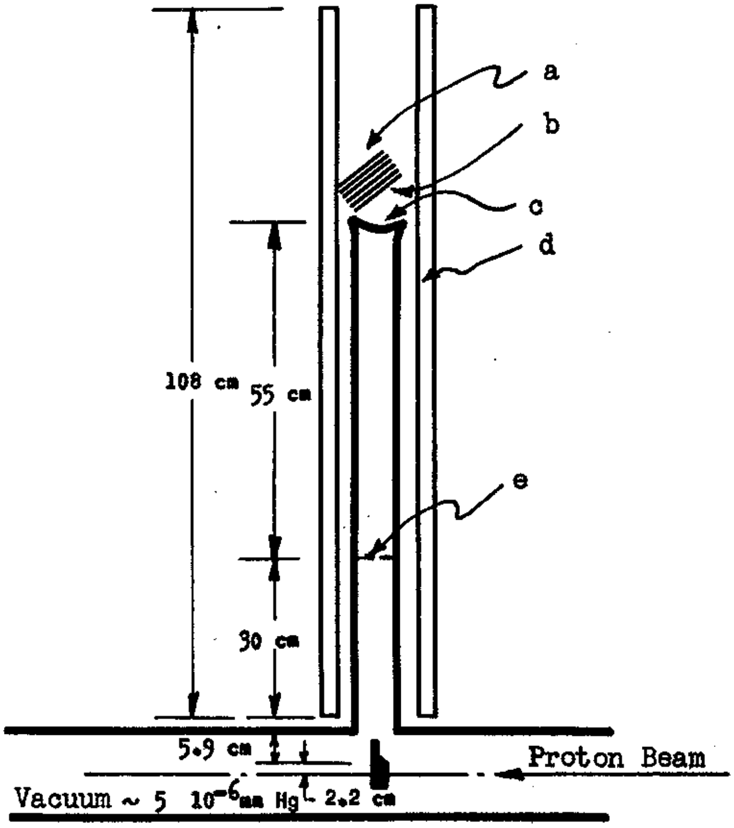
Main features of the various experiments

Experiment	Target	Target thickness g/cm^2	Magnetic field at the target (oersted)	Total number of circulating protons	Proton energy GeV
II	Graphite	3.3	310 (at surface) 250 (average)	2.64×10^{14}	27.2
I	"	"	60.000	"	27.2
I	Al	2.70	75.000	1.297×10^{15}	25.0
I	Cu(98%) - Cr(2%)	5.34	150.000	1.040×10^{15}	25.0
I	Polyethylene (10 mm) + Al (1.75 mm)	1.39	150.000	0.814×10^{15}	25.0

TABLE 2

Results

Experiment	Target	5% confidence limit: $\sigma \times 10^{40} cm^2$	Mass limit (m_p)	Valid range of monopole binding energies		Reservations
				Internal (eV)	Surface (No. O_2 Molecules)	
II	Graphite	12.7	2.94	$E < 07$(6)	$N < 8$	None obvious when the two experiments are taken together, except for the region N=8 to 10.
I	Graphite	12.7	2.94	0.6(9) $< E < 24$(10)	$10 < N < 250$	
I	Al	4.0	2.79	$0.6 < E < 30$(10)	$8 < N < 250$	Some because of possible too weak binding of poles in metal.
I	Cu(98%)-Cr(2%)	1.9_5	2.79	$0.6 < E < 60$(10)	$4 < N < 250$	Some because of possible too strong binding of poles in chromium
I	Polyethylene-Al	7.4	2.79	$0.6 < E < 60$(10)	$14 < N < 250$	Some because of possible too weak binding of poles in metal



a - Five KO emulsions of 200μ each.

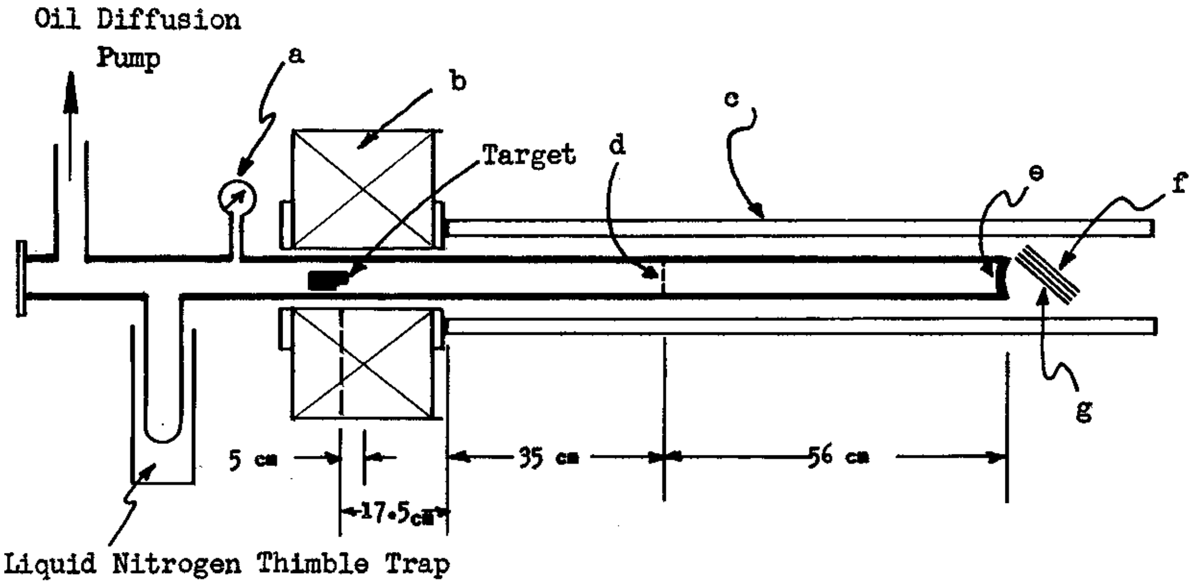
b - 0.07 mm. Black peper.

c - 0.14 mm. Mylar window.

d - Solenoid 108 cm. Long ~ 2.1 kilogauss at center mean radius 6.5 cm. Pulsed~600m.s. flat-top, each accelerator pulse.

e - Plastic stripping foil ~ 0.5μ Thick.

Fig. 1



a - Phillips ion gage.

b - Pulsed magnet.

c - Two Giacomelli solenoids 108 cm. winding length.

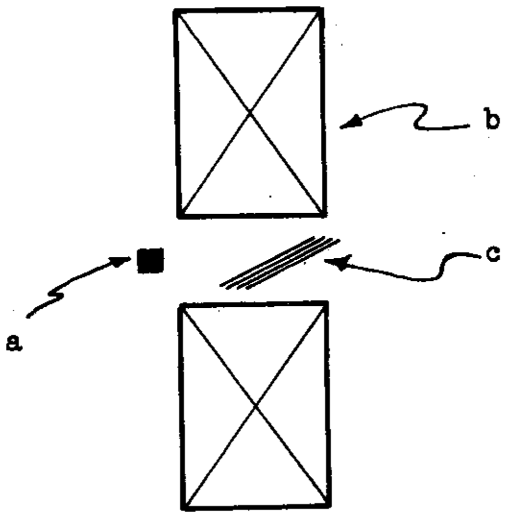
d - Plastic stripping foil ~ 0.05μ thick.

e - Mylar 30μ thick.

f - Eleven K5 pellicles $200\ \mu$ thick.

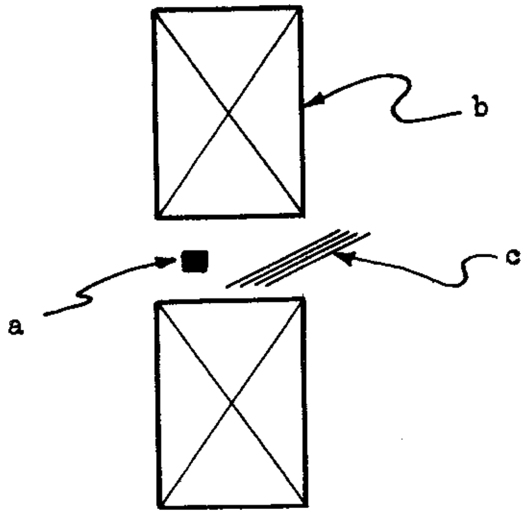
g - Black paper 70μ thick.

Fig. 2



a - Al target.
b - Pulsed magnet.
c - G5 Emulsions.

Fig. 3



a - Target Cu - Cr (and) Al-Polythene.
b - Pulsed magnet.
c - G5 Emulsions.