## SEARCH FOR DIRAC MONOPOLES IN THE 70-BeV PROTON SYNCHROTRON

L. M. BARKOV,[1] I. I. GUREVICH, M. S. ZOLOTAREV,[1] L. A. MAKAR'INA, V. P. MARTEM'YANOV,
A. P. MISHAKOVA, V. V. OGURTSOV, V. S. OKHAPKIN,[1] M. N. TARAKANOV,[2] V. G. TARASENKOV,
S. Kh. KHAKIMOV, and L. A. CHERNYSHEVA

Kurchatov Atomic Energy Institute; Nuclear Physics Institute, Siberian Division, U.S.S.R. Academy of Sciences; Institute of High Energy Physics

Submitted June 21, 1971

Zh. Eksp. Teor. Fiz. 61, 1721-1736 (November, 1971)

A search for the Dirac monopole has been carried out at the 70-BeV proton synchrotron, with use of ferromagnetic traps. It is found that the upper limit of the cross section for production of monopoles in proton-nucleon collisions is $\sigma(95\%) \leq 2.1 \times 10^{-43}$ cm$^2$ for $m_g \leq 5.15$ $m_p$ and $g \geq 68.5$ e.

IN 1931 Dirac[1] suggested the existence of an isolated magnetic charge which has since been called the Dirac monopole. Using the general principle of quantum mechanics, he obtained an expression relating the electric and magnetic charges with the universal constants:

$$ge = \tfrac{1}{2}\hbar cn, \tag{1}$$

where g is the magnetic charge, e is the electric charge, ℏ is Planck's constant, c is the velocity of light, and n = ±1, 2, ... is an integer.

An important consequence follows from Eq. (1): the existence of even one monopole in the world leads to the possibility of explaining the empirical fact of electric charge quantization.

Introduction of magnetic charges is attractive also from the point of view of achieving more complete symmetry of Maxwell's equations. With the addition of magnetic charge, the equations predict that a single Dirac monopole produces in the surrounding space a magnetic field

$$\mathbf{H} = g\mathbf{r}/r^3. \tag{2}$$

In order that this field have the same transformation properties as the magnetic field of an electric current, the magnetic charge must be a pseudoscalar. In spite of the apparent simplicity of Maxwell's equations, the electrodynamics of magnetic charges encounters substantial difficulties, especially if we wish to use the Hamiltonian formalism, which is highly developed for

electrically charged particles. A review of the problems arising and the attempts at their solution can be found in a collection of articles on the Dirac monopole.[2]

Since the possible existence of the Dirac monopole does not contradict any well established law of nature, attempts have repeatedly been made to search for monopoles both in cosmic rays and among the secondary particles produced in high-energy accelerators. Negative results have been obtained in all search experiments. This fact, together with the striking agreement of experiments on verification of quantum electrodynamics with the theoretical predictions, would appear to solve beforehand the problem of existence of monopoles. However, it appears that to draw such a conclusion is premature. An appreciable contribution of magnetic charges to electromagnetic processes can be observed if the kinetic energy in the c.m.s. of the interacting-particle system is equal to or greater than the threshold energy for production of a monopole-antimonopole pair. The simplest models[2] indicate that the monopole mass may be equal to several proton masses or larger. However, at these energies, electromagnetic processes have not been studied very thoroughly.

Recently, theoretical papers have appeared in which magnetic charges have been used to construct a dynamical theory of hadrons. Schwinger[3] modifies the quark model to the model of dyons, assigning to quarks, in addition to electric charge, also a magnetic charge. Then, on the assumption that dyons inside a hadron interact electromagnetically, an attempt is made to provide a basis for the experimentally observed "mass formulas."

---

[1]Nuclear Physics Institute, Siberian Division, USSR Academy of Sciences.

[2]Institute of High Energy Physics, Serpukhov.

Barut[4] builds hadrons from spinless dyons in analogy with the hydrogen atom.

Naturally, it is necessary to obtain an answer experimentally to the question of the existence of Dirac monopoles.

## 1. MAIN EXPECTED PROPERTIES OF A DIRAC MONOPOLE

Any experiment on the search for the Dirac monopole is based on the assumption of certain properties of the monopole.

**Magnetic charge.** It follows from Eq. (1) that the magnetic charge of the monopole is g = 68.5ne, i.e., the least magnetic charge is $68.5e = 3.29 \times 10^{-8}$ cgs esu. Another condition is due to Schwinger:[5] $ge = 2 \hbar cn$, according to which the minimal charge is 274e. The charge quantization conditions are valid also for dyons. Barut's model is consistent with the existence of dyons with an electric charge equal to the electronic charge and a magnetic charge g = 68.5en. Schwinger's dyons have a fractional electric charge like quarks.

**Mass.** The existing theories, in essence, leave the question of the mass of the Dirac monopole free. If we assume the monopole is a purely electromagnetic object with a radius equal to the classical electron radius, we obtain for the monopole mass the expression $m_g c^2$ = 2.4 BeV. Schwinger estimates the mass of the dyon as $m_D c^2 \approx 6$ BeV.[3]

**Spin.** The question of whether monopoles are fermions or bosons remains completely open. Dirac considered monopoles to be fermions with spin $\frac{1}{2}$. Schwinger also assumed dyons to be fermions, while Barut proposes a proton model of spinless dyons. In connection with the spin question, it should be noted that if the monopole turns out to be a fermion, it will have an electric dipole moment equal to

$$d = \hbar g / 2 m_g c = e r_g. \tag{3}$$

**Stability.** If we postulate the existence of magnetic charge conservation in analogy with the law of electric charge conservation, then monopoles cannot decay into particles not having magnetic charge. Therefore monopoles with the least mass must be stable.

## 2. THE MONOPOLE IN AN EXTERNAL FIELD AND IN MATTER

**Acceleration in a magnetic field.** Proceeding from the symmetry of Maxwell's equations, it is reasonable to suppose that a monopole moving in an electromagnetic field experiences a Lorentz force:*

$$\mathbf{F} = g\mathbf{H} - \frac{g}{c}[\mathbf{uE}],$$

where **u** is the velocity of the monopole. From this it follows that a monopole moving along the lines of force of a uniform magnetic field will acquire in 1 cm of path an additional energy equal to

$$\Delta E = gH = 20.55 \text{ MeV/kG-cm} \tag{4}$$

Consequently, there is the possibility of efficiently accelerating magnetic charges under laboratory conditions. The weak magnetic field of the Earth in its action

---

*$[\mathbf{uE}] \equiv \mathbf{u} \times \mathbf{E}$.

on a monopole with charge 68.5e is equivalent to the action on an electron of an electric field of $10^4$ V/cm, and therefore the possibility of free monopoles remaining for an extended time in the atmosphere or in most surface rocks of the Earth is practically excluded.

**Interaction with an electron and with atomic nuclei.** Malkus[6] has solved the quantum-mechanical problem of motion of a particle with spin $\frac{1}{2}$ and electric charge Ze in a monopole field (3). In particular, he has shown that a bound state cannot be formed in the monopole-electron system. If we consider the classical equation of motion of an electron in the field of a monopole at rest,

$$m\ddot{\mathbf{r}} = \text{grad}(\mu H) + \frac{e}{c}[\mathbf{vH}],$$

where m, $\mu$, and e are the mass, magnetic moment, and charge of the electron, we can obtain the result that the trajectory of the electron motion is a spiral on the surface of a cone at whose vertex is located the monopole. As the electron approaches the region of strong magnetic field near the monopole, it gradually slows down and then is reflected. The electron approaches the monopole no closer than a distance

$$r_{min} = r_0 \left( 1 - \frac{v_{0r}^2}{v_0^2 - 2\mu g/m r_0^2} \right)^{1/2};$$

the subscript zero refers to values taken at the initial moment of time. A similar result has been obtained by Lapidus and Pietenpol[7] and by Lenart.[8]

Between a monopole and nucleus, in addition to the force of paramagnetic attraction, there should exist forces of diamagnetic repulsion arising because of the Larmor precession of the nuclear protons in the field of the monopole. An appreciable polarizability of a nucleus is possible in the field of a monopole. Finally, we cannot exclude the existence of other effects as yet unknown.

An important contribution to the forces of attraction in a monopole-electron or monopole-nucleus system can be provided by the electric dipole moment of the monopole if the monopole is a Fermi particle. If we take into account Eq. (3) the corresponding attractive potential has the form

$$V = -d Z e / R^2 = -Z e^2 r_g / R^2.$$

Amaldi et al.[9] have given potentials calculated in this way for several elements (for example, for Al—4.6 MeV, for Cu—5.8 MeV).

**Energy loss in matter.** One of the most distinctive properties of the Dirac monopole is its substantial energy loss in matter. Just this fact is utilized in most search experiments.

Let us discuss the features of the ionization loss. A moving magnetic charge g creates an electric field of intensity $E \sim \beta g$. The energy transferred by this field to an electron of a medium is

$$\Delta \varepsilon \sim (eE\Delta t)^2 \sim e^2 g^2.$$

This means that the ionization loss of a monopole is practically independent of its velocity and is larger by a factor $(g/e)^2$ than for a relativistic particle with Z = 1. For monopoles with charge g = 68.5e the specific ionization in matter is approximately 8 BeV/(g/cm²). Martem'yanov and Khakimov[10] have calculated the energy

loss of a monopole in metals by the impact-parameter method. According to the calculations the ionization loss $\epsilon$ of a relativistic monopole ($pc$ = 30 BeV) with g = 68.5e in various metals is as follows: in aluminum $\epsilon_{Al}$ = 22 BeV/cm, in iron $\epsilon_{Fe}$ = 59 BeV/cm, in copper $\epsilon_{Cu}$ = 65 BeV/cm, in lead $\epsilon_{Pb}$ = 72 BeV/cm, and in tungsten $\epsilon_W$ = 120 BeV/cm.

As the monopole slows down to a velocity less than the velocity of atomic electrons, further ionization of atoms becomes impossible. However, even in this case slowing down of monopoles occurs as the result of scattering by atoms through the orbital and spin magnetic moments of the electrons. This mechanism becomes particularly effective at an energy equal to or less than several electron volts,[9] since the scattering cross section reaches atomic dimensions at this energy. Martem'yanov and Khakimov[10] give an estimate of the energy loss of slow monopoles ($u < 10^8$ cm/sec) in the conduction electrons in metals:

$$\frac{dE}{dx} = -4\pi^2 g^2 \frac{u}{v_e} \frac{Ne^2}{mc^2}.$$

This mechanism alone limits the range in a metal of a monopole with energy 25 keV and with mass $m_g = 5m_p$ to a value of $\sim 10^{-3}$ cm.

**A monopole in diamagnetic and paramagnetic media.** Monopoles in matter rather rapidly lose energy to the thermal level, and will drift under the action of both the oscillations of the atoms of the medium and the external magnetic fields (if they exist). The velocity of this drift depends strongly on the nature and magnitude of the potentials for interaction of the monopole with the atoms of the medium. The problems of local binding of a monopole with atoms or molecules have been discussed in detail by Malkus[6] and Amaldi et al.[9] We present the principal results.

Repulsive forces should exist between a monopole and diamagnetic atoms or molecules. These forces are proportional to $r^{-5}$, and the potential energy associated with them at atomic distances is $\sim 1$ eV. However, inside the crystal lattice at whose sites the diamagnetic atoms or ions are located, the shape of the potential energy for the monopole may have a minimum of depth of the order of a tenth of an electron volt. In order for the monopole to be able to penetrate into a diamagnet, it is necessary to do work against the repulsive forces produced by polarization of the medium by the magnetic field of the monopole. The energy necessary for the monopole to overcome the barrier is equal to the magnetization energy of the medium:

$$Q = \int_V \epsilon(r)\, dV, \qquad (5)$$

where $\epsilon(r)$ is the magnetization energy density:

$$\epsilon(r) = \int H\, dM = \tfrac{1}{2}\chi H^2,$$

and $\chi$ is the magnetic susceptibility.

In paramagnetic media, the combination of paramagnetic attraction and diamagnetic repulsion can lead to formation of bound states with energy of the order of the chemical binding energy. The average interaction energy of a monopole with the atoms in a paramagnet can be estimated from Eq. (5). The results of such estimates

**Table I**

| Material | $\chi \cdot 10^6$ [11] | Q, eV |
|----------|------------------------|-------|
| Al | +1.65 | +0.35 |
| Cu | −0.77 | −0.18 |
| Pb | −1.26 | −0.22 |
| W | +5.3 | +0.94 |

for several diamagnetic and paramagnetic materials are listed in Table I.

If the value of the external magnetic field is such that $gHa \ll Q$ (where a is the crystal lattice constant), the monopole will be held in the paramagnetic material for a certain time. For a field strength $gHa \gg Q$, the monopole will drift rapidly along the lines of force of the field. For tungsten, for example, H = Q/a = 1500 G.

It is necessary to discuss especially the interaction of a monopole with an oxygen molecule $O_2$. This is important because, in the first place, the surface of the materials used in the experiment may be covered by a layer of $O_2$ and, in the second place, monopoles leaving the surface of the materials enter air, which is rich in oxygen. The potential energy of the monopole-$O_2$ molecule system is

$$W = -\mu H = -\mu \frac{g}{r^2} = -\frac{5.4 \cdot 10^{-16}}{r^2}\,[\text{eV}] \qquad (6)$$

where $\mu = 2.83\ \mu_B$ is the magnetic moment of $O_2$. (The "oxygen" problem will be discussed in more detail in Section 4.)

**Ferromagnetic media.** Attractive forces act between a monopole and ferromagnets. In contrast to diamagnets and paramagnets, a more complex functional relation exists between the magnetization and magnetic fields for ferromagnets. As a result of this, the binding energy of a monopole in a ferromagnetic medium cannot be calculated with Eq. (5). An analysis of the passage of a monopole through a ferromagnetic medium has been made by Martem'yanov and Khakimov.[11]

We will discuss the main features of the interaction of a monopole with a ferromagnet, which have been used in several experiments.[12-14]

For simplicity we will consider a monopole at rest at a distance z from the surface of a ferromagnet which we will assume to be ideally soft. For materials which are saturated at small values of the magnetic field H, this approximation is justified. If the medium is initially unmagnetized, it will attract the monopole as the result of the induced magnetization. The force attracting monopoles located far from the surface of the medium is found by the image method and is

$$F(z) = g^2 / 4z^2.$$

When the monopole is directly at the surface or inside the ferromagnetic material, it will completely magnetize the medium around it in the direction of the lines of force of its own strong magnetic field (2). If we know the total magnetization energy

$$Q = \int_V H M_s\, dV,$$

we can obtain an expression for the force attracting the monopole to the ferromagnet:

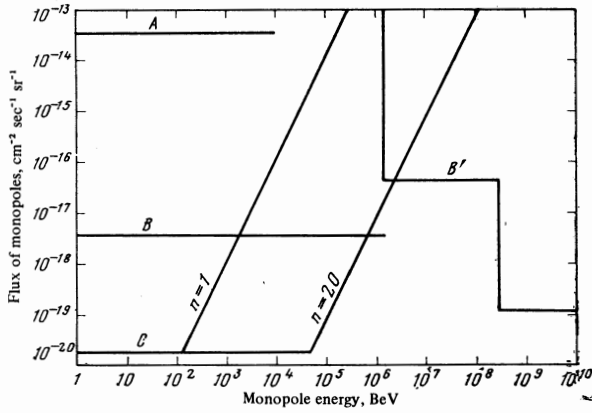$$F(z) \approx 2\pi M_s g \ln (R/z), \qquad (7)$$

FIG. 1. The search for monopoles of cosmic-ray origin: A—search in the Earth's atmosphere [15]; B—search in magnetic minerals of the ocean [14]; B'—analysis of tracks in mica [14]; C—search in lunar material [17]; D—experiments in 30-BeV accelerators; E—results of the present work. The confidence level is 95%.
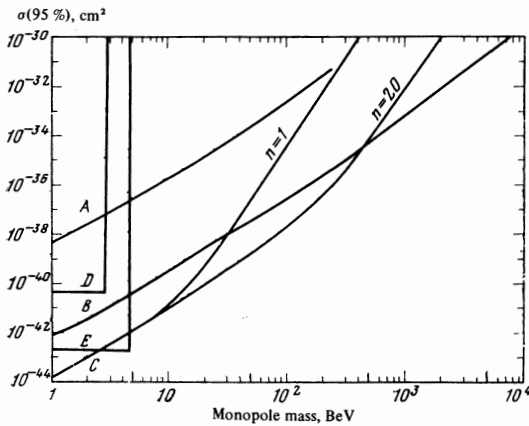


FIG. 2. Upper limit for monopole production cross section. The designations are the same as in Fig. 1.

where R is the radius of the sphere of complete magnetization, which for purposes of estimation we can take in the form $R = (g/4\pi M_S)^{1/2}$.

The value of z cannot be less than the interatomic distance. The values of the holding magnetic fields $H(z_{min}) = F(z_{min})/g$ obtained from Eq. (7) reach tens of kilogausses for various ferromagnetic materials; the use of ferromagnetic materials in the search experiments is based on this fact.

## 3. EXPERIMENTS IN SEARCH OF THE DIRAC MONOPOLE

All experiments on the search for monopoles can be divided into two groups. In one of these groups are the searches for monopoles of cosmic radiation or produced by cosmic rays in the atmosphere.[6, 12-17] The general distinguishing feature of this type of experiment is the possibility of searching for monopoles of large mass (up to $10^4$ BeV), since the upper energy limit of cosmic radiation is quite high. The result of such experiments is an estimate of the upper limit of the flux of monopoles and the cross section for their production in nucleons. The estimates of the monopole production cross section involve assumptions regarding the proton energy spectrum, the energy dependence of the monopole pro-

duction cross section, and so forth.

The results of several experiments are shown in Figs. 1 and 2. The curves A correspond to results of a search for monopoles in the Earth's atmosphere by means of a special collecting magnet.[15] The detecting system permitted recording of monopoles with charge up to n = 3. Curves B and B' are the results of searches for monopoles in magnetic minerals from the ocean floor and from analysis of tracks in mica and volcanic glass.[14] The lowest values of upper limits for the existence of the monopole have been obtained by Alvarez et al.,[17] who investigated 8.37 kg of material obtained from the lunar surface by the spaceship Apollo 11. These results were obtained as the result of the exceptionally great age of the Moon rock (3–4) $\times 10^9$ years, on the assumption that during this entire period there was no magnetic field on the Moon and that no mixing of the rock occurred to depths greater than 10 m. This experiment employed an original technique for detection of monopoles. The apparatus consists of a magnetic galvanometer constructed from superconducting elements. However, it cannot be completely excluded that the zero result of the experiment is due to existence of monopoles and antimonopoles in pairs in the samples studied.

The other group of experiments are those done with accelerators.[9, 18-22] Of course, the range of possible monopole masses is greatly limited in these experiments; however, the high fluxes of primary particles permit lower values to be obtained for the upper limit of the monopole production cross section. In addition, there is less ambiguity in interpretation of the results of the accelerator experiments. The general result of studies with accelerators of ∼30 BeV is that, if monopoles with mass $m_g \le 3m_p$ exist, the cross section for their production in proton-nucleon collisions is $\sigma(95\%) \le 5 \times 10^{-41}$ cm². In these experiments the detecting apparatus was sensitive to monopoles with charge n = 1 and 2. Blagov et al.[21] have reported the results of a search for monopoles with small charge g = (1–7)e in a γ-ray beam from a 600-MeV synchrotron. The production cross section is $\sigma(95\%) \le 3 \times 10^{-29}$ cm² if the monopole mass is $m_g c^2 \le 200$ MeV. A preliminary result of the present work on the search for monopoles in the 70-BeV proton synchrotron at the Institute of High Energy Physics has been reported by Gurevich et al.[22]

## 4. SEARCH FOR DIRAC MONOPOLES IN THE 70-BeV SYNCHROTRON

Monopoles can be produced in proton-nucleon collisions if the energy in the center of mass of the colliding particles is sufficient for production of two new particles (a monopole and an antimonopole).

$$p + N \rightarrow p + N + g^+ + g^-. \tag{8}$$

For sufficiently high momentum of protons incident on a stationary nucleon, the maximum value of monopole mass allowed is determined with high accuracy by the formula

$$\frac{m_g}{m_N} = \sqrt{\frac{1}{2}\left(1 + \frac{p_N c}{m_N c^2}\right)} - 1. \tag{9}$$

It follows from Eq. (9) that for 70-BeV/c protons incident on a hydrogen target, monopoles with mass up to
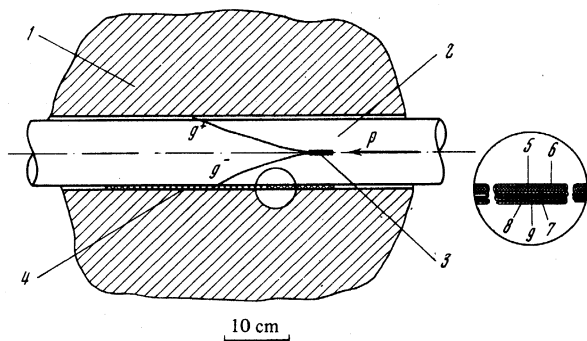
FIG. 3. Experimental arrangement in the accelerator. 1—accelerator magnet; 2—accelerator vacuum chamber; 3—target; 4—samples; 5—tungsten plates; 6—copper foil; 7—Permalloy 50H; 8—Permendur foil; 9—Permalloy 79HM.



FIG. 4. Stopping power of tungsten and lead plates, $r = E_{kin}/\Delta E_{max}$.

$5.15\ m_p$ can be produced. If the target is a nucleus, the Fermi motion of the nucleons in the nucleus leads to an increase in the limiting monopole mass, but the probability of realization of such events drops rapidly with increasing $m_g$.

The experiment was carried out in two stages. In the first stage the monopoles should have been accumulated in a ferromagnetic trap, and in the second stage—extracted from the trap and detected from their tracks in nuclear emulsion. The two stages were separated in place and in time. This apparatus permits the monopole accumulation time in the accelerator to be increased substantially without the danger of background accumulation in the detecting emulsion chamber.

"Accumulation" of monopoles. In Fig. 3 we have shown a diagram of the accelerator experiment. In the space between the vacuum chamber 2 and the magnet poles 1 of the accelerator, we placed samples 4 consisting of tungsten and lead plates 5 of total thickness 3 mm and ferromagnetic foils (100 $\mu$ Permendur 8, 200 $\mu$ Permalloy 50 H 7, and 200 $\mu$ Permalloy 79 HM 9). The plates and foils were wrapped in copper tape 6. The accelerator target was an aluminum wire 20 mm long and 3 mm in diameter. The samples, each of dimensions 40 × 40 mm, were placed in the gap along the axis of the accelerator vacuum chamber in such a way that the first sample was directly under the target. The total length of the row of samples was 480 mm. As the result of the accelerator magnetic field (H = 12000 G), only $g^-$ monopoles could hit the samples.

The idea of using ferromagnetic materials as monopole traps has already been utilized by Goto et al.[12] and Fleischer et al.[14] for monopoles previously thermalized in the atmosphere or in sea water. The conditions in an accelerator are considerably more severe. Since the ferromagnetic traps were placed in a region of rather large external magnetic field, it was impossible to accomplish a preliminary thermalization of the monopoles. The capturing ability (7) of the ferromagnets, which is rather high for thermal velocities of the monopole, falls off with increasing velocity as the result of the decrease in the effective interaction time of the monopole with the atoms of medium, and the characteristic relaxation times in ferromagnets, as is well known, are relatively large. Therefore the efficiency of a ferromagnetic material located in an external mag-
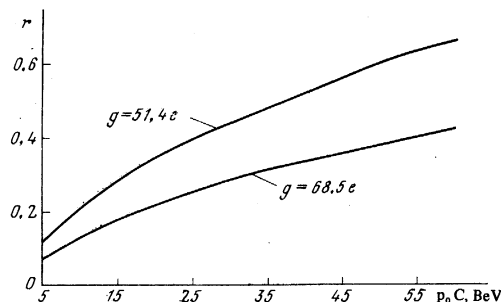
netic field as a monopole trap was analyzed[10] by Martem'yanov and Khakimov.

The calculations show that, inside the ferromagnet, monopoles are slowed down to a definite velocity which depends on the properties of the magnetic material, the strength of the external magnetic field, and the magnetic charge of the monopole. Thus, for Permendur in an external field of 12 000 G, this velocity is $u \approx 10^6$ cm/sec for g = 68.5e, i.e., significantly greater than the thermal velocity ($\sim 10^5$ cm/sec). Near the surface of the ferromagnet, the retarding force acting on the monopole is

$$F(z) = g\pi M_s \left(1 - \frac{2A}{gM_s}\right) \ln\left(1 + \frac{g^2\gamma^2}{z^2 u^2}\right), \tag{10}$$

where z is the distance from the surface, $4\pi M_s$ is the saturation induction, $\gamma$ is the gyromagnetic ratio for the electron, and A is the exchange interaction constant of the ferromagnet. In Fig. 2 of Ref. 10, the decelerations are given for monopoles with mass $m_g = 5m_p$ in various ferromagnetic materials located in a field of 12 000 G. It is evident from this figure that monopoles with g ≥ 51.4e are slowed down to thermal velocity without reaching the surface of the material. Thus, the ferromagnetic foils used in the present experiment can serve as an efficient trap for monopoles with charge g ≥ 51.4e.

In the experiment, metallic plates were placed over the foils for preliminary slowing down of the monopoles. These plates were either tungsten or a combination of tungsten and lead with thickness ratios of 2:1 and 1:2. Figure 4 shows the stopping powers of the plates $r = E_{kin}/\Delta E_m$ (where $E_{kin}$ is the kinetic energy of the monopole, and $\Delta E_m$ is the maximum possible energy loss of a relativistic monopole) as a function of monopole momentum for the trajectory corresponding to this value of $E_{kin}$. For a ratio of the thicknesses of tungsten and lead 1:2 the energy loss is

$$\Delta E_m = (\varepsilon_W \cdot 0.1 + \varepsilon_{Pb} \cdot 0.2) \left(\frac{g}{68.5e}\right)^2 \frac{1}{\sin \alpha}, \tag{11}$$

where $\alpha$ is the angle of entry of the monopole into the plate.

It is evident from the figure that plates of thickness 3 mm provide preliminary slowing down of monopoles hitting them with charge g ≥ 51.4e. This means that the total efficiency of the foils as monopole traps reduces to the geometrical efficiency of the experiment, i.e., to the fraction of monopoles whose trajectories intersect the samples.
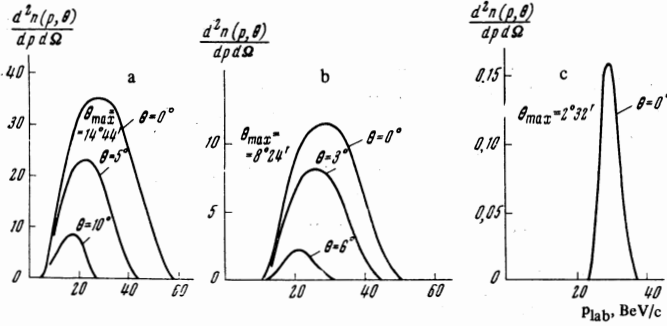
FIG. 5. Momentum spectrum of monopoles in the reaction p + N → p + N + g⁺ + g⁻ for three values of monopole mass: a—$m_g$ = 3 $m_p$, b—$m_g$ = 4 $m_p$, c—$m_g$ = 5 $m_p$.



FIG. 6. Movement of a monopole from the target to the samples ($m_g$ = (3−5)$m_p$); x is the range, α is the entry angle into the samples, and $l$ is the length of the row of samples.

In Fig. 5 we have shown momentum distributions of monopoles in reaction (8) for masses (3–5)$m_p$. The calculations were made on the basis of statistical theory, on the assumption that there is no interaction between secondary particles.[23] The monopole momentum spectrum occupies the region from 4 to 58 BeV/c, and the direction of emission at the time of production is limited by a cone with a polar angle $\theta_{max}$ = 14° 44′. The trajectory of a monopole in a uniform magnetic field H with initial momentum $p_0 \perp$ H is represented by the catenary

$$z = \frac{E_0}{gH}\left(\operatorname{ch}\frac{gHx}{p_0 c} - 1\right) \quad (12)$$

where $E_0^2 = p_0^2 c^2 + m_g^2 c^4$, and the z axis is directed along H.

Figure 6 shows the range x of a monopole as a function of initial momentum for z = 5 cm, H = 12 000 G. The experimental conditions allow x ≤ 46 cm. Also shown in Fig. 6 is the reciprocal of the sine of the entrance angle of the monopole into the samples, which is used in Eq. (11).

The geometrical efficiency η can be defined as

$$\eta = 1 - \frac{1}{n} \int_0^{\theta_{max}} \int_{(p_0 c)^*}^{(p_0 c)_{max}} \frac{d^2 n(p,\theta)}{d\Omega\,dp} f(\theta, p)\,dp\sin\theta\,d\theta, \quad (13)$$

where

$$f(\theta, p) = \begin{cases} \mathscr{P} & \text{for} \quad \mathscr{P} \leqslant 1 \\ 1 & \text{for} \quad \mathscr{P} > 1 \end{cases}, \quad \mathscr{P} \equiv \frac{p_0 c - (p_0 c)^*}{\varepsilon_{Al} l},$$

$(p_0 c)^*$ is the maximum momentum for a given angle $\theta$ for which all monopoles still hit the samples, and $f(\theta, p)$ takes into account slowing down of the monopoles in the aluminum target. Figure 7 gives calculated values of η for various values of the monopole mass and charge. We can assume that all monopoles with g ≥ 68.5e produced in the target are captured by the ferromagnetic foils.

**Detecting system.** Three series of sample bombardments were carried out in the accelerator. After termination of each series, the ferromagnetic foils were subjected to a pulsed magnetic field in order to extract monopoles from them. The necessary value of magnetic field intensity $H_0$ is determined by the condition

$$gH_0 \geqslant F(z_{min}).$$

In Table II we have shown the minimum values of magnetic field intensities for the ferromagnetic materials used in the present experiment. The assembled stack of
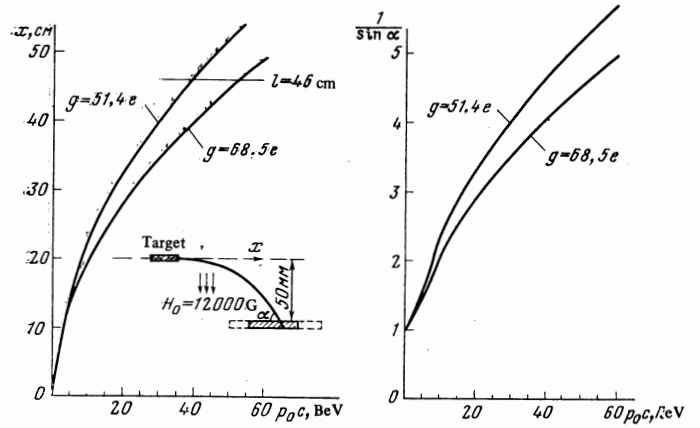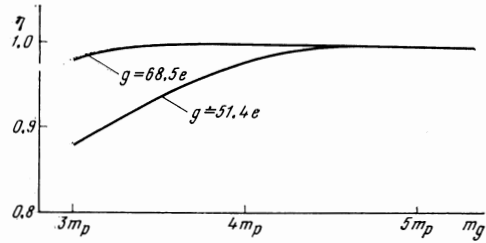


FIG. 7. Fraction captured by the ferromagnetic foils of the total number of monopoles produced in the target, for various values of mass and charge of the monopoles.

| Ferromagnetic material | $H_0$ min, G | I, keV/μ |
|---|---|---|
| Permendur | 44300 | 75 |
| Permalloy 50H | 31300 | 53 |
| Permalloy 79HM | 15900 | 27 |

foils was placed in the center of a pulsed magnet,[24] in which the magnetic lines of force lay along the plane of the foil. The field pulse lasted 7 msec and had an amplitude of 220 kG.

Type Br. 2 nuclear photoemulsion was used as the monopole detector. Two emulsion layers 59 mm in diameter and each 400 μ thick, each one marked with a calibration grid, were placed on each side of the ferromagnetic samples at a distance of 15 mm. In the first series of irradiations, both the ferromagnetic foils and the absorbing tungsten plates were subjected to the pulsed magnetic field simultaneously, and in the next two series—only the foils. Figure 8 shows the detecting system used in the last series of experiments. The pairs of emulsions mounted transverse to the extracting field were supplemented by two emulsion stacks 44 × 50 × 25 mm whose emulsions were placed along the assumed direction of the monopoles.

Monopoles leaving the ferromagnet must move in the magnetic field a distance of 15 mm through air. The energy acquired by the monopoles up to their entry into the first emulsion layer will depend to a strong degree on the formation of an oxygen complex around the monopole. The possibility of formation of such complexes
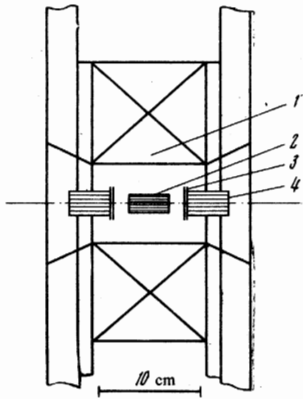
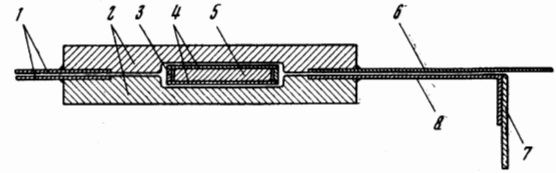FIG. 8. Detecting system: 1—pulsed magnet, 2—ferromagnetic foils, 3—emulsion layers, 4—emulsion stack.



FIG. 9. Detecting system with 800-kG magnetic field: 1—current leads, 2—body of magnet, 3—field probe, 4—nuclear emulsion, 5—stack of foils, 6—high-voltage electrode of mechanical spark gap, 7—shorting plate, 8—ground electrode of mechanical spark gap.

has been investigated in detail by Amaldi et al.[9] What happens is that when the monopole leaves the ferromagnet, it has relatively low velocity and can efficiently attract to itself oxygen molecules from the surface of the foil and from the surrounding medium. The size of the complex formed can be estimated from formula (6):

$$5.4 \cdot 10^{-16}/r_0{}^2 = kT = 2.5 \cdot 10^{-2}, \quad r_0 = 14.7 \text{ A}.$$

If we assume the density of the complex to be equal to the density of liquid oxygen ($1.14 \text{ g/cm}^3$), we can obtain for the number of molecules in such a complex $\approx 70$. The mean free path of the complex in air under standard conditions will be

$$\lambda = 1/\pi r_0{}^2 \cdot 2.7 \cdot 10^{19} \approx 5.5 \cdot 10^{-7} \text{ cm}.$$

In a distance $\lambda$ in a field of intensity $H_0$ min the complex acquires an additional energy $\Delta E \approx 180$ eV ($H_0$ min = 15 900 G). Since the degree of elasticity in collision of a complex with oxygen molecules is unknown, we will discuss two limiting cases.

If the collision is absolutely inelastic (the oxygen molecule becomes attached to the complex), the energy released is $\sim (M_{O_2}/M_c) \Delta E \approx 2.6$ eV. This energy is sufficient for evaporation of a substantial number of molecules of the complex, since the binding energy even of the oxygen molecules located closest to the monopole is $\sim 0.4$ eV. In an absolutely elastic collision the number of molecules of the complex is not increased, and as a result of the Maxwellian distribution of the molecules in the complex in energy, an effective evaporation will occur.[9] The considerations presented permit us to hope that in the process of acceleration of the monopole by the magnetic field, rapid destruction of the complex will occur, if it is initially formed.

In traversing the 15 mm path, a monopole with charge g = 68.5e in the experiment with Permalloy 79 HM acquires an energy $\sim 0.5$ BeV, and in the case of the other ferromagnetic materials a still higher energy. All of this energy will be lost in the first layer of the emulsion, and beyond that the ionization loss, I, will correspond to the equilibrium motion of the monopole in the applied magnetic field (see Table II). An ionization loss of magnitude I = 27 keV/$\mu$ corresponds to the ionization of a 3-MeV proton, i.e., monopoles should leave black tracks.

At the time of operation of the pulsed magnetic field, the transverse emulsion layers were together in the holder for not more than 3–9 minutes. Since about two

weeks elapsed from preparation of the emulsion to its development, the probability of observation of tracks intersecting the two layers is not more than $4 \times 10^{-4}$. In scanning the emulsion we selected gray and black tracks having a length in the microscope field of view $\leq 75 \mu$. In a magnetic field of intensity 220 kG, a monopole with charge g = 68.5e can acquire within one cell of the crystal lattice of the ferromagnetic material an energy of the order $\sim 110$ eV. This is considerably greater than the binding energy of an individual ion, and therefore it is improbable that the monopole will remain in the foil, even if it is strongly bound to an ion.[12] Nevertheless, in order to take into account the possibility of an anomalous interaction of monopoles with matter, the ferromagnetic foils of the first and second series of irradiations were subjected to an additional magnetic-field pulse of intensity about 800 kG.

The foils were cut into portions 40 × 20 mm (foils of the second series of irradiations) and collected into 21 stacks of dimensions 40 × 20 × 6.5 mm, each foil being wrapped in 20 $\mu$ Teflon sheet to avoid contacts between the foils. Each stack was covered with two layers of nuclear emulsion directly before being mounted in the pulsed magnet, in such a way that all possible monopole trajectories intersected both emulsion layers. The magnetic field was obtained by discharging a capacitor bank of 5 kV × 0.014 F into a magnet by means of a mechanical spark gap.

The arrangement of the emulsion in the magnet and spark gap is shown in Fig. 9. The main flat plates of the magnet body are made of steel. All current-carrying parts of the apparatus were covered with Textolite, steel, and lead blocks and thoroughly tightened. In several cases, unfortunately, the emulsion layers were burned in places in spite of careful packing with Teflon film and the use of a fast-acting device which removed the stack and emulsion from the working region of the magnet.

## 5. EXPERIMENTAL RESULTS

In scanning the emulsion layers, no tracks were found intersecting both layers with an ionization exceeding the ionization of a particle with z = 1.

Knowing the number of proton interactions with the target, we can determine an upper limit of the cross section for monopole production in reaction (8):

$$\sigma(95\%) \leqslant 3.0/\eta N_p N_{Al} A^k, \quad (14)$$

where $N_p$ is the effective number of protons which passed through the target, $N_{Al}$ is the number of aluminum atoms per $\text{cm}^2$, and $A^k$ is the effective number of nucleons in the nucleus. The quantity $N_p N_{Al}$ was de-

termined from the induced radioactivity of $Na^{22}$ nuclei produced in the reaction $Al^{27}(p, 3p3n)Na^{22}$. The cross section for this reaction was assumed to be 10 mb.[25] The combined value of $N_p N_{Al}$ for the three series of irradiations is $\approx 5.35 \times 10^{41}$. In previous attempts to search for the Dirac monopole, it was assumed that the effective number of nucleons in the nucleus was $A^k$ = 1, i.e., it was assumed that the nucleus was completely transparent to protons. On this assumption the result of the present work is

$$\sigma(95\%) \leqslant 2.1 \cdot 10^{-43} \text{ cm}^2$$

If we consider the nucleus nontransparent ($k = \frac{2}{3}$) as has been done by some authors,[23] the following value is obtained:

$$\sigma(95\%) \leqslant 6.3 \cdot 10^{-42} \text{ cm}^2$$

Since the force holding the monopole on the surface of the ferromagnet has a logarithmic dependence on the value of the magnetic charge,[11] the present result is extended to monopoles with higher charge. The experimental result also can be extended to dyons.[3, 4]

The authors thank V. M. Galitskiĭ for taking part in analysis of the interaction of monopoles with matter, A. A. Logunov, A. A. Naumov, and Yu. D. Prokoshkin for assistance in planning the experiment, A. A. Zhuravlev, A. P. Kurov, and the crew of the Ring Accelerator Section, IHEP synchrotron, and also V. I. Nikitkin, A. V. Tel'nov, V. P. Smazkin, and V. S. Khlestov for assistance in performing the experiment.

[1] P. A. M. Dirac, Proc. Roy. Soc. (London) A133, 60 (1931); Phys. Rev. 74, 817 (1948).

[2] Monopol' Diraka (The Dirac Monopole), Collection of articles, Mir, 1970.

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

[4] A. O. Barut, XV Intern. Conf. on High Energy Physics, Kiev, 1970.

[5] J. Schwinger, Phys. Rev. 144, 1087 (1966); 173, 1536 (1968).

[6] W. V. R. Malkus, Phys. Rev. 83, 899 (1951).

[7] I. R. Lapidus and J. L. Pietenpol, Am. J. Phys. 28, 17 (1960).

[8] B. Lenart, Dynamics of Charged Particles (Russ. Transl. Atomizdat, 1967).

[9] E. Amaldi, G. Baroni, H. Bradner, H. G. deCarvalho, L. Hoffman, A. Manfredini, and G. Vanderhalghe, CERN 63-13 (preprint) 1963.

[10] V. P. Martem'yanov and S. Kh. Khakimov, Zh. Eksp. Teor. Fiz. 62, 1 (1972) [Sov. Phys.-JETP 35, No. 1 (1972)].

[11] G. Hebert, Short Handbook of Physics (Russ. transl., Fizmatgiz, 1963).

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

[13] V. A. Petukhov and M. N. Yakimenko, Nucl. Phys. 49, 87 (1963).

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

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

[16] W. Z. Osborne, Phys. Rev. Lett. 24, 1441 (1970).

[17] L. W. Alvarez, Ph. M. Eberhard, R. R. Ross, and R. D. Watt, Science 167, 701 (1970).

[18] H. Bradner and W. M. Isbell, Phys. Rev. 114, 603 (1959).

[19] M. Fidecaro, G. Finocchiaro, and G. Giacomelli, Nuovo Cimento 22, 657 (1961).

[20] E. M. Purcell, G. B. Collins, T. Fujii, J. Hornbostel, and F. Turkot, Phys. Rev. 129, 2326 (1963).

[21] M. I. Blagov, V. A. Muraschova, T. I. Syreitschikova, Yu. Ya. Telnov, Yu. D. Usachov, and M. N. Yakimenko, XV Intern. Conf. on High Energy Physics, Kiev, 1970.

[22] I. I. Gurevich, S. Kh. Khakimov, V. P. Martemianov, A. P. Mischakova, V. V. Ogurtzov, V. G. Tarasenkov, L. M. Barkov, and N. M. Tarakanov, Phys. Lett. 31B, 394 (1970).

[23] W. Galbraith, High Energy and Nuclear Physics Data Handbook, 1953. Yu. M. Antipov, V. N. Bolotov, M. I. Devishev, et al., Institute of High Energy Physics, Experimental Physics Section, SÉF 67-24.

[24] L. M. Barkov, V. P. Martem'yanov, V. V. Ogurtsov, V. G. Tarasenkov, and S. Kh. Khakimov, Prib. Tekh. Éksp. 2, 241 (1968); V. P. Martem'yanov, V. V. Ogurtsov, V. G. Tarasenkov, and S. Kh. Khakimov, Report IAÉ-2095, Kurchatov Atomic Energy Institute, 1971.

[25] P. Duteil, L. Gilly, et al., Rev. Sci. Instr. 35, 1523 (1964).

Translated by C. S. Robinson
179