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TO THE FIFTIETH ANNIVERSARY OF THE DIRAC MONOPOLE PROBLEM

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1. INTRODUCTION

Half a century passed since Dirac* predicted the possibility of existence of free magnetic charges in nature. It seems the history of physics does not know another precedent when such a great amount of human efforts have been bent to the confirmation of serious and concrete theoretical predictions, without solving the problem.

For more than ten years the authors used the excellent opportunities of collecting information of the publications concerning the problem of magnetic monopole. These data have been used as a foundation for the bibliography /1/. It contains more than 1700 references followed in the majority of cases by the abstracts of original articles.

The bibliography /1/ allows one to follow the history of magnetic monopole problem. In a short history review further below we try to attract attention to some interesting and little known facts.

2. HISTORY OF MAGNETIC CHARGE PROBLEM

As a consequence of the Dirac monopole theory the Maxwell equation obtains a symmetrical form:

$$\mathrm{div}\vec{E} = 4\pi\rho_e; \quad -\frac{1}{c}\frac{\partial\vec{E}}{\partial t} + \mathrm{rot}\vec{B} = \frac{4\pi}{c}\vec{j}_e, \tag{1}$$
$$\mathrm{div}\vec{B} = 4\pi\rho_m; \quad -\frac{1}{c}\frac{\partial\vec{B}}{\partial t} - \mathrm{rot}\vec{E} = \frac{4\pi}{c}\vec{j}_m,$$

where ρ_m and $\vec{j}_m$ are the densities of magnetic charges and magnetic currents. The known empirically established symmetry of electric and magnetic phenomena makes this sequence of Dirac's theory most attractive. Not many know, perhaps, that Heaviside /2/ back in 1892 reduced the system of the Maxwell equations to a bit different but also completely symmetrical and dynamically complete form:

$$\mathrm{curl}(\vec{H} - \vec{h}) = 4\pi k\vec{E} + c\dot{\vec{E}}, \tag{2}$$
$$\mathrm{curl}(\vec{e} - \vec{E}) = 4\pi g\vec{H} + \mu\dot{\vec{H}},$$

*P.A.M.Dirac. Proc.Roy.Soc.A, 1931, vol.133, p.60.

where $\vec{H}, \vec{E}$ (according to Heaviside) denote the intensities of magnetic and electric fields; $\vec{e}$ is the amount of energy taken in by electromagnetic field per second per unit volume per electric current, and $\vec{h}$ is similarly related to magnetic current; k is the coefficient of electric conductivity, g is the coefficient of magnetic conductivity; c is the dielectric permeability, μ is the magnetic permeability.

And, evidently, only the fictitiousness of the concepts used by him (magnetic charges and currents) was the reason for the fact that these mathematically refined equations have not gained general recognition. It is also interesting that two completely different approaches (Dirac's and Heaviside's) bring to the same result - symmetrization of electrodynamics system of basic equations.

We think Heaviside should be regarded as an author of the first published theoretical paper directly related to the magnetic charge problem*. This paper opens the present Bibliography.

The little known presently** investigation by Pierre Curie /3/ should be regarded evidently as the first experimental attempt to solve the problem of existence of free magnetism. The parallelism of electric and magnetic phenomena, according to Curie, gives ground for the following question - whether this analog is more complete. He writes in his paper: "Is it really absurd to suggest that there exist also the magnetism conductors, conductors of magnetic currents, of free magnetism?" And after giving a detailed analysis of the problem whether such phenomena contradict the principles of energetics (l'Energetique) or symmetry conditions, he comes to the conclusion that "... from the viewpoint of energetics and from the viewpoint of symmetry one may think seriously about magnetic currents and magnetic charges". P.Curie concludes this paper with the words: "It would have been too daring, of course, to conclude from

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* The papers by Carrigan /4,5/ cite the Epistola Petri Peregrini de Maricourt de magnete (1269), which he thinks to be probably the earliest recorded observation along these lines "Procul dubio omnes lineae (magneticae) Hujusmondi in duo puncta concurrent sicut omnes orbes meridiani in duo concurrent polos mundi oppositos". (All such lines (magnetic) undoubtedly, gather in two points as well as all meridians meet in the two opposite poles of the world.

** The paper by P.Curie has been pointed out to us by I.M.Frank.

this that these phenomena really exist. But, if it is so, they should answer the above-mentioned requirements".

Simultaneously, P.Curie attempts to find experimentally the magnetic conductivity basing on the "dynamic effect" suggested by him. The concept of the experiment has been as follows: "... in case magnetic conductivity really exists, the transformer, analogous to the AC-transformer but possessing a magnetism conductivity ring yoke, will transform one direct current into another direct current". He checked whether this phenomena was observed with a soft-iron yoke, but obtained no effect.

Among the papers related to the magnetic charge problem and preceding the fundamental investigations by Dirac, one should pay special attention to the Ehrenhaft publications. We have managed to find more than 60 of his publications. The majority of them are experimental papers. By the number of publications Ehrenhaft's investigation is comparable with the total number of experimental searches for the magnetic monopole carried out in the world until present. For more than 20 years Ehrenhaft has been sure that he registers magnetic charges in his experiments. It is difficult to tell now what was his mistake. The fact is - all these works are practically forgotten.

Dirac[6] in 1931 when trying to explain why the observed electric charge is always multiple to the electron charge "e" and why the value of charge "e" is just the one, we know from experiment, made a sudden discovery. He solved the problem completely, assuming that in nature there exist isolated magnetic charges. This situation resembles a bit Heaviside's case. Trying to reduce the Maxwell equations to symmetrical form, Heaviside had to make analogous supposition. In 1948 Dirac developed the general theory of charged particles and poles interacting through electromagnetic field[7]. It should be noted still that in contrast to Heaviside, who regarded magnetic charge as fictitious, Dirac introduced this charge as a naturally existing one and thus layed the foundation of the magnetic charge theory.

The first experimental estimation of the upper limit of Dirac monopole production in atmosphere by primary cosmic rays has been undertaken by Malkus in 1952[8]. The results of this experiment have demonstrated that the number of monopoles reaching the surface is less than $10^{-10} cm^{-2} s^{-1}$.

The Dirac monopoles have been first searched for with accelerator by Brandner and Isbel[9] in 1959 at the 6 GeV proton Bevatron of Massachusetts Institute of Technology. In the pp-collisions at these energies there could appear monopole

SEARCHES FOR MAGNETIC MONOPOLE

COSMIC RAYS

searches in the primary component of cosmic radiation

a) upper layers of the Earth atmosphere (balcon search) /776/

b) Alpine search (Tien Shan) /338/

c) searches at the sea level /310/,/1296/, /241/

d) deepwater searches /312/,/313/

searches for monopoles produced in the interactions of cosmic radiation with matter

a) meteorites: /156/,/955/

b) moon matter speciments /342/,/436/, /579/

c) Earth atmosphere /100/, /1133/, /205/,/439/,/633/, /700/

d) samples from the Earth surface (old rocks, snow from the poles, etc.) /1521/,/211/,/272/, /698/,/700/.

e) samples from the ocean bottom (Pacific, Atlantic) /244/,/365/,/373/, /431/,/447/.

ACCELERATORS

irradiation of the target with high and superhigh energy protons

a) Bevatron MIT-6 GeV /117/

b) CERN-28 GeV /130/,/33/, /148/

c) Brookhaven-30 GeV /159/

d) Serpukhov 70 GeV /669/, /369/

e) Batavia-300, 400 GeV /551/,/613/,/711/, /992/

f) CERN- 2x30 GeV /410/,/598/,/711/, /1321/, /1569/.

irradiation of the target with superhigh energy electrons

a) SLAC-20 GeV 711

irradiation of the target with a beam of secondary particles

a) Neutrons - 100-300 GeV /696/

b) neutrino /699/

c) γ -quant /355/,/485/

ESTIMATION OF MAGNETIC CHARGE VALUE FOR DIFFERENT PARTICLES

a) proton /286/,/69 /1518/

b) neutron /286/

c) electron /286/

d) μ-meson et al. /691/

Fig.1

of masses between π-meson and proton masses. This experiment enabled to define the cross section upper limit $\sim 10^{-35}$ cm^2 of producing monopole pairs with masses approximately equal to proton mass.

Since that time there have been carried out more than 50 experimental searches for magnetic charges. Figure 1 gives a fairly good idea about all experimental searches for Dirac monopole.

The majority of experiments have been based on the predicted by Dirac large value of the magnetic charge $g = 68.5$ e. It is not, generally, difficult to detect particles of such charges at the contemporary level of physical experiment technique. In the performed experiments the monopole has been detected through such effects as: characteristic ionization; abnormally large intensity of Vavilov-Cherenkov radiation; annihilation of monopole-antimonopole pair, and excitation of emf in the closed circuit at the moment a magnetic charge passes through it.

There have been measured also the values of magnetic charge, from which there have been established the upper limits of magneric charges of an electron, proton, μ-meson and other elementary particles.

All sorts of methods have been used in searching for Dirac monopoles. Many of them used a combination of strong pulse magnetic fields - sort of collectors, "extractors" and "accelerators" of magnetic charges with their subsequent registering over one of the above-mentioned methods. The majority of methods suggest, as a rule, a substantial time gap between the moments of monopole production and registration,.which is infavourable since it is necessary to make many different assumptions on the behaviour of monopoles during this time. Some methods, though, allow one to decrease this gap to 10^{-10} s /41,46/

It is also necessary to mention the attempted searches for "non-Dirac" monopoles of magnetic charge g equal to e and (or) less than e /55/.

The following results are obtained now in the main directions of searches for monopoles: the lowest limit of a flux of "cosmic monopoles" $\sim 10^{-19}$ cm^{-2} s^{-1} * has been obtained in the experiments by Fleicher et al. /15,16/, according to whom it is possible to put a stop to further monopole searches.

The construction of more and more powerful accelerators moved further the upper limit of the mass, up to which magnetic monopoles in p-p interactions were not found. The diapason

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* less than two monopoles at the whole Earth surface per second.

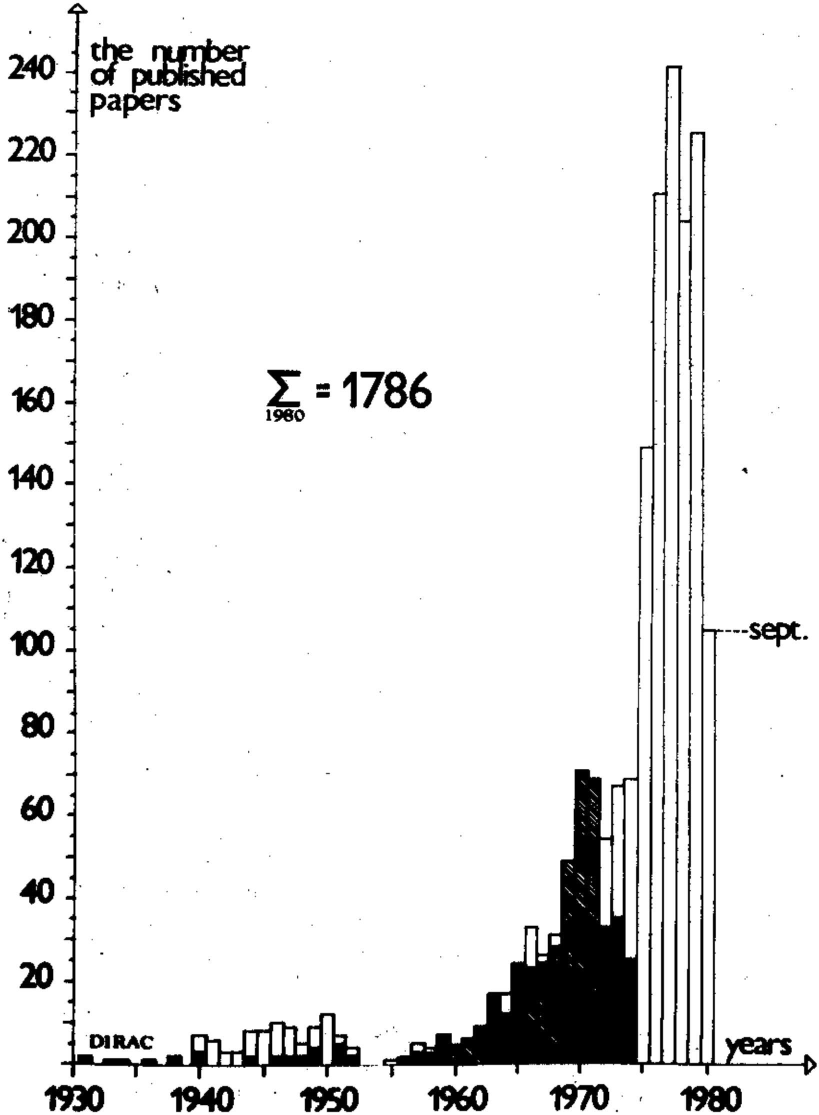

Fig.2

of probable masses of produced monopoles with the upper limit of 1,3,5.5,12,14 m_p has been investigated consequently at cross sections reaching in certain cases the order (10^{-40}–10^{-43}) cm^2.Recent experiments carried out on the colliding proton beams at CERN have moved the upper limit of investigated monopole masses to 30 m_p, though at somewhat higher cross section of their production $10^{-35}cm^2$.

There has been proved the magnetic neutrality of protons, neutrons, electrons and other elementary particles. The limit of the probable nuclear magnetic charge reached $\sim 10^{-26}$ – the value of Dirac minimal charge.

Such a big number of unsuccessful attempts to find the magnetic monopole have ground for certain scepticism even with the author of magnetic charge theory. We do not know whether this or some other factors have given an impulse to further investigation, but after 1975 one can note a quick growth of the number of publications on the subject (see Fig.2). The shadowed part of this figure is based on the data in the possession of the authors in 1975. The figure demonstrates also that a tendency to rapid growth of the number of publications has been present earlier. This has been noted by Academician Vonsowski /59/ in 1973, but the annual number of papers published after 1975 is now more than 200. The total number of articles published in the 50 years of this problem existence has exceeded by now 1700.

A part of this papers develops the Dirac theory by removing from it some earlier difficulties (see for example papers by Yang, Frankel et al.). Other papers, give a variety of different original approaches to magnetic charge problem. Without going into detail we shall illustrate them with just a list of current names of the magnetic monopole.

Beside Dirac monopole one can come across: Schwinger's dyon, Sommerfield-Prasad monopole (dyon), t'Hooft-Polyakov monopole, Wu-Yang monopole, Yang-Mills-Higgs monopole, BPS (Bogomolny-Prasad-Sommerfield) monopole, Abelian monopole, non-Abelian magnetic monopole, SU(3) magnetic monopole, coloured magnetic monopole, topological monopole, tachyon monopole, gravitational magnetic monopole, a.o. The Dirac theory does not give concrete predictions of the magnetic monopole mass* and if one does not take into account (such alternative) a chance that it does not exist, all the negative results of monopole searches with accelerators find a natural explanation in the fact that the monopole mass is essentially higher than the limit obtained by modern accelerators. Due to this the search for magnetic monopoles is carried out systematically with construction of more powerful accelerators.

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* According to the Polyakov-t'Hooft theory the magnetic charge mass $m_g \sim \frac{m_W}{\alpha}$. At the W boson mass of $m_W = 80$ GeV the mass m_g equals 11 TeV.

Presently, there are intensions to search for magnetic charges on the accelerators LEP [60], VBA [61] and colliding p–p beam machine [62].

The authors do not regard themselves as competent enough to systematize all the theoretical papers concerning the magnetic charge problem. But upon the whole, one can conclude assuredly that the magnetic charge problem becomes one of the probable directions on the way to solve the problem of inner structure of elementary particles. Of considerable interest here are the papers by Schwinger [63], Barut [64], Sawada [65], Fryberger [66] and others. Note also that one of the authors of this bibliography [67] has pointed out the simple relation connecting the electron magnetic momentum μ and the Dirac magnetic charge g, which has been unnoticed until now: $\mu = \frac{e\hbar}{2m_e c} = \frac{e}{2\alpha} \cdot r_e = g \cdot r_e$, where r_e is a classical electron radius. In case we express the electric charge through the magnetic charge $e = g \cdot 2\alpha$ we find that two basic characteristics of elementary particle are directly related to the magnetic charge. Isn't it, perhaps, an indirect indication to the fact that the magnetic charge should be a value characterizing not the particle itself but the components of its structure?

To conclude this brief historical review the authors would like to express their hope that with all the interest given now to the magnetic charge problem it will be finally solved soon.

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