The magnetic monopole after its jubilee

A. D. Dolgov

Usp. Fiz. Nauk **144**, 341–346 (October 1984)

Fifty years is quite a venerable age for a physical theory devoid of experimental support. And yet the Dirac monopole which has celebrated its jubilee has never attracted so much attention from physicists of different specialities as during the last several years. The magnetic monopole has become one of central objects of research in the physics of elementary particles, tens of experimental and theoretical papers has been devoted to it. Probably the reason for all this attention is that the Grand Unification models having indicated the necessity for the existence for monopoles as real physical objects have at the same time explained why such objects have not been discovered until now: the mass of the monopole predicted by these models lies far beyond the limits of the customary scale of elementary particle physics, it must be of the order of 10^{16} GeV. At the same time progress in experimental techniques, in the first instance the construction of new apparatus utilizing superconducting elements and of giant detectors designed for the investigation of cosmic neutrinos and also for checking another prediction of the Grand Unification Theory—the instability of nuclear matter, have made it possible if not to obtain an indication of the real existence of monopoles, then at least to make a significant advance in establishing the upper limit on their existence in nature, and first of all in cosmic rays.

The aim of the present note is to indicate the experimental data obtained at present and to indicate certain more interesting theoretical ideas developed since Coleman's review, the translation of which is published in the current issue of Usp. Fiz. Nauk. Evidently the clearest and unambiguous indication of the existence of a monopole would be given by the discovery of the magnetic flux associated with it (cf., the discussion of this question in the above mentioned review[1], Sec. 2a). It is an essential point that such an effect is independent of the mass and the velocity of the monopole which are not known in advance. A change in the magnetic flux can be observed using the phenomenon of electromagnetic induction. Let the magnetic charge of magnitude ng_0, where $g_0 = \hbar c/2e$ is the elementary magnetic charge, e is the electric charge of the electron, pass through a current carrying circuit. Then the magnetic flux encircled by the circuit changes by the amount $4\pi ng_0 = 4\pi n\hbar c/2e = 2n\varphi_0$, where $\varphi_0 = 2.07\cdot10^{-7}\,\text{G}\cdot\text{cm}^2$ is the quantum of the magnetic flux in a superconducting circuit. The current in the circuit will be changed correspondingly, and with a sufficiently low background this change can be observed by an apparatus. In the early 1970's the group of L. Alvarez in California began an investigation of the possibility of applying this effect to the search for monopoles by utilizing the superconducting quantum interferometer—SQUID. In February 1982 B. Cabrera[2] recorded a discontinuous jump in the readings of the instrument in his apparatus, constructed utilizing the above principle, and interpreted this phenomenon as the trace of a monopole which passed through his equipment. The superconducting circuit was a loop of niobium wire with the diameter of the loop being 5 cm. A special feature of the apparatus was the particularly low level of the external magnetic field over the loop, less than 10^{-7} G which was attained with the aid of a superconducting screen. In order to shield the apparatus from different variations of the external magnetic field it was, moreover, surrounded by a shield of a magnetic alloy. As a result the level of the background did not exceed 1% of the level of the signal recorded in the equipment. Further observations using this equipment, and also an improved instrument with increased efficiency which utilized a triple superconducting loop of diameter much greater than the earlier one ("triaxial detector") did not record any new signals.[3] This led to the conclusion that the flux of monopoles is bounded by a value of the order of $10^{-11}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$. Although until now no specific deficiencies have been noted in Cabrera's experiment, a single event cannot be regarded as convincing proof of the existence of a monopole. We note that in the past there has been only one serious paper claiming the discovery of a monopole[4]; we are referring to a specific track in mica which was observed in an apparatus lifted by a high altitude balloon. Probably this track was made by a heavy nucleus.[5]

In experiments which were made prior to the early 1980's monopoles could have been observed if they satisfied one of the following three conditions:

1. The monopole mass is not too great, so that monopole-antimonopole pairs could be produced by the existing accelerators. Experiments of this kind have been carried out repeatedly. The most accurate measurements have been carried out at CERN[6] on colliding pp-beams of energy 540 GeV. The limit obtained on the creation of monopole pairs naturally depends on the charge and the mass of the monopole; it is asserted that the production cross section is less than 10^{-32}–10^{-31} cm^2 for monopoles of charge g_0 and of mass $M \leqslant 140$ GeV.

2. The monopoles are efficiently captured by ordinary

0038-5670/84/100786-04$01.80

matter and are confined in it by magnetic forces. Then by applying a sufficiently strong external magnetic field one might be able to extract a monopole and direct it to a detector. A search for monopoles was made in meteorites[7], and it was established that their matter contained less than one monopole per 10^{27} nucleons (on the assumption that the mass M does not exceed $5\cdot10^{14}$ GeV). It is natural to attempt to look for monopoles in magnetic minerals within which very strong internal magnetic fields exist. A proposal was made[8] to install equipment capable of detecting and recording monopoles in a concentrating mill treating iron ore.

3. Monopoles move quite rapidly; in doing so they ionize matter significantly more strongly than usual charged particles. It is using this particular principle that old style detectors of monopoles were constructed, particularly those which were designed to search for monopoles in cosmic rays.

We note that the determination of the ionizing power of a monopole if it is not ultrarelativistic is quite a complex theoretical problem. Several papers[9–11] have appeared recently devoted to the calculation of ionization losses of monopoles, but this problem has not been finally solved since the results due to different authors show significant divergence. A suggestion has been made to use for the discovery of monopoles the thermoacoustic effect associated with ionization, but the signal-to-noise ratio due to thermal fluctuations is not sufficiently great in the present case for a dependable observation of the effect.[12]

None of the above conditions is suitable for the superheavy monopoles in the Grand Unification models. Such particles could be accelerated by galactic magnetic fields to velocities not exceeding 10^{-2} of the velocity of light c. At velocities of the order of $10^{-4}\,c$ the monopoles are captured by the solar system, but the most probable velocities are of the order of the velocity of motion of the sun within the galaxy, i.e., $\beta = v/c \approx 10^{-3}$. Superheavy monopoles, even the not very rapid ones, have too great an inertia and therefore cannot be stopped by atomic magnetic fields; thus, these particles must have a very high penetrating power.

To make a search for superheavy monopoles, giant underground detectors were utilized which have been constructed in recent years for the investigation of cosmic neutrinos, and also for checking the most prominent prediction of the Grand Unification Theory, in the hope of observing proton decay. Several experiments have been conducted[13–19] for the detection of monopoles that might be present in cosmic rays. Tremendous masses of the detecting substance with a relatively low background have made it possible to decrease significantly the upper limits on the fluxes of cosmic monopoles with high penetrating power. The best experimental limitation has been obtained using the Baksan neutrino detector[19]: $F < 5\cdot10^{-15}$ cm^{-2} s^{-1} sr^{-1} for $\beta \approx 5\cdot10^{-4} - 0.2$. Limits higher by an order of magnitude have been established[17] in the range $\beta \approx 10^{-3} - 10^{-2}$ with the aid of the SOUDAN-1 detector intended for the detection of proton decay. The experiment of Ref. 15 utilizing plastic scintillation counters in the underground detector of cosmic rays in Utah (USA) gave a limit of $F < 5\cdot10^{-12}$ cm^{-2} s^{-1} sr^{-1} for $10^{-4} < \beta < 3\cdot10^{-2}$. Of the same order of magnitude are also the limits obtained by other groups using detectors for proton decay.

If monopoles had been found in cosmic rays at such a high level this would have been surprising from the point of view of astrophysics. If free monopoles existed in the galaxy they would have been accelerated by large-scale magnetic fields the existence of which is well known. Domogatskiĭ and Zheleznykh[20] have shown that in the presence of a sufficiently great number of monopoles in cosmic space the energy of the galactic magnetic field would have been expended in producing magnetic currents, and the fields could not exist. This consideration was utilized by Parker and other authors[21–26] in order to estimate the maximum monopole fluxes admissible from this point of view. The results are not very definite but the expected flux can hardly exceed 10^{-16}–10^{-15} cm^{-2} s^{-1} sr^{-1} for $\beta \sim 10^{-3}$. Of course, there still exists a possibility that the flux of cosmic monopoles near the earth exceeds by many times the average fluxes in the galaxy, for example due to the effect of the sun.[26] Only in this case does a hope remain that cosmic monopoles will be discovered.

The problem of the monopoles arising as complex field systems in gauge theories with spontaneous symmetry breaking is one of the remarkable examples of the mutually enriching connection between the physics of elementary particles and cosmology, a connection the importance of which has become evident in recent years.[27] The point is that the superheavy monopoles could be produced in a natural manner only at an early stage of the development of the universe near the phase transition which violates the symmetry of the Grand Unification which existed in the world at the superhigh temperatures immediately after the Big Bang. In the phase transition a nonvanishing vacuum average appears in the case of the Higgs fields and if this process occurs as a drop condensation of stream independently in different regions of space, then in the resultant hot chaos conditions are produced for the formation of localized field configurations with nontrivial topology—the monopoles. However, it has turned out that in the usual Big Bang model the density in the universe of monopoles that might be preserved until our time is catastrophically great.[28,29] Different considerations have been advanced in order to overcome this difficulty (cf. reviews devoted to the connection of the theory of elementary particles with cosmology[27,30,31]). Apparently the most sensible solution of the problem of the monopoles is obtained in the inflationary model[32–34] which also seems attractive from other points of view. In this model the phase transition occurs in the process of the exponential expansion due to the tremendous store of energy contained in the vacuum which is symmetric with respect to the Grand Unification group. During the period of expansion following the phase transition the region of the nonsymmetric phase inflates to the dimensions of the whole visible universe. In such a development of events one can explain the homogeneity of the universe and its almost flat geometry, and also the fact that there are no relict monopoles in space, since in the phase transition they could be formed only at the boundaries between phases with differently broken symmetry. In principle the monopoles could also be produced in pairs in the collision of particles, for example quarks or photons which are produced in the explosive condensation of vacuum. However, a rough estimate of this effect[35] gives an upper limit which is by many orders of magnitude lower than the limit obtained from the existence of galactic magnetic fields. Thus, it is not excluded that the superheavy monopole will for a long time remain an exotic object exhaustively studied theoretically, but unattainable for experimental observation, since it is not possible to create it artificially, and if it occurs in nature at all it does so extremely rarely. This conclusion is all the more disappointing, since possibly a most interesting phenomenon is associated with the monopole which was recently predicted theoretically.

The Grand Unification monopole could be easily observed due to the destructive effect which it produces in nuclear matter. Rubakov[36] noted (later the same conclusion was also reached by Callan[37] and Wilczek[38]) that the monopole must catalyze the decay of the nucleon predicted by the Grand Unification model due to the existence of transitions of quarks into leptons. We refer to a reaction of the type

$$M + p \to M + \mu^+ + \text{hadrons}, \qquad (1)$$

which according to Rubakov's predictions must take place with a high cross section possibly attaining values of 10^{-26} cm^2. In the presence of significant fluxes of cosmic monopoles the effective lifetime for the proton would be essentially decreased compared to the value obtained on the basis of estimating the probability of spontaneous decay.[39,40] Particularly sensitive to fluxes of monopoles are neutron stars since they produce powerful gravitational fields and possess a high density of nuclear matter. On entering a neutron star monopoles must lead to the decay of neutrons and this would lead to intensive radiation in the x-ray and ultraviolet regions which could be recorded on earth.[41,42]

Naturally all the quantitative estimates depend in an essential manner on the total cross sections of all the processes of the type of (1). Callan[43] has proposed the following qualitative explanation of why this process must occur with a high cross section. Let us consider the scattering of an electric charge by a magnetic pole. As is well known (cf., for example, the review by Coleman[1], Sec. 2d), the angular momentum of the system includes a term $eg\mathbf{n}$ determined by the field, where $\mathbf{n}$ is the unit vector indicating the direction from the monopole towards the charge. For the scattering of a charge of spin 1/2 (in contrast to a scalar particle) in a state with the lowest angular momentum there is no centrifugal barrier and nothing prevents the charges from coming close to one another. However, for forward scattering in a frontal collision the vector $\mathbf{n}$ must change sign, and this is allowed by the conservation of angular momentum only if at the same time the product eg changes sign, i.e., charge exchange occurs. Thus, in the immediate vicinity of the center of the monopole the process of the transition of a quark into an antiquark dominates over elastic scattering. Conservation of color and electric charge would not have allowed the antiquark to move out of the region of space occupied by the monopole, but in the core of the monopole there exists a heavy boson field predicted by the Grand Unification Theory, which is colored and charged, and the conversion of which into another antiquark and a lepton (for example, a positive muon) guarantees the conservation of color and charge for the process as a whole. The baryon charge is not conserved in this case. It could be expected that proton decay will occur if one of the quarks contained within it collides with the monopole, and therefore it seems natural that the cross section for the process of catalysis of proton decay must be of the order of its geometrical cross section, 10^{-26} cm^2. The enhancement of charge exchange in an S-wave is also confirmed by a careful investigation based on the Dirac equation of the relativistic scattering of a charge by a monopole.[44–46] An additional enhancement of the effect is predicted[47] on the basis of an analysis of the radiative capture of a monopole by an atom, by analogy with the enhancement of μ-capture. The role of atomic effects has also been discussed in other papers.[48a] However, the principal question still remains not completely elucidated at present[48b]: how can one correctly describe the interaction of a quark with quantized boson fields within the monopole? This interaction occurs at such small distances which are unattainable for investigation in other processes.

The prediction of the Rubakov effect and Cabrera's experiment served as additional stimuli for the investigation of monopoles. Conferences are convened regularly to discuss new ideas in this field; such a conference took place in Orsay[49] in the fall of 1983. A number of new projects for experimental installations to search for monopoles was presented. They should make possible to bring the upper limit on the flux of monopoles from space to a level allowed by astrophysical considerations.

To books containing the "old" theory of monopoles[50–52] a number of reviews and collections of papers[1,53–57] has been added in which newest attainments of theory and experiment are discussed.

[1] S. Coleman, The Magnetic Monopole Fifty Years Later, In "The Unity of the Fundamental Interactions", A. Zichichi ed., Proc. of the 1981 School on Subnuclear Physics, held at Erice, Sicily, Plenum Press, N.Y. 1983. [Russ. Transl. Usp. Fiz. Nauk **144**, 277 (1984)].

[2] B. Cabrera, Phys. Rev. Lett. **48**, 1378 (1982).

[3] B. Cabrera, M. Taber, R. Gardner and J. Bourg, Phys. Rev. Lett. **51**, 1933 (1983).

[4] P. B. Price, E. K. Shirk, W. Z. Osborne and L. S. Pinsky, Phys. Rev. Lett. **35**, 487 (1975); Phys. Rev. **D 18**, 1382 (1978).

[5] K. Kinoshita and P. B. Price, Phys. Rev. **D 24**, 1707 (1981).

[6] B. Aubert, P. Musset, M. Price and J. P. Vialle, Phys. Lett. **B 120**, 465 (1983).

[7] P. H. Eberhard, R. R. Ross, L. W. Alvarez and R. D. Watt, Phys. Rev. **D 4**, 3260 (1971).

[8] D. Cline, In: Magnetic Monopoles/Ed. R. A. Carrigan and W. P. Trower, Plenum Press, N.Y., 1983, p. 245.

[9] S. P. Ahlen and K. Kinoshita, Phys. Rev. **D 26**, 2347 (1982).

[10] S. P. Ahlen and G. Tarlé, Phys. Rev. **D 27**, 688 (1983).

[11] S. D. Drell, N. M. Kroll, M. T. Mueller, S. J. Parke and M. A. Ruderman, Phys. Rev. Lett. **50**, 644 (1983).

[12] C. W. Akerlof, Phys. Rev. **D 26**, 1116 (1982); **D 27**, 1675 (1983).

[13] J. D. Ullman, Phys. Rev. Lett. **47**, 289 (1981).

[14] R. Bonarelli, P. Capiluppi, I. D'Antone, G. Giacomelli et al., Phys. Lett. **B 112**, 100 (1982); **B 126**, 137 (1983).

[15] D. E. Groom, E. C. Loh, H. R. Nelson and D. M. Ritson, Phys. Rev. Lett. **50**, 573 (1983); **51**, 941 (1983).

[16] J. K. Sokolowski and L. R. Sulak, In: Proc. of the XXI Intern. Conference on High Energy Physics, Paris, 1982.

[17] J. Bartelt et al., Phys. Rev. Lett. **50**, 655 (1983).

[18] T. Mashino, K. Kawagoe and M. Koshiba, J. Phys. Soc. Jpn. **51**, 3067 (1982).

[19] E. N. Alekseev, M. M. Valiev, A. E. Chudakov et al., Preprint IYaI AN SSSR (Institute for Nuclear Research, Acad. Sci. USSR) No. PO268, Moscow, 1983; Lett. Nuovo Cimento **35**, 413 (1982).

[20] G. V. Domogatskiĭ and I. M. Zheleznykh, Yad. Fiz. **10**, 1238 (1969) [Sov. J. Nucl. Phys. **10**, 702 (1970)].

[21] E. N. Parker, Astrophys. J. **160**, 383 (1970).

[22] G. Lazarides, Q. Shafi and T. F. Walsh, Nucl. Phys. **B 195**, 157 (1982).

[23] M. S. Turner, E. N. Parker and T. J. Bogdan, Phys. Rev. **D 26**, 1296 (1982).

[24] J. Arons and R. D. Blanford, Phys. Rev. Lett. **50**, 544 (1983).

[25] a) Y. Raphaeli and M. S. Turner, Phys. Lett. **B 121**, 115 (1983) b) J. Stein-Schabes and J. D. Barrow, Phys. Lett. **B 122**, 31 (1983).

[26] S. Dimopoulos, J. P. Preskill and F. Wilczek, Phys. Lett. **B 119**, 320 (1983).

[27] A. D. Dolgov and Ya. B. Zel'dovich, Usp. Fiz. Nauk **130**, 559 (1980) [Rev. Mod. Phys. **51**, 1 (1981)].

[28] Ya. B. Zeldovich and M. Yu. Khlopov, Phys. Lett. **B 79**, 239 (1978).

[29] J. P. Preskill, Phys. Rev. Lett. **43**, 1365 (1979).

[30] J. D. Barrow, Fundam. Cosmic Phys. **8**, 83 (1983).

[31] A. D. Dolgov, Progress in Particle Physics and Modern Cosmology: Preprint ITEP, Moscow, 1983.

[32] A. H. Guth, Phys. Rev. **D 23**, 347 (1981).

[33] A. D. Linde, Phys. Lett. **B 108**, 389 (1982).

[34] A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. **48**, 1220 (1982).

[35] M. S. Turner, Phys. Lett. **B 115**, 95 (1982).

[36] V. A. Rubakov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 658 (1981) [JETP Lett. **33**, 644 (1981)]; Preprint IYaI AN SSSR (Inst. Nucl. Res. Acad. Sci. USSR) R-0204, Moscow, 1981; Nucl. Phys. **B 203**, 311 (1982).

[37] C. G. Callan, Phys. Rev. **D 25**, 2141 (1982); **D 26**, 2058 (1982).

[38] F. Wilczek, Phys. Rev. Lett. **48**, 1146 (1982).

[39] J. Ellis, D. V. Nanopoulos and K. A. Olive, Phys. Lett. **B 116**, 127 (1982).

[40] F. A. Bais, J. Ellis, D. V. Nanopoulos and K. A. Olive, Nucl. Phys. **B 219**, 189 (1983).

[41] E. W. Kolb, S. A. Colgate and J. A. Harvey, Phys. Rev. Lett. **49**, 1373 (1982).

[42] S. Dimopoulos, J. Preskill and F. Wilczek, Phys. Lett. **B 119**, 320 (1982).

[43] C. G. Callan, Nucl. Phys. **B 212**, 391 (1983).

[44] A. S. Blaer, N. H. Christ and J. F. Tang, Phys. Rev. Lett. **47**, 1364 (1981); Phys. Rev. **D 25**, 2128 (1982).

[45] V. P. Nair, Phys. Rev. Lett. **51**, 631 (1983).

[46] C. G. Callan and S. R. Das, Phys. Rev. Lett. **51**, 1155 (1983).

[47] L. Bracci and G. Fiorentini, Phys. Lett. **B 124**, 29 (1983); Nucl. Phys. **B 232**, 236 (1984).

[48] a) J. Arafune and M. Fukugita, Phys. Rev. Lett. **50**, 1901 (1983) b) T. F. Walsh, P. Weisz and T. T. Wu, Nucl. Phys. **B 232**, 349 (1984).

[49] CERN Courier **23**, 318 (1983).

[50] Monopol' Diraka (Dirac Monopole), Collection of articles, Eds. V. M. Bolotovskiĭ and Yu. D. Usachev, Mir, M., 1970.

[51] S. V. Vonsovskiĭ, Magnetizm mikrochastits (Magnetism of Microparticles), Nauka, M., 1973.

[52] V. I. Strazhev and L. M. Tomil'chik, Elektrodinamika s magnitnym Zaryadom (Electrodynamics with a Magnetic Charge) Nauka i tekhnika, Minsk, 1975.

[53] Monopoles in Quantum Field Theory, Eds. N. S. Craigie, P. Goddard and W. Nahm, World Sci. Publ. Singapore, 1982.

[54] R. A. Carrigan and W. P. Trower, Sci. Am. **246** (4), 102 (1982) [Russ. Transl. Usp. Fiz. Nauk **139**, 333 (1983)].

[55] B. Cabrera and W. P. Trower, Found. Phys. **13**, 195 (1983).

[56] Magnetic Monopoles, Eds. R. A. Carrigan and W P Trower, Plenum Press, N. Y., 1983.

[57] R. A. Carrigan and W. P. Trower, Nature **305**, 673 (1983).

Translated by G. M. Volkoff