Flux Limit on Cosmic-Ray Magnetic Monopoles from a Large Area Induction Detector

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The design and performance of a superconducting induction detector with two 60-cm-diam superconducting loops is presented. During eight months of data taking, no candidate events were observed and an upper limit on the flux of cosmic-ray magnetic monopoles $F_m \lesssim 6.7\times10^{-12}$ cm^2 sr^{-1} sec^{-1} (90% C.L.) is set. The detector demonstrates the possibility of operating large induction detectors in ambient magnetic fields greater than 1 mG.

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The concept of magnetic monopoles was invented by Dirac[1] in 1931 as a possible explanation for the quantization of charge. In 1974 t' Hooft[2] and Polyakov[3] showed that magnetic monopole states are to be expected in unified gauge theories, and that the monopole mass could well be very large (up to $\sim 10^{20}$ GeV/c^2). The large mass has strong implications for previous searches: these monopoles could be too heavy to be produced at accelerators,[4] too energetic to stop readily and be trapped in surface material,[6] and possibly too slow to ionize heavily.[6] In this paper we present a cosmic-ray monopole flux limit measured using Faraday induction, a technique independent of monopole velocity or mass.

From Faraday's law of induction,[7] a magnetic monopole passing through a closed superconducting loop induces a current $I=4\pi g/L$, where g is the magnetic charge of the monopole, and L is the inductance of the loop. Dirac quantization[1] predicts that the magnetic flux from a monopole is an integer multiple of $4\pi g_{\mathrm{D}}=4.14\times10^{-7}$ G cm^2. Magnetic induction as a method of monopole detection is unique in that the signal is produced by a *macroscopic* change in the field at the loop. The method is thus accessible to direct calibration, and the signal depends only on the magnetic charge of the monopole. In contrast, other known detection techniques are quite complex in detail and depend on unknown monopole properties such as mass, velocity, and even whether or not it has attracted and bound a companion nucleus.[8] These properties influence the interaction of the monopole with atomic electrons and nuclei. As the signal depends upon the microscopic details of this interaction, detectors of this type cannot be directly calibrated.

The use of magnetic induction for detecting monopoles was suggested by Alvarez[9] in 1963 and independently by Tassie[10] in 1964. The experiments by Alvarez *et al.*[11] in 1964 and by Vant-Hull[12] in 1968 were searches for monopoles trapped in matter in which material was passed through a search coil. In 1981 Cabrera[13] made the first use of magnetic induction to search for cosmic-ray monopoles by operating a 5-cm-diam coil in a carefully constructed region where the ambient magnetic field had been reduced to 5×10^{-8} G. A striking candidate for a single-charge Dirac monopole was found in an exposure of 151 d. This one event, if taken as a monopole, would yield a monopole flux of 6.1×10^{-10} cm^{-2} sr^{-1} sec^{-1}. A second experiment by Cabrera has seen no events, and has published a flux limit of 3.7×10^{-11} cm^{-2} sr^{-1} sec^{-1} (90% C.L.), equivalent to 37 times the exposure of the first experiment.[14]

Although the induction technique is comprehensive and inherently simple, the requirement of an ultralow magnetic field environment precludes very large detectors. This limitation would be a serious drawback in the search for cosmic-ray magnetic monopoles in view of astrophysical considerations which place a bound on the flux of these particles at the surface of the earth. In particular, Parker and colleagues[15] have shown that the survival of the galactic magnetic field limits this flux to $F_m \lesssim 1\times10^{-15}$ cm^{-2} sr^{-1} sec^{-1}. A flux at this bound could be detected in 1 yr with a 1000-m^2 detector. In this paper we present the results from a prototype induction detector for which we have overcome the requirement of a low ambient magnetic field.

The signal from a monopole in a 1-m^2 loop corresponds to a change in the average magnetic field of $\sim 10^{-11}$ G. To see signals at this level, one alternative is to work in ultralow fields[13]; we have asked instead that the field be stable. This is done by completely surrounding the loop with a superconducting Pb shield. When the shield is cooled below the critical point, the ambient field is trapped within and subsequent changes in the external field are shielded from the loop by the superconductor.

A problem encountered in designing a large area detector is due to the inductive coupling of the superconducting loop and the surrounding superconducting shield. A monopole passing through the shield and the loop induces currents in each. The currents induced in the shield are responsible for a magnetic flux which impinges upon the detector loop. This induces a current in the loop which opposes the current induced by the monopole. The shield therefore has the net effect of reducing the signal. In the case of a circular loop inside of a closed cylindrical shield this effect increases as the diameter of the loop is increased. When the loop and shield are of equal diameter no signal can be obtained. We have solved this problem, as have other groups,[16,17] by twisting the loop into a gradiometer pattern of cells. (The solution is not new: Ampere invented it in 1820 to reduce the effects of the earth's field in his experiments.[18]) The field from currents in the shield induces opposing currents in neighboring cells which cancel one another with greater efficiency for finer grid patterns. The gradiometer loop used in our detector[19] is shown in Fig. 1. Our detector has two identical gradiometer loops, each of diameter 60 cm and cell width 5 cm, separated by 21 cm. They are located inside cylindrical shields of the same diameter. The endcaps of the shields are domed for mechanical stability. The distance between the gradiometer and the endcaps thus varies between 4.25 and 9.50 cm. Each loop is coupled, via an impedance matching transformer,[20] to a SHE Corporation Model 30 SQUID.[21]

The detectors operate in a magnetic field of $\sim$1–10 mG which is trapped by the superconducting shields at the time of the transition to the superconducting state. This field is 5 orders of magnitude larger than the ultralow field used by Cabrera and is obtained by reducing the earth's field with the aid of a 183-cm diameter, 213-cm tall, steel pipe. In the presence of a large field, vibration can lead to spurious signals by initiating flux jumps in the loop circuit or by causing motion of the shield relative to the loop. To safeguard against these possibilities, the gradiometer loop is rigidly connected to the shield in each detector and the detectors are suspended from support rods extending to vibration-isolation devices on the exterior shell of the cryostat. This also mechanically decouples the detectors while allowing access for vibration-sensitivity tests.

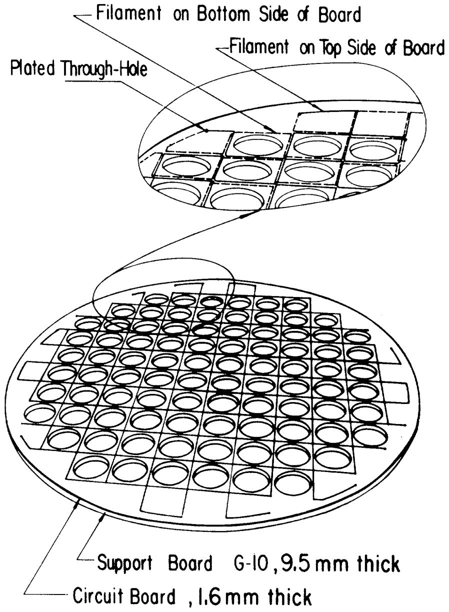

FIG. 1. A perspective view of the gradiometer circuit board mounted to a 1-cm thick G-10 support plane. The gradiometer pattern uses both sides of the circuit board. Holes are cut to reduce mass for economy in cooling to 4 K.

More isolation is obtained by operating the detectors in vacuum and cooling by conduction. This eliminates vibration caused by bubbling and pressure changes which are encountered when cooling by immersion in a liquid-helium bath. Cooling by conduction also ensures that thermal time constants are large enough that no abrupt or localized temperature changes can occur, and that all thermal gradients (which cause currents to flow) are small and stable.

We have found that disturbances in the environment of the apparatus can cause dc offsets[22] in the signal from the detector which are similar to the offset expected for the passage of a monopole. The most common sources of these signals are magnetic field fluctuations and mechanical vibration of the SQUID systems. Radio-frequency (rf) radiation can also cause offsets by interfering with the rf biasing of the SQUID. To distinguish these background signals from true events, we have installed a variety of monitoring devices. These measure ambient magnetic field, vibration, rf radiation, sound, pressure of the nitrogen system, and the temperature and pressure of the cryostat. The data from the detector and some of the monitors are recorded by an eight-channel strip chart recorder. A PDP-11 computer with a 32-channel analog-to-digital system samples all of the monitors and the SQUID's at 10.1 Hz and records the data onto magnetic tape.

The detector sensitivity is calibrated indirectly to better than 10% by measuring the self-inductance of the gradiometer. A direct calibration, good to better than 5%, is obtained by exciting any of six slender solenoids ("pseudo poles"), which thread each shield and detector loop, to the level of a monopole flux. The two results are in agreement and predict a signal[23] of 5.0 mV for a single Dirac-charge monopole penetrating the detector along the axis of the cylindrical shield. To evaluate the effect of the mutual inductance of the shield and the detection loop, we have calculated the response function of our detector by solving in closed form the boundary-value problem of a monopole passing through a cylindrical shield with top and bottom endcaps. The response function was obtained by generating events with random trajectories through the shield, and calculating the detector response for each. The resulting probability curve is shown in Fig. 2.

There were no coincident offsets observed. A histogram of unexplained[24] offsets greater than 1 mV appearing in either of the detector loops is shown in Fig. 2. Although the long tail of the detector response curve extends down to the region of the small offsets, the total integrated probability below 3.2 mV is only 1.2%. The complete absence of offsets in the high-probability region of the curve indicates that the unexplained single offsets are part of a spurious signal background and are not monopole candidates at the 90% C.L. One large offset of 12.7 mV, not shown in Fig. 2, was observed. This offset is not consistent with a singly charged Dirac monopole, or even an integral number of Dirac charges.[25]

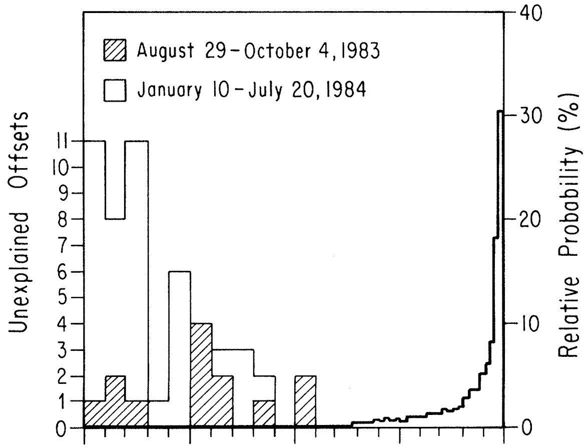

FIG. 2. The measured spectrum of events (left-hand scale), and the calculated response function of the detector to a single-Dirac charge monopole (right-hand scale). The cross-hatched events are from the first "shakedown" run.

In conclusion, we have demonstrated that inexpensive, large area superconducting detectors can be stably operated in easily obtained ambient magnetic fields. No monopole candidate events have been recorded for either detector loop in 200 d of operation. The total sensitive area for a monopole passing through either or both of the loops is 2100 cm^2 averaged over all angles. This exposure thus sets a 90%-C.L. limit, $F_m \lesssim 6.7\times10^{-12}$ cm^{-2} sr^{-1} sec^{-1} on the flux of cosmic-ray magnetic monopoles at the earth's surface, independent of monopole velocity.[26] This experiment corresponds to 215 times the sample of Cabrera's first experiment. The probability that these two results are compatible is less than 0.5%.

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[1] P. A. M. Dirac, Proc. Roy. Soc. London, Ser. A **133**, 60 (1931), and Phys. Rev. **74**, 817 (1948), and Int. J. Theor. Phys. **17**, 235 (1978).

[2] G. t' Hooft, Nucl. Phys. **B79**, 276 (1974).

[3] A. M. Polyakov, Zh. Eskp. Teor. Fiz. Pis'ma Red **20**, 430 (1974) [JETP Lett. **20**, 194 (1974)].

[4] See, for example, P. Musset, M. Price, and E. Lohrmann, Phys. Lett. **128B**, 333 (1983); B. Aubert, P. Musset, M. Price, and J. P. Vialle, Phys. Lett. **120B**, 465 (1983).

[5] See, for example, P. H. Eberhard, R. N. Ross, L. W. Alvarez, and R. D. Watt, Phys. Rev. D **4**, 3260 (1983).

[6] A very complete description of ionization techniques

and experiments is given in T. M. Liss, S. Ahlen, and G. Tarlé, Phys. Rev. D **30**, 884 (1984).

[7] *Faraday's Diary,* edited by Thomas Martin (Bell, London, 1932) Vol. 2.

[8] See, for example, the review by S. Ahlen, in Proceedings of Monopole '83, Ann Arbor, Michigan, edited by J. Stone (to be published).

[9] L. W. Alvarez, Lawrence Berkeley Laboratory Physics Note No. 470, 1963 (unpublished).

[10] L. J. Tassie, Nuovo Cimento **38**, 1935 (1965).

[11] L. W. Alvarez, private communication. A nonsuperconducting detector, capable of detecting magnetic charges of 0.2 Dirac charges was built in 1964 by L. W. Alvarez, A. J. Schwenin, Robert Smith, and Robert Watt. The later, superconducting detector of Ref. 5 was used to search lunar material. The 1963 Lawrence Berkeley Laboratory note of Ref. 9 explicitly mentions superconductivity.

[12] Lorin L. Vant-Hull, Phys. Rev. **173**, 1412 (1968). To our knowledge this is the first published use of a SQUID (superconducting quantum interference device) in a monopole detector.

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

[14] B. Cabrera *et al.*, Phys. Rev. Lett. **51**, 1933 (1983).

[15] E. N. Parker, Astrophys. J. **160**, 383 (1970); M. S. Turner, E. N. Parker, and T J Bogdan, Phys. Rev. D **26**, 1296 (1982).

[16] C. D. Tesche *et al.*, Appl. Phys. Lett. **43**, 384 (1983); C. C. Tsui, in *Magnetic Monopoles,* edited by Richard Carrigan, Jr., and W. Peter Trower (Plenum, New York, 1983), p. 201.

[17] J. G. Park and C. N. Guy, to be published; C. N. Guy, in Proceedings of Monopole '83, Ann Arbor, Michigan, edited by J. Stone (to be published).

[18] Andre-Marie Ampere, *Theorie des Phenomenes Electro-dynamiques* (Mequignon-Marvis, Paris, 1826), p. 14 and Fig. 1.

[19] Our intention was to use a pattern of square cells. As a result of a mistake in the layout of the pattern, the cells do not alternate in sign along one Cartesian coordinate. The effect of this mistake has been directly measured by the pseudopoles. The long tail on the response curve in Fig. 2 is the result of this mistake.

[20] Impedance matching between the 21-μH loop and the 2-μH input of the SQUID is necessary to obtain the maximum signal. In this detector we used a niobium-wire superconducting transformer—we have since realized that one can link the gradiometer element in a series-parallel arrangement to make the loop impedance equal to the SQUID impedance. (J. Incandela *et al.*, Enrico Fermi Institute Report No. 84-10, to be published in Nucl. Instrum. Methods).

[21] SHE Corporation, 4174 Sorrento Valley Blvd., San Diego, CA 92121.

[22] The dominant source of offsets we see is in the SQUIDs themselves. A detailed study of this has been done by A. Clark, M. Cromar, and F. Fickett of NBS, in Proceedings of Monopole '83, Ann Arbor, Michigan, edited by J. Stone (to be published).

[23] The signal-to-noise ratio is $\geqslant 20$ at 0.1-Hz bandwidth.

[24] An "unexplained" offset is one for which no disturbance in the environment of the detector was measured by our monitors. The most common "explained" disturbances are large changes in the magnetic field due to occasional trucks in the alley next to our building, people moving large iron objects in the building, vibrations, and occasional rf interference.

[25] This 12.7-mV step occurred 1 h after recovering from a catastrophe in which the power cord to the computer caught fire. This was prior to the installation of the rf interference monitor. We suspect that this offset was due to rf interference.

[26] The area of coincidence of the two detectors is 700 cm^2 when averaged over all angles. The coincidence limit from this experiment is thus 2.00×10^{-11} cm^{-2} sr^{-1} sec^{-1} (90% C.L.).