Flux Limit of Cosmic-Ray Magnetic Monopoles from a Multiply Discriminating Superconducting Detector

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A multiply discriminating, three-loop superconducting monopole detector was operated for 1 yr. During this period 8523 h of data were accumulated. The sensing area averaged over solid angle for trajectories passing through a loop was 178 cm^2. With inclusion of double-coincidence events from trajectories passing through the shield but not through a loop, the total sensing area averaged over solid angle was 1195 cm^2. No candidate monopole events were observed; this leads to an upper limit on the flux of cosmic-ray magnetic monopoles of 5.0×10^{-12} cm^{-2} sr^{-1} s^{-1} with a 90% confidence level.

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This paper presents the results of the search for magnetic monopoles at the National Bureau of Standards Boulder Laboratories. The predictions by grand unified theories[1] of the existence of supermassive magnetic monopoles have led to renewed interest in experimental searches for these particles. Cabrera's report[2] of the possible observation of a monopole with a superconducting inductive detector stimulated further interest among experimentalists. Several groups have operated detectors of moderate size and some are planning larger ones.[3]

An inductive monopole detector consists of a superconducting loop coupled to a superconducting quantum interference device (SQUID). The passage of a monopole would change the current in the superconducting loop by an amount $\Delta I = 2\phi_0/L$, where $\phi_0 = hc/2e = 2.07\times10^{-15}$ Wb is the flux quantum and L is the inductance of the superconducting loop.[2,4] This change in current results in a corresponding change in the SQUID output. If the superconducting loop is within a superconducting shield, the detector is also sensitive to monopoles passing through the shield but not the loop. In this case the size of the resulting signal depends on the relative areas of the loop and shield and on the trajectory of the monopole.[5] The magnitude of the signal for a given trajectory is independent of the speed and mass of the monopole. This characteristic makes the inductive detector particularly attractive.

Figure 1 is a schematic drawing of the detector. Three independent superconducting pickup loops and a calibration loop were mounted on a 16-cm-diam glass sphere at the center of a superconducting shield. Each loop consisted of two turns of 127-μm-diam Nb wire. The pickup loops were concentric and mutually orthogonal with their planes parallel to the faces of a cube with its [111] direction vertical. The calibration coil was concentric with the pickup loops and its axis was vertical. The connections from the pickup loops to the SQUID's were tightly twisted pairs routed along the coil form to the top of the superconducting shield.

The superconducting shield was 30 cm in diameter, 89 cm long, and 3 mm thick. It was fabricated by rolling and welding a Pb sheet. The bottom was a disk of the same material welded to the rolled cylinder. The top of the shield was a Pb disk soldered to the underside of a brass plate. To close the can this plate was screwed to an annular brass ring soldered to the top of the cylindrical Pb can. The annular ring, and all other

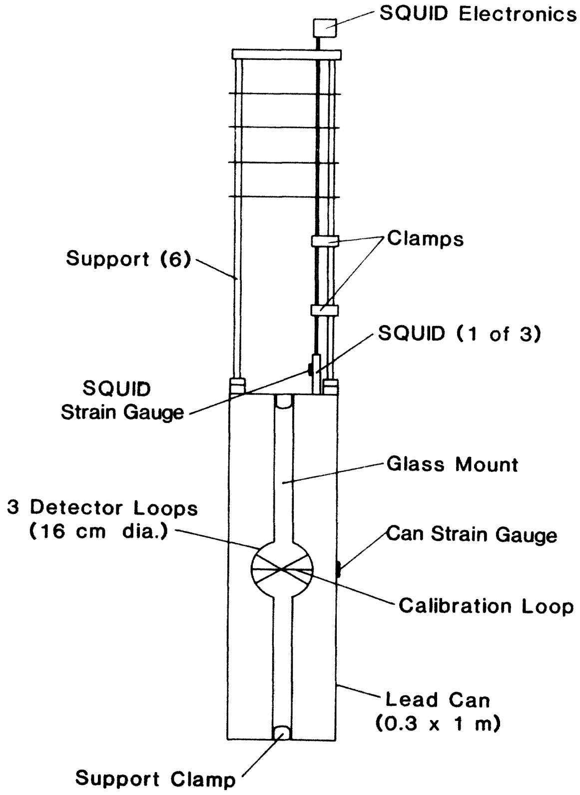

FIG. 1. Schematic drawing of the detector.

normal metal inside the Pb shield, was plated with PbSn solder. Small holes near the top and bottom of the shield admitted liquid helium to the can without degrading the shielding. Low-frequency flux noise was present when the liquid-helium level was above the top of the Pb shield. The untreated surfaces of the Pb sheet and the PbSn solder may have caused this noise. Clem[6] has observed large effective penetration depths in similar materials. With a large effective penetration depth, small changes in temperature, in this case driven by convection of the liquid helium, can result in significant changes in the effective cross-sectional area of the superconducting shield. Since the total flux in the shield is constant, a change in the effective area produces a change in the magnetic field at the pickup loop. Treatment of the Pb surfaces to remove contaminated material might be expected to reduce the severity of this effect. Because of this noise the detector was operated with the liquid-helium level below the top of the shield. In this condition the low-frequency noise was greatly reduced and the intrinsic SQUID noise dominated other noise sources.

A commercial rf SQUID was connected to each of the pickup coils. Each SQUID was housed in a niobium shield screwed into the top of the brass plate which formed the top of the Pb shield. The leads from the pickup coils were shielded with 1-mm PbSn tubes as they passed through the brass plate. Small forces on the SQUID shield resulted in shield motion, which produced significant signals at the output. Distortions of the coaxial line in the probe resulted in smaller but still significant signals. To eliminate these problems the SQUID probes were rigidly clamped to the supporting structure near the SQUID shield and at the top of the apparatus.

A rigid support structure suspended the shield can in the Dewar. The lowest-frequency mode of the loaded structure was at 3.25 Hz; this prevented any large low-frequency oscillations. The length of the structure from the top of the Dewar to the bottom of the superconducting shield was 209 cm.

Two miniature piezoelectric strain gauges were mounted on the apparatus to monitor mechanical disturbances. One was located on the outside of the superconducting shield about 45 cm above the bottom; the other was mounted on one of the SQUID shields. These devices were sensitive enough to detect both the entry of a person into the laboratory and small motions of the Dewar. We applied mechanical shocks to the system to induce changes in the SQUID outputs. Any shock that created an observable signal on the SQUID output caused a large signal from the strain gauge.

The Dewar containing the experiment was superinsulated with a fiberglass inner wall (32 cm i.d.), four aluminum radiation shields, and an aluminum outer wall. No liquid-nitrogen shielding was used. The Dewar loss rate averaged 7 liters/d; this allowed for 9.5 d of operation between liquid-helium refills.

The Dewar was surrounded by two room-temperature magnetic shields of a high-permeability alloy. These cylinders were closed at the bottom, open at the top, and extended to the top of the Dewar. The transverse components of the ambient magnetic field were attenuated by a factor of approximately 1000 resulting in a field of 50 nT (0.5 mG) at the detector loops.

The SQUID's were operated with a passband from dc to 100 Hz so that the characteristic transition duration of a candidate offset could be observed. The signals from the three SQUID's and two strain gauges were recorded on an analog strip chart and sampled by a digital data acquisition system. The digital data acquisition system, shown schematically in Fig. 2, sampled each input channel every 5 ms and temporarily stored the data in a rotating buffer arrangement. Each buffer of data was checked for events meeting criteria for transition duration and voltage change. When an event meeting the criteria was detected, data for the 20 s before and after the event were stored on the disk for later analysis. Each stored buffer contains the date, time, and output-voltage time series for the SQUID's and strain gauges.

Aberrations in main power were recorded with a separate monitor which stored the type of disruption and the time of occurrence.

Figure 3 is a portion of the digital record created

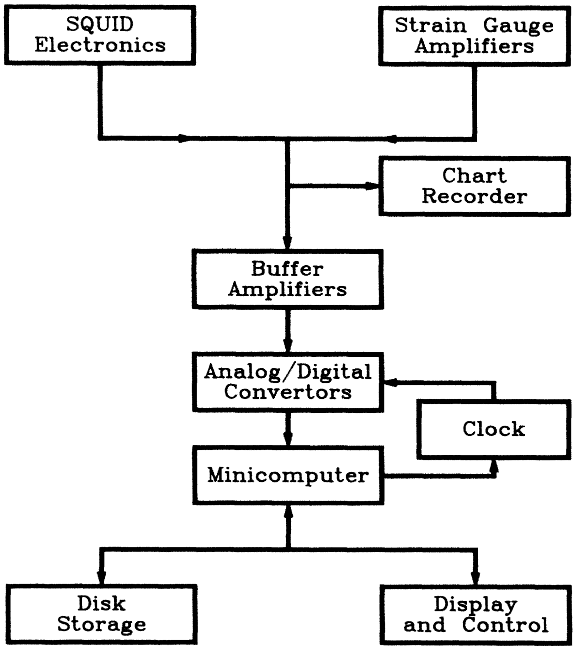

FIG. 2. Block diagram of the data acquisition system.

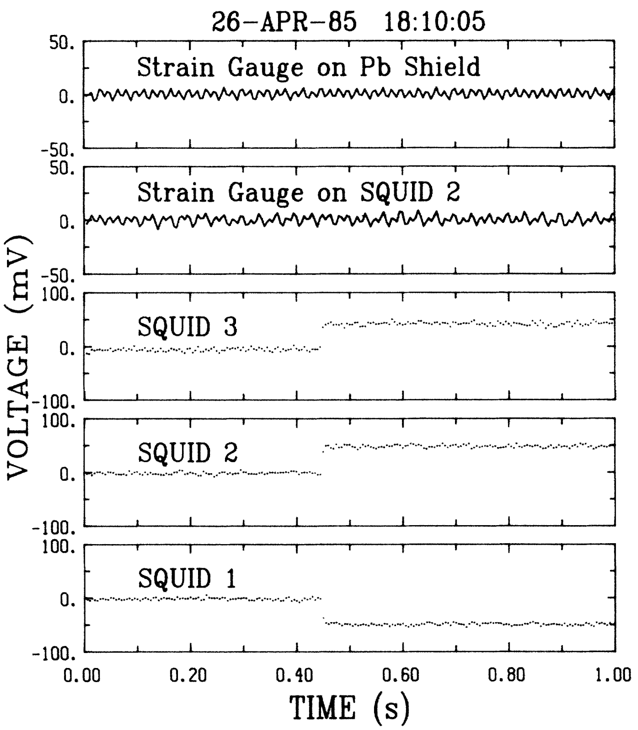

FIG. 3. Digital data record showing a test signal applied with the calibration coil.

during a response and calibration test. A current calculated to produce a response similar to that for a maximum-signal monopole trajectory was switched into the calibration coil approximately 450 ms after the start of the buffer. The signal size agreed with the calculation, and the transition duration was as fast as the response of the SQUID electronics with the dc to 100 Hz passband.

Cabrera, Gardner, and King[5] have calculated the response of a similar detector for arbitrary monopole trajectories. Using their results, we find that for a trajectory intersecting a detector loop the flux change in the SQUID would have been in the range from $0.016\phi_0$ to $0.023\phi_0$, depending on the trajectory. The broadband noise of the detector was limited by the intrinsic SQUID noise, which was $1.5\times10^{-4}\phi_0/\mathrm{Hz}^{1/2}$ referred to the SQUID. For trajectories passing through a detector loop the signal-to-noise ratio for a 10-ms averaging time would have been in the range from 11 to 15. For a 1-s averaging time the range would have been from 107 to 153. Thus, for trajectories intersecting one or more detector loops the signal-to-noise ratio would have been adequate to observe the event with sufficient bandwidth to discriminate between the fast transition expected for a monopole passage and the slower transitions which we have observed for mechanically induced flux changes. The sensing area averaged over solid angle for trajectories passing through one or more loops was 178.1 cm^2.

A near-miss trajectory passing through the superconducting shield but not through any of the loops would have resulted in a signal in the range $0 < \phi_{\mathrm{sq}} < 0.005\phi_0$. (No trajectory would have produced a signal in the range $0.005\phi_0 < \phi_{\mathrm{sq}} < 0.016\phi_0$.) The ability to detect near-miss signals significantly increases the sensing area of our detector. We observed several small signals each month with amplitudes less than $0.0015\phi_0$ referred to the SQUID. Some of these events were obviously mechanical in origin, but their small signal-to-noise ratio often obscured the transition duration. Because of these events we adopted a double-coincidence criterion for near-miss events. Twenty-one signals were not immediately rejected for having clear mechanical or electrical origins. Of these, fourteen were rejected as single-channel near misses, six were rejected because of long transition durations, and one was in the forbidden zone between near-miss and loop-intersecting trajectories. Accepting single-channel events for trajectories passing through a loop, requiring double coincidence for near misses, and rejecting signals with amplitudes less than $0.0005\phi_0$, referred to the SQUID, gave a total sensing area, averaged over solid angle, of 1195 cm^2.

The last cooldown of the detector began on 18 July 1984, and the experiment was terminated on 7 August 1985. During this period there were 8523 h of quiet operation. No candidate monopole events were detected. These data imply an upper limit on the flux of magnetic monopoles of $5.0\times10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$ with a 90% confidence level.

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