

IMPROVEMENTS OF A MAGNETIC MONOPOLE DETECTOR *

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ABSTRACT

Modifications to our previously described detector of magnetic monopoles resulting in substantial improvements in performance have been made. The sensitivity has been increased a factor of 35 by using a sensitive magnetometer (SQUID) to measure changes in current. The modifications, new measurement techniques, and implications for past and future experiments are described.

I. INTRODUCTION

Our electromagnetic detector of magnetic monopoles has been described previously.¹ The equipment is adequate to measure magnetic charges accurately, can handle kilograms of material in a search for monopoles, and does not alter the samples in any way. It can detect a non-zero magnetic charge in a range extending from below the minimum value predicted by the Dirac theory² to many times that minimum, and it is insensitive to magnetically neutral samples. If a monopole signal is seen, the equipment can be tested for proper functioning, and the measurement of the same sample can be repeated in the same conditions for verification as many times as it is desired.

The detection principle relies on the change of current in a super-conducting loop caused by the displacement of a magnetic charge through the loop. A substantial improvement in sensitivity, motivated by the desire to shorten the time necessary for the measurements, has been obtained by modifying the technique by which the current is measured. The modified detector has been used for a search for monopoles in lunar sample.³ The goal of this paper is to describe the modification. With further modifications described briefly in Sec. IV B it will be used again for a search in material exposed to 300 or 400 GeV protons.⁴

A. Detection Principle

As before the alteration, a monopole trapped in one of the tested samples would be detected by the magnetic charge that it would have conferred to the whole piece of material. The sample is carried on a path that traverses a coil (sensing coil) that is part of a closed

superconducting circuit, as shown on Fig. 1. The starting and finishing points are located well outside the superconducting shield. The circuit, in which the magnetic charge would induce the change of current, is surrounded by the superconducting lead shield to protect it against inductions from variations of the outside magnetic field. The cryogenic equipment has a normal temperature bore along the axis of the coil, open at both ends, so that the sample does not have to be cooled down to be tested. Details on the cryogenic equipment and the transport system are given in Ref. #1.

B. The Current Change

We define N_p to be the number of times the sample has been passed through the sensing coil, $I_f(I_i)$ the current in the superconducting circuit after (before) the N_p passes, g the magnetic charge of the sample, n the number of turns of the coil, and L the self inductance of the super-conducting circuit. The difference ΔI between the current I_f and I_i is used to measure the magnetic charge g .

$$\Delta I = I_f - I_i = K 4\pi g \frac{N_p n}{L} \quad (1)$$

where K is a reduction factor due to the current induced in the shield by the monopole displacement. In our equipment, n is about 1200, $K = 0.83$, and $L = 75$ mH within about 1%.

A magnetic charge is bound to induce a current change and this effect can be tested by placing a long solenoid through the hole in the cryostat and the shielding. Because of the interchangeable role played by current of magnetic charge, \vec{J}_m , and the time derivative of

the magnetic induction, \vec{B} , in the Maxwell equation,

$$\text{curl } \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} - \frac{4\pi}{c} \vec{J}_m \quad (\text{gaussian units}) \quad (2)$$

the current \vec{J}_m can be faked by a variation of \vec{B} . Therefore the sensitivity of the equipment can be tested as if monopoles were available for the test.

Changes in I not related to the magnetic charge of a sample sometimes occur when the equipment is not working properly. Indeed, the values of I_f and I_i can be different if there has been a temporary loss of superconductivity or if there is a difference in the magnetic flux induced in the circuit. The first one of these causes can be tested because ΔI would depend on the initial value I_i stored in the loop. The change of magnetic flux induced by external causes is essentially eliminated by an adequate magnetic shielding. A change in the frozen flux in the superconducting material may induce a change in I, but it rarely amounts to as much as the signal from a Dirac monopole. If it ever occurs, it is unlikely that it will recur to distort the measurement of the magnetic charge several times by the appropriate amount and the sample can be tested as many times as needed to test the equipment. Except for these malfunctions of the detector that can be recognized, a magnetically neutral sample cannot produce a change in the current I, whatever its magnetic dipole and higher order multipoles.

In the first version of this detector, the current I was measured by the voltage pulse developed across the sensing coil when a

mechanical switch was opened in the superconducting circuit. In this new version, (Fig. 1), an additional coil (field coil) has been inserted in the circuit with a very sensitive magnetometer placed inside. The current change ΔI is detected by a change in the output signal of the magnetometer.

II. THE MAGNETOMETER

A. The Device

The magnetometer is a superconducting quantum interference device (SQUID).⁵ It consists of two half cylinders of bulk superconducting vanadium (Fig. 2), electrically connected to one another by the contacts A and B of two niobium screws. A DC current (bias current) can be applied between C and D and the voltage can be measured. A one turn coil (SQUID coil) and a 1000 turns coil used as the field coil are wound around the whole assembly.

When well adjusted, the contacts A and B work as Josephson junctions with critical currents of $\sim 4 \mu\text{A}$. With the DC bias current also adjusted, the voltage between C and D is a periodic function (Fig. 3a) of the magnetic flux ϕ through the area surrounded by the superconducting material (contour ACBD). The voltage is of the order of a few μV and the periodicity ϕ_0 is exactly one flux quantum of superconductivity,

$$\begin{aligned}\phi_0 &= 2\pi g_0 = 2 \times 10^{-7} \text{ G cm}^2 \text{ (i.e. } 2 \times 10^{-15} \text{ Webers)} \\ g_0 &= 3.3 \times 10^{-8} \text{ emu}\end{aligned}\tag{3}$$

g_0 is also the Dirac unit of magnetic charge².

(Note that ϕ_0 is 1/2 the value of Φ_0 in Ref. 1.)

A 200 Hz square wave current is fed into the 1 turn SQUID coil with a typical peak to peak amplitude corresponding to a flux change of $1/2 \phi_0$. The voltage between C and D has therefore a 200 Hz component that is phase lock amplified, rectified, integrated with a time constant of 300 ms and measured as the signal U. The low value of 200 Hz has been chosen to simplify the problems generated by the need to protect the SQUID against radio frequency noise. U is a periodic function of the DC component of the flux ϕ as shown on Fig. 3b. The shape is well approximated by a sine function and we will use that approximation for the purpose of explaining the principle of operation.

$$U = U_{\max} \sin \left(2\pi \frac{\phi}{\phi_0} \right) \quad (4)$$

B. The γ -Measurement

Because of the periodic behavior of $U(\phi)$, ϕ cannot be known from U any better than modulo the quantity ϕ_0 . We define ρ

$$\rho = \frac{\phi}{\phi_0} \quad (5)$$

ρ is known only modulo 1. We define

$$\gamma = \text{"fractional part of"} \rho \quad (6)$$

where "fractional part" means the difference between a quantity and the nearest integer. The fractional part is always smaller than 1/2 in absolute value.

The value of γ is unique. The measurement of γ consists of reading the magnetometer output U, then introducing a perturbation in ϕ

using a slowly varying current (calibration pulse) in the SQUID coil and recording the output signal on an oscilloscope. The calibration pulse is large enough that the signal reaches its maximum possible value U_{\max} . From U , U_{\max} and the sign of the derivative $\frac{dU}{dt}$ of the signal at the beginning of the perturbation, γ is determined between $-1/2$ and $+1/2$ so that

$$\sin(2\pi\gamma) = \frac{U}{U_{\max}} \quad (7)$$

$$\text{sign of } \{\cos(2\pi\gamma)\} = \text{sign of } \left\{ \frac{dU}{dt} \right\} \times \text{polarity of calibration pulse.} \quad (8)$$

Note that there is an insensitive region around the value $\gamma = 1/4$ where $U = U_{\max}$ and $\frac{dU}{d\gamma} = 0$ in Eq. (7). The measurement is very inaccurate there and special precaution is taken to avoid that region.

C. Detection of Changes in the Current I

The measurements are used to detect changes in the current I in the superconducting circuit of Fig. 1. Let M_F be the mutual inductance between the field coil and the SQUID (M_F is of the order of $1 \mu\text{H}$). A change ΔI in the superconducting circuit results in a change in ϕ , therefore in ρ .

$$\Delta\rho = \frac{\Delta\phi}{\phi_0} = \frac{M_F}{\phi_0} \Delta I = \frac{\Delta I}{J} \quad (9)$$

$J = \frac{\phi_0}{M_F}$ is measured to be $\sim 2\text{nA}$ for this equipment.

Given two measurements γ_i and γ_f before and after the change in I, only the fractional part $\Delta\gamma$ of $\Delta\rho$ can be determined.

$$\Delta\gamma = \text{"fractional part" of } \Delta\rho = \text{"fractional part" of } (\gamma_f - \gamma_i) \quad (10)$$

$$- 1/2 < \Delta\gamma < 1/2 \quad (11)$$

Note that, for slowly varying currents I , it is possible in addition to count the number of quantum changes of $\Delta\rho$ by continuously monitoring γ , therefore, making many measurements of γ . Hence $\Delta\rho$ can be completely determined. However, in the monopole search, when the sample is inside the sensing coil, its magnetic moment induces variations in the current I which are too rapid to allow reliable measurements of γ . We have to restrict ourselves to γ measurements at the time the sample is out of the detector; therefore, the fractional part $\Delta\gamma$ of $\Delta\rho$ can be determined only between consecutive passes. The current is therefore known only modulo the quantity J between consecutive passes. The sensitivity of our current measurements was determined during testing of the lunar samples.³ We found that the error in $\Delta\gamma$, ϵ , was $\epsilon = 0.036$ corresponding to errors in ΔI of ± 70 pA.

III. SEARCH FOR MONOPOLES

The search for monopoles in a sample consists of series of tests that would reveal almost any monopole consistent with the Dirac theory. Actually, the search may be interpreted as a measurement of the sample magnetic charge (modulo a constant f defined below) independently of any quantization prediction. Therefore, the search covers a continuous range of charges extending below the minimum predicted by Dirac.

A. Test Procedure

Before a test, we make sure that the current I is adjusted so that the initial value γ_1 of γ is quite far from the insensitive region near $\gamma = \pm 1/4$. This is done by adjusting a small current in an auxiliary coil magnetically coupled to the sensing coil and shown on

Fig. 1. A test consists of measuring γ_i , circulating the sample N_p times through the sensing coil, measuring the final value γ_f of γ , and determining $\Delta\gamma$ from Eq. (10). Using Eqs. (1), (3), and (9), the change in ρ should be

$$\Delta\rho = \frac{vN}{f}P \quad (12)$$

where $v = \frac{g}{g_0}$ = magnetic charge in Dirac units (13)

and $f = \frac{L}{M_F} \frac{1}{2nK} = 36.0 \pm 1.0$ (14)

The quantity that can be measured is:

$$\Delta\gamma = \text{"fractional part" of } \left(N_p \frac{v}{f} \right) \quad (15)$$

B. Detection of Dirac Monopoles

The Dirac theory predicts v to be an integer.² Tests are performed for $N_p = 1, 2, 4, 8$ and 16 passes, resulting in measured values $\Delta\gamma_1, \Delta\gamma_2, \Delta\gamma_4, \Delta\gamma_8$, and $\Delta\gamma_{16}$. If $v = 0$, there is no change in ρ . The $\Delta\gamma$'s are all consistent with zero. If $v \neq 0$, $\Delta\rho$ increases by a factor of 2 between each test. For $v = 1$, $\Delta\gamma_{N_p}$ increases by a factor of two for each test until $N_p = 16$ and $\Delta\gamma_{16} = .44$. The monopole would be easily detected. If $1 < |v| \leq \frac{f}{2}$, $\Delta\gamma_{N_p}$ increases by a factor of 2 between each γ measurement, until $N_p > \frac{f}{2|v|}$; then $\Delta\gamma$ changes sign. Therefore, one can show that there would be at least one of the γ measurements for which $|\Delta\gamma| > 1/3$ and this would be easy to detect. Actually, this will be true for any integer or fractional value of v that satisfies

$$|v - jf| \geq \frac{1}{3} \cdot \frac{1}{16} \cdot f \approx 0.75 \quad (16)$$

for every integer value of j .

The first non-zero value of ν compatible with the Dirac theory that would not satisfy (16) and not give $|\Delta\gamma| > 1/3$ is near the value of f and therefore very large ($\nu = 36$). Other values of ν not satisfying (16) are even larger.

Monopoles might still be missed in the search if there is an equipment failure causing the circuit to lose its superconducting property during the sample circulation. If the current I ends up to be zero, and if that zero value of I happens to correspond to the same value γ as the initial γ_1 , $\Delta\gamma$ will be zero. To be sure that this has not happened, two series of tests as described above are performed for each sample, one with $\gamma_1 = 0$, the second with $\gamma_1 = 1/2$. Both values of γ_1 cannot correspond to $I = 0$ simultaneously.

C. Measurement of the Magnetic Charge

If we ignore the Dirac condition, ν is no longer restricted to integral values and we can interpret the results of a series of tests as a measurement of the sample magnetic charge. Since N_p is an integer in Eq. (15), only the fractional part of $\frac{\nu}{f}$ can be determined, whatever N_p is. We define

$$\nu_{\text{meas}} = f \cdot \text{"fractional part" of } \left(\frac{\nu}{f} \right) \quad (17)$$

$$- \frac{f}{2} < \nu_{\text{meas}} < \frac{f}{2}$$

$$\Delta\gamma = \text{"fractional part" of } \left(N_p \frac{\nu_{\text{meas}}}{f} \right) \quad (18)$$

In the first test, with $N = 1$, $\Delta\gamma$ measures ν_{meas} with an error σ , (see Eq. 22). σ is equal to the product of f and ϵ , the error in determining $\Delta\gamma$. With $N_p = 2$, $\Delta\gamma$ determines two possible values of ν_{meas} ; their difference is $\frac{f}{2}$ and the error on each of them is $\frac{\sigma}{2}$. One of those

two values is eliminated by the test with $N_p = 1$ and the combination of both tests results in one value for v_{meas} with an error $\frac{\sigma}{2}$. A similar argument applied to the tests with $N_p = 4, 8, \text{ and } 16$ shows that v_{meas} is determined unambiguously with the error $\frac{\sigma}{16} \approx 0.08$. By increasing the number of passes N_p , one would reduce that limit to any arbitrary value. To maximize the information given by the $\Delta\gamma$'s of a given run, an experimental value of v_{meas} satisfying Eq. (17) is determined using Eq. (18) and a least square technique. This technique decreases slightly the error on v_{meas} below the value $\frac{\sigma}{16}$.

In principle, the values of $\Delta\gamma$ are derived from Eqs. (10) and (7) that assume a sinusoidal dependence of U upon γ . Therefore, the value v_{meas} is dependent on that assumption too. However, as long as no monopoles are found, $\Delta\gamma$ is always measured to be consistent with zero and our results are reasonably independent of the sinusoidal assumption. When a non-zero magnetic charge is detected, the quantity v_{meas} could be measured accurately, making a test with a large number of passes N_p and watching the evolution of $\Delta\gamma$ at each pass. One can define a number m of flux quanta changes corresponding to the test, counting +1 (-1) each time the $\Delta\gamma$ defined with respect to the initial value γ_i changes from a value near +1/2 (-1/2) to a value near -1/2 (+1/2) between two consecutive passes. Then

$$v_{\text{meas}} = \frac{m + \Delta\gamma}{N_p} f \quad (19)$$

For large enough N_p , $\Delta\gamma \ll m$, hence v_{meas} is determined by m which is independent of the sinusoidal assumption.

From the result of these measurements of the magnetic charge, one can detect monopoles with charge within a wide range. However, there are two restrictions to our search; namely, we will not detect

- a) the magnetic charges that are so small that their signal is not significantly different from zero. Requiring arbitrarily a minimum three standard deviations signal, we find that the limit is around $1/4$ of the Dirac charge for our standard measurement. Of course, for the Dirac monopoles, this restriction does not apply.
- b) the values of v that coincide with a multiple of f within errors because the only measured quantity is v_{meas} of Eq. (17) and it would be near zero. However, f is near 36 and the smallest charge that could be missed is as high as 35 or 36 times the minimum predicted by Dirac.

D. Calibration

The calibration determines the factor f of Eq. (14) by a direct measurement. As before,¹ we use a long solenoid with a constant area and a constant current density. As mentioned in Sec. I B, turning on a current in the solenoid simulates the passage of a magnetic charge along the path represented by the solenoid.

First of all, the solenoid is calibrated by placing a calibrating coil of arbitrary dimensions but of known number of turns (1000) over the center of the solenoid. The mutual inductance M_{CAL} between the calibration coil and the solenoid is measured. Then, the solenoid is placed inside the sensing coil with the ends protruding well beyond the shielding. We then measure J_{CAL} ; i.e., the amount of solenoid current

necessary to produce a variation $\Delta\phi = \phi_0$ in the SQUID.

$$f = \frac{\frac{M_{CAL}}{1000} J_{CAL}}{2\phi_0} \quad (20)$$

f has been determined to be 36.0 ± 1.0 for this equipment. A more precise determination is not necessary for detection of non zero magnetic charges but would have been possible, had they been discovered.

E. Performance

For values of v near zero, the error δv is due essentially to the uncertainty ϵ in determining $\Delta\gamma$, as seen in Sec. III C .

$$\delta v = \frac{\sigma}{N_p} \quad (21)$$

$$\sigma = f \cdot \epsilon \quad (22)$$

σ is characteristic of the equipment and it determines the number of passes N_p necessary to reach a given accuracy δv . ϵ is .036 and σ is about 1.3.

Before modification, δv was of the form (21) and σ was 45. The improvement in sensitivity is a factor of 35. With this improvement, the measuring time is reduced for each test. However, with the increased sensitivity, the measurements are more dependent on the variations of the frozen flux in the superconducting material. Before running a sample, stability tests are performed to make sure that the conditions are stable enough for a measurement. During the first 30% of the time available between two helium fills, the equipment is not stable enough to make measurements. Yet, altogether, the number of samples measured per unit time has been increased considerably.

In addition, it has been possible to perform a search for a kind of monopole forbidden by the Dirac theory, in a charge range from $\frac{g_0}{100}$

to g_0 , using 700 passes and intermediate γ measurements at 100, 300, and 500 passes. The duration of the test was 1/2 hour. With the unmodified detector, such high sensitivity would have required more time than was available between two helium refills.

IV. FURTHER MODIFICATIONS

A. The Desensitized Mode

The original detector was built with 3 different sensing coils for reliability. After the alteration, one of these coils (#1) was used as the sensing coil and another one (#2) was used to allow a decrease in sensitivity. In the low sensitivity mode of operation, a small coil of 0.4mH was connected, short circuiting coil #2. That additional circuit acted as a shield in tight coupling with the sensing coil, the constant K of Eq. (1) dropped from .83 to .10, and the constant f of Eq. (15) changed from about 36 to about 305. With the low sensitivity, monopoles of charge near a multiple of 36 but not near a multiple of 305 can be detected. But the sensitivity to small charges is reduced.

In April 1971, 11 kg of lunar material were searched for monopoles³ using this detector in the normal sensitivity mode. For sake of completeness, 0.8 kg of this material was also analyzed with the detector in the desensitized mode.

B. The Detector for NAL Experiment

In preparation for a future analysis of targets from the National Accelerator Laboratory⁴, we made more modifications in our detector, aimed at making the operation less cumbersome:

- a) We have increased the liquid helium capacity, replaced the sensing coils and improved the SQUID magnetic and radio-frequency shielding.

- b) Two field coils each containing one SQUID are now connected in series with the sensing coil. For SQUID 1, $M_{F1} = 1.2 \mu\text{H}$ and $f_1 \approx 34$, for SQUID 2, $M_{F2} = .15$ and $f_2 \approx 290$. The presence of the two SQUIDs modifies the restriction b) of Sec. III C because some charges missed by one SQUID could be seen by the other. The first charge that can be missed by both SQUIDs at the same time from restriction b) of Sec. III C is as high as 580 times g_0 .
- c) A feedback circuit has been introduced for each SQUID with about 70% negative feedback. The output signal U' is then of the form shown on Fig. 3c. There is only one value of γ for one value of U' and the determination of $\frac{dU}{d\gamma}$ by the calibration pulse is not necessary anymore. However, we still use a calibration pulse in our γ measurement to check that the SQUID is operating satisfactorily.
- d) The square wave current in the SQUID coil is interrupted just before the γ measurement, turning off the SQUID operation and bringing the output U' to zero. After resumption of the SQUID operation, with the square wave on again, the feedback circuit will always bring the signal U' to a value where $\frac{dU'}{d\gamma} \neq 0$ (solid portion of the curve on Fig. 3c). The insensitive region around $\gamma = \pm 1/4$ has disappeared now.

- e) A run of a sample now consists of only one series of tests with N_p in geometrical progression. To insure against equipment failures of the type mentioned in Sec. III B, we change the initial value γ_i of γ between each run only.
- f) The desensitized mode is now realized via another technique. By the action of two switches, the 3 sensing coils can be placed in series in the circuit instead of the single coil mentioned up to now. Then the self inductance $L = 722$ mH, $n = 3600$ while M_F stays the same for the two SQUIDS. In this new condition, the values of f for SQUID 1 and 2 are about 100 and 830 respectively. Therefore, the desensitized mode is about 3 times less sensitive than the normal mode of operation.

ACKNOWLEDGEMENTS

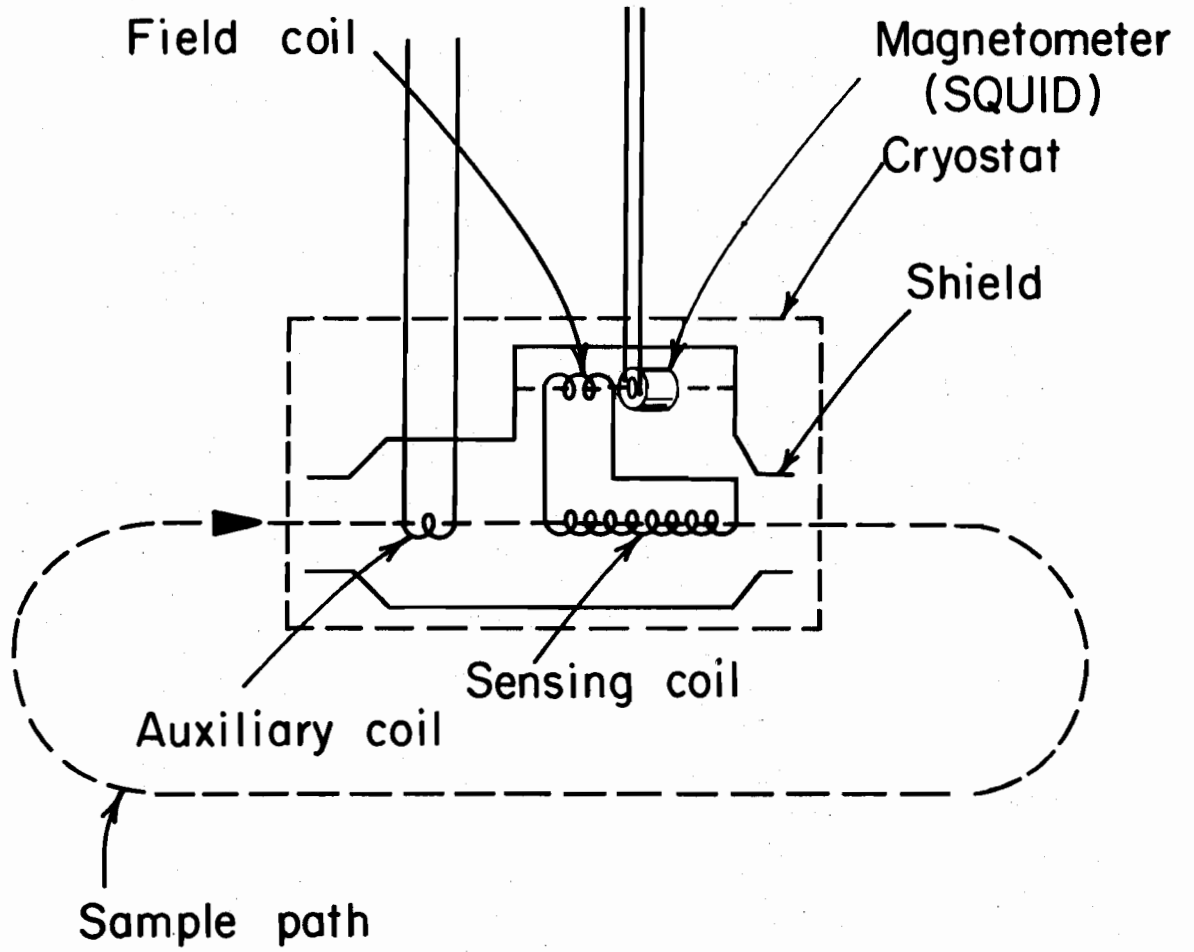
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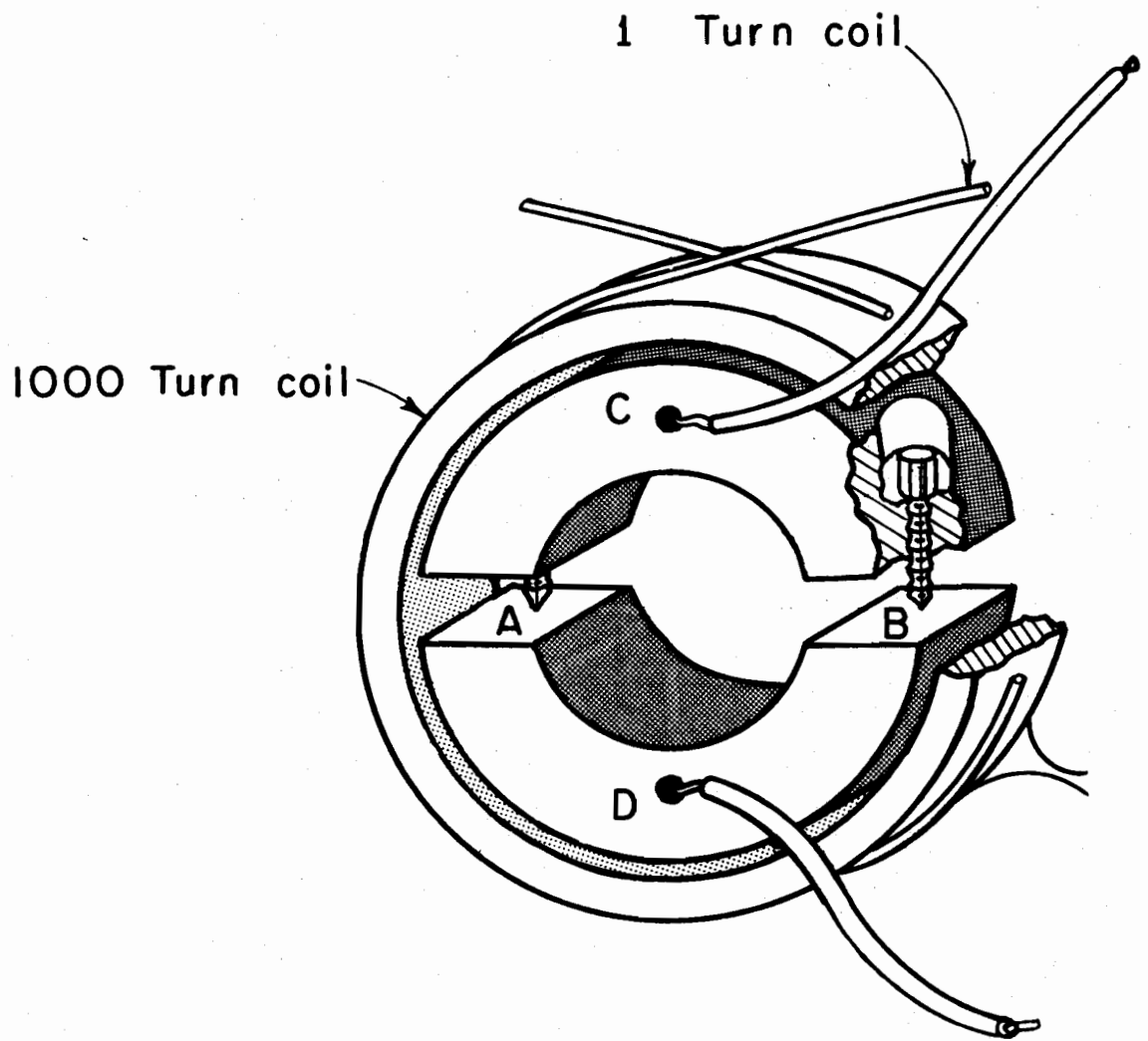
Figure Captions

1. Schematic view of the detector. The sample is moved around the dashed curve labeled sample path. The superconducting circuit is shown with the sensing coil and the field coil connected in series. The magnetometer and the auxiliary coil are also shown inside of the cryostat.
2. Schematic view of the SQUID in perspective. The two vanadium half cylinders are electrically connected through the screw contacts A and B. The SQUID voltage is read and the DC bias current is fed using the leads connected to points C and D. The 1000 turn field coil and 1 turn SQUID coil are wound around the assembly. The overall dimension is about 1 in³.
3. Output signal from the SQUID
 - a) Voltage between points C and D of Fig. 2 as a function of the flux ϕ when a DC current near the critical current of the junctions is applied.
 - b) Output U of the phase lock amplifier as a function of the DC component of ϕ when a square wave reference current is fed into the SQUID coil.
 - c) Response U' as a function of the DC component of ϕ when the feedback circuit described in Sec. IV B is on. The solid portion is used in γ measurements and the dashed portion is excluded as described in Sec. IV B (d).



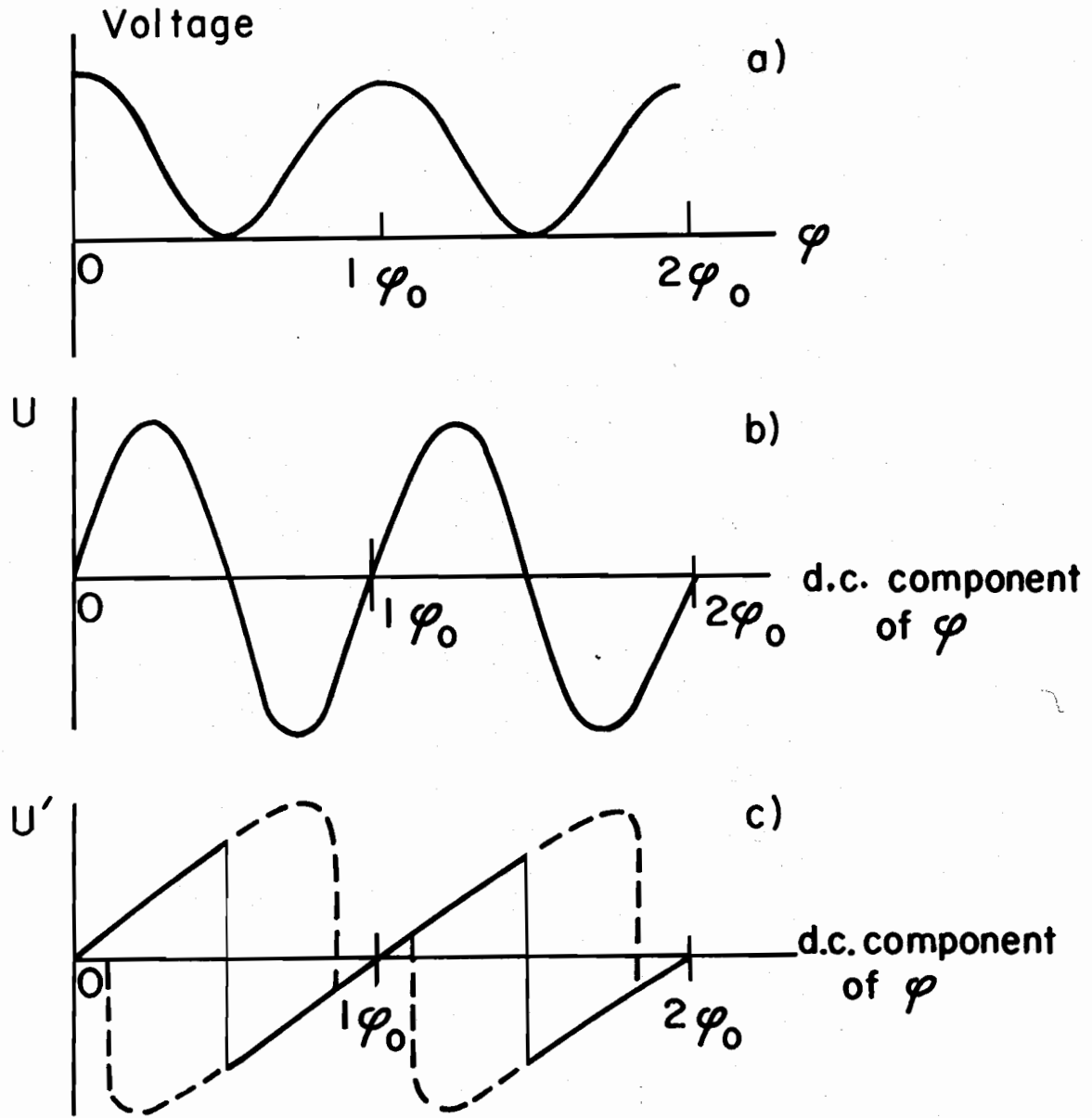
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Fig. 1



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Fig. 2



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Fig. 3