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New superconducting-quantum-interference-device-based constraints on the abundance of magnetic monopoles trapped in matter: An investigation of deeply buried rocks

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Current experimental limits on the number of magnetic monopoles bound in matter are based on only a few dozen kilograms of material, and of the former experiments only a handful used superconducting-quantum-interference-device- (SQUID) based detection techniques. Furthermore, all previous searches for trapped monopoles used material formed or gathered from either the surface of the Earth or Moon, where ultramassive grand unified field theory monopoles would not be expected to stop. Using a new type of ultraefficient SQUID magnetometer which allows large volumes of room-temperature matter to pass directly through a superconducting loop, we examined a suite of high-pressure metamorphic rocks which had been buried at depths of up to 25 km and yet remained below the Curie temperature of the ferromagnetic minerals present. In addition, we also examined large volumes of manganese nodules and seawater, for a total mass of 643 kg of rock and 180 kg of seawater. No monopoles were found, suggesting that their cosmic abundance is either extremely low or they are not easily stopped or trapped by passage through a minimum of 25 km of the Earth's crust. We suggest that the next best place to look for monopoles is in cometary dust.

I. INTRODUCTION

Dirac[1,2] first proposed the existence of particles bearing quantized magnetic charge as an explanation for the observed quantization of electric charge and as a means to make Maxwell's equations fully symmetric. Experimental work in subsequent years was directed towards finding magnetic charge in matter assuming that any such elementary particles would have properties similar to those of other nucleons (e.g., Vant-Hull[3]). A variety of methods were used to test for the presence of magnetic charge, including ionization tracks as the particles passed through plastic sheets[4] and the persistent current generated and left in a superconducting loop as a magnetic charge passes through.[5-9] Bound monopoles have been searched for in moon rocks,[6-8] ferromanganese pavements on the ocean floor,[10-11] and even seawater.[12]

About ten years ago, a mechanism for the production of magnetic monopoles using the high energies of the "Big Bang" was predicted using the grand unified field theories (GUT's).[13,14] The grand unification mass scale sets a value for the mass of the monopole between 10^{14} and 10^{15} GeV, or about 20 ng (about the mass of a bacterium). Subsequent work has shown that these GUT monopoles would have much slower velocities ($< 10^{-3}c$) than previously expected in the cosmic background radiation, and their greater momentum might give them large deceleration path lengths through matter.[15] In retrospect, it is clear that few of the previous searches for magnetically charged particles would have been able to detect the presence of these supermassive GUT monopoles.

It is also surprising to note that very little matter has actually been directly searched for the presence of magnetic charge by passing it through a superconducting loop and monitoring the persistent current change with the use of superconducting quantum-interference devices (SQUIDs). This was done by Vant-Hull,[3] but because the matter which was examined had to be at liquid-helium temperatures, only a limited volume of material could be processed (Table I). Alvarez et al.[6-8] used a conveyor belt to move room-temperature lunar samples many times through a superconducting loop, and by monitoring the pulse of current with a storage oscilloscope when the circuit was broken they were able to place constraints on the magnetic charge. Unfortunately, they did not use SQUIDs, and even with the multiple cycling these system had a high background noise and consumed 6 l of liquid helium per hour. Cryogenic technology has improved greatly in subsequent years, principally as a result of the commercial development of ultra-efficient SQUID-based magnetometer systems for use in biomedical and geophysical research. The state-of-the-art SQUID magnetometer used for the study of paleomagnetism, for example, now consumes about 1/3 l of helium per day on a 100-l Dewar, and has a 7.5-cm-diam room-temperature access port passing completely through one of the pickup loops.[20] As we note below, a single pass through one of these systems is sufficient to detect the presence of a bound monopole with a Dirac charge, and it is therefore possible to examine much larger volumes of matter than has been previously possible.

We note, however, that all previous induction-based experimental searches for monopoles have only examined materials from either the surface of the Earth or Moon, where even in the most favorable circumstances GUT monopoles would be unlikely to come to rest. A better

TABLE I: Summary of previous experimental searches for monopoles trapped in matter.

Samples	Type of detector	Amount of material	References
Meteorite	Emulsion	0.56 kg	16
Meteorite	Particle detector	0.060 kg	17
Deep-sea nodules	Plastic	113 cm^3	10
Ferromanganese pavement	Plastic	7.73 kg	11
Ocean-floor sediment	Particle detector	1.6×10^6 cm^3	18
Seawater	Particle detector	1.63×10^6 cm^3	12
Air	Particle detector	6.84×10^7 cm^3	12
	Induction	Total mass examined (kg)	
Ti, Cu, Al brass, Teflon	SQUID	0.00172	19
Au, Cu, W	SQUID	0.03006	3
Moon rocks	non-SQUID	47.8	6-8
Seawater	SQUID	180	This study
Mn nodules	SQUID	145	This study
South Fork Mt. schist	SQUID	56.7	This study
Rand Mt. schist	SQUID	441.3	This study

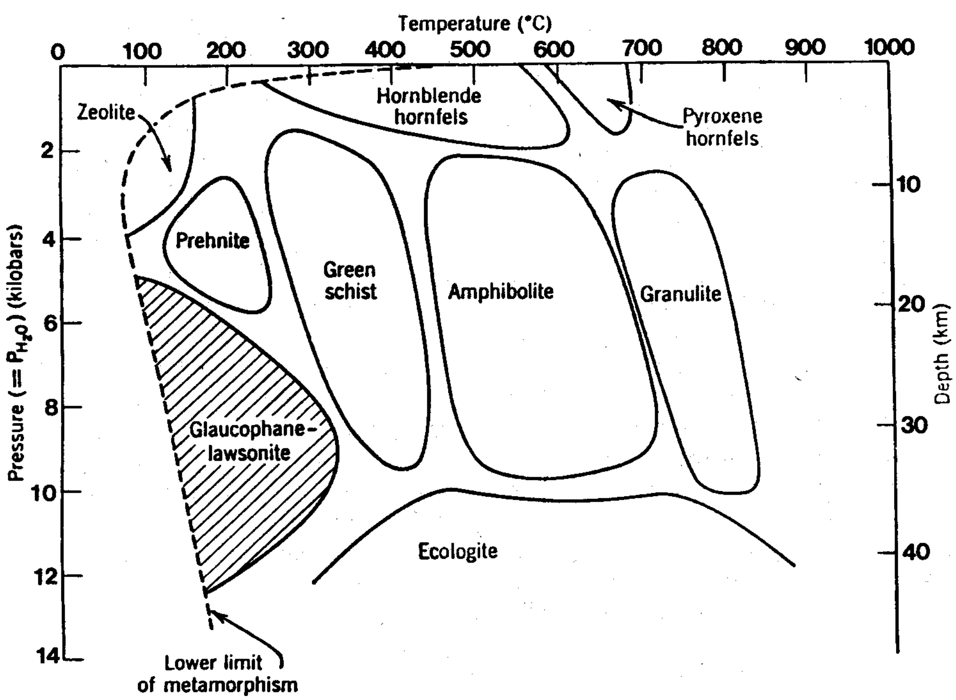

FIG. 1. Approximate boundaries of metamorphic facies as a function of temperature and depth [adapted from Verhoogan et al. (Ref. 21)]. Samples of both the Rand Mountain schist and the South Fork Mountain schist examined for magnetic charge in this study have metamorphic mineral assemblages suggesting that they equilibrated within the glaucophane-lawsonite (blueschist) field (shown as lightly hatched).

place to look would be in rocks which had been buried for long periods of time at great depth within the Earth, providing that they were never heated above the Curie temperatures of their ferromagnetic minerals. Monopoles reaching such a rock would have to pass through tens to hundreds of kilometers the Earth's crust, perhaps allowing them sufficient time to decelerate and stick to a suitable ferromagnetic mineral like magnetite (Fe_30_4). Geologists have known for many years that two types of metamorphic rock, blueschists and ecologites, have been subjected to prolonged periods of high pressures (up to 15 kbar or 45 km deep) and moderately low temperatures (< 500 °C, Fig. 1). Blueschists and ecologites are now known to form in the accretionary wedges of subduction zones where they are dragged to great depths by downgoing oceanic plates, and are subsequently brought back to the surface after the subduction subsides. Based on extensive laboratory calibration experiments, it is now possible to place strict constraints on the depth and temperatures experienced during this subduction-related burial metamorphism.[21] Rocks of this sort are common along many convergent plate margins, and often comprise extensive terranes such as the Franciscan melange of central and northern California.

We report here the first results from two such high-pressure, low-temperature assemblages, and have in addition examined two materials (manganese nodules and seawater) which had not been properly examined before. Results from this study increase by a factor of approximately 20 the total amount of matter ever directly examined for magnetic charge by passing through a superconducting loop.

II. MATERIALS AND METHODS

The instrument we used in this experiment is a two-axis rf-driven **SQUID** magnetometer housed in a 100-l cryocooled Dewar, and the entire system is housed in a magnetically shielded, dust- and particle-free clean laboratory, which has been described elsewhere.[22] Two superconducting loops arranged as Helmholtz pickup coils are wrapped around a 7.5-cm-diam room-temperature sample access tube and are linked to the SQUIDs through a flux transformer. The sample tube passes through the z-axis Helmholtz pair, and it is this axis upon which all of our experimental analyses were done. We calibrated it directly in terms of the magnetic flux quantum by centering a solenoid (140 cm long, 6.1 cm in diameter with 39 turns per cm) in the sample access tube and used it to generate a series of known fluxes through the sensing coils. We found a linear relation between magnetic flux and panel reading such that a Dirac monopole charge of $2F_{\mathbf{o}}$ (or hc/e or 4×10^{-7} G cm^2) would produce a change in panel reading of 0.0090±0.0002, compared to an average background noise in the ~0.0005 range. The signal-to-noise ratio of about 20 for the system clearly allows a direct measurement of the monopole's charge if one happened to pass through the z-axis coils.

It is well known that only the charge of a magnetic monopole will leave a net flux as it passes through a superconducting loop, and any magnetic field produced by moving electric charges or magnetic dipoles associated with it will only cause a spike-like transient in the persistent current. A monopole trapped in a rock would therefore leave a measurable signal in our z-axis loop as it passes through, despite the presence of ferromagnetic materials in the rock. However, mechanical vibrations, thermal stress in the coils, and intermittent rf signals can sometimes create spurious readings. Since we can pass the samples through the instrument many times, an abnormal or otherwise interesting response can be reexamined if necessary. Thus, if a monopole did exist in one of the samples it would be possible to crush the rock into progressively smaller fragments and eventually locate the grain or particle to which the monopole was bound.

We examined three types of material for magnetic charge and/or magnetic monopoles, including (1) the South Fork Mountain schist and the Rand Mountain schist, (2) manganese nodules, and (3) seawater.

The Rand Mountain schist is one of three major exposures of metasedimentary rock in the Southern California area which show clear mineralogic evidence of having been buried at least 20 km in depth and held at temperatures below about 300°C.[23] These rocks are thought to have originated during Jurassic time (ca 150 million years ago) as deep-sea sediments which were then buried and subjected to low-temperature, high-pressure metamorphism in the accretionary wedge of a subduction zone operating off of the Pacific coast of North America. These rocks are characterized by the presence of blue amphiboles which give them the bluish texture, places constraints on the depth and temperature of burial, and is the source of the term "blueschist." In our search, we collected samples of a ferrigenous quartzite layer which was interbedded with the Rand schist but contained higher concentrations of ferromagnetic minerals.[24] Our samples of this material display a coercivity spectrum typical of fine-grained magnetite, and the saturation remanence implies that between 1% and 5% of the sample volume is magnetite. They therefore contain many potential binding sites for the monopoles.

The South Fork Mountain schist is a sequence of metasedimentary rock within the Franciscan complex which crops out in the Mendocino National Forest of Northern California. Our samples come from the Pickett Peak Terraine near Round Mountain. These sediments originally formed as the distal portion of a submarine fan complex around 140 million years ago (in the early Cretaceous), and were subjected to deep burial metamorphism between 115 and 120 million years ago.[25] Like the Rand Mountain schist, they contain a characteristic assemblage of the high-pressure, low-temperature minerals lawsonite and glaucophane, which implies burial depths of between 20 and 40 km and maximum temperatures near 300°C (Fig. 1). Measurements of the saturation remanent magnetization and coercivity spectra of these rocks imply the presence of roughly 10^8 fine-grained magnetite crystals per gram, evenly dispersed throughout the volume of the material. There are therefore an ample number of potential binding sites for magnetic monopoles.

After the rocks were collected, they had to be carefully processed before we could do the measurements. Each rock could not exceed more than a few hundred grams in mass because they had to fit through the 7.5-cm-diam room-temperature access tube. We crushed them using a mechanical jack and sledge hammer, and placed them in plastic bags to reduce contamination in the clean lab where the magnetometer is housed. Each sample was weighed using a digital balance and its mass recorded by a microcomputer. Following this step, the sample was gently lowered through the z-axis coils of the magnetometer by a string. The instrument readings were monitored before and after the sample passed through. If a change greater than that of even half a monopole charge occurred, the sample was remeasured. In total, 498 kg of these rocks were examined and no monopoles were found.

The manganese nodules and ferromanganese pavement were borrowed from the core lab of the Scripps Institution of Oceanography in La Jolla, California. Again, their coercivity spectra and saturation remanence indicate the presence of abundant ferromagnetic particles, implying that many possible binding sites exist. Manganese nodules tend to concentrate the microscopic extraterrestrial material found in deep-sea sediments.[26] From the saturation remanence curve of our samples, we estimate that approximately 300 g of extraterrestrial material was in the 145 kg of nodules measured. Although the softer ferromanganese material was easier to crush, we used the same measurement process as with the blueschists. Again, we found no monopoles in 145 kg of the ferromanganese nodules.

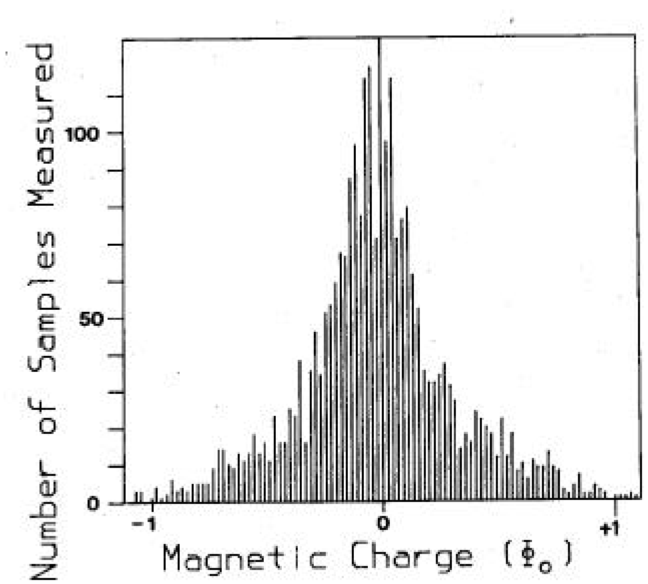

FIG. 2. Histogram of the number of samples vs their measured magnetic charge. All solid samples measured in this study (blueschists and manganese nodules) are included, and varied in size from about 50 to 600 g each (average about 200 g). The mean of the distribution is centered on zero. Although the variance is larger than would be expected from the electronic noise alone, we found that mechanical noises from vibrations during the measuring process were capable of producing the observed scatter. The expected charge for a Dirac monopole is $2F_o$, which is off scale on this diagram. The few samples with readings greater than $1F_o$ were remeasured and found to be less magnetic.

Figure 2 is a histogram of the number of samples measured versus their measured magnetic charge for the total 643 kg of rock (blueschist plus manganese nodule) measured in this study. The measurements clearly have a bell-shaped distribution centered on zero with a standard deviation of 0.180, and it is clear that nothing we measured had a magnetic charge near the Dirac value of $2F_o$. The scatter of measurements around the zero value is a good measure of the total noise of the system, including that due to the electronics and as a result of mechanical vibrations during the measurement process.

Finally, we investigated seawater collected from the beach at La Jolla, California, mainly because large amounts of it can easily pass through the magnetometer and limited quantities had been previously examined for magnetic charge using non-SQUID-based techniques by Carrigan et al.[14] We used a pump to circulate the water through a plastic hose that ran directly through the instrument and the z-axis coils. While the instrument output was continuously recorded on a strip chart, a microcomputer was programmed to shut down the pump if any changes of even half a monopole charge were found. Once more, in 180 kg of seawater, no monopoles were found.

III. DISCUSSION

The number of monopoles in bulk matter is small with none found in 643 kg of stable, highly magnetic material measured in this experiment and an additional 180 kg of seawater. This total of 823 kg of matter is roughly 20 times larger than the total amount of material directly searched for magnetic charge by all previous searches as shown in Table I, and is over 25,000 times more than all previous experiments using SQUID-based techniques. This suggests that the cosmic flux of monopoles has remained small over the past 150 million years or that matter does not easily stop monopoles even after a passage of 25 km through the Earth's crust. Current experimental and theoretical limits on the monopole flux[27] seem adequate to explain the results obtained.

The only other consideration that remains involves the ability of matter to bind GUT monopoles. Their large mass suggests that small accelerations might be able to dislodge them from a ferromagnetic binding site.[17] Since all the samples had to undergo to certain amount of mechanical shock in the collection and crushing process, any monopoles that did come to rest inside the material could have been knocked loose. In addition, the Rand Mountains are in the vicinity of the Garlock fault, and during the Tertiary period it has probably been subjected to repeated seismic accelerations with peak intensities on the order of a few gravities.

Thus, the data obtained in this experiment actually represent the number of tightly bound monopoles and not all the possible bound-monopole configurations. Since it only places a lower constraint on the number of bound monopoles, further experiments must attempt to include not only materials with different properties and geologic histories, but also a means to catch those displaced during processing.

On the other hand, our experimental results suggest that magnetic monopoles will not be found bound to terrestrial or other matter from chemically differentiated planetary bodies. GUT monopoles, if they exist, might only become trapped in matter if they have the opportunity to travel together with ferromagnetic particles at very low relative velocities. Interparticle velocities of this sort are thought to exist in nebular gas and dust clouds of the type which led to the formation of our solar system, and it has been suggested[28] that a cloud of relict GUT monopoles might still be in solar orbit and yield occasional events like that observed by Cabrera.[9] We suggest, however, that if these monopoles were indeed part of the solar nebula, they should now be bound to Ni-Fe dust particles and be trapped by the icy matrix of cometary nuclei. Due the large mean distances of comets from the sun and their low density, the probability of an intercometary collision during the lifetime of the solar system is negligible. This implies that after they become bound to a dust particle and are trapped by gaseous condensation onto an accreting cometary nucleus, they should not experience accelerations strong enough to dislodge them during the rest of geologic time. Also, if they are, in general, trapped in cometary nuclei, limits. on their cosmic abundance set by the magnitude *of* the interstellar magnetic field (the Parker bound[27]) would not apply.

We suggest, therefore, that the next best place to search for bound monopoles would be in the dust oblating from the surface of a comet during a traverse through the inner solar system. The Jet Propulsion Laboratory is in the planning stages for a comet rendezvous mission which is scheduled for launch sometime during 1992; technology and power limitations permitting, it could conceivably be provided with a SQUID-based detector for measuring magnetic charge in passing dust particles.

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