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MEASUREMENT OF THE STATIC MAGNETIZATION OF SPIN-POLARIZED ATOMIC HYDROGEN WITH A SQUID MAGNETOMETER

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The operation of a squid magnetometer system for the measurement of the magnetization of H↓ in a high magnetic field is described.

1. INTRODUCTION

We have measured the magnetization of a gas of spin-polarized atomic hydrogen (H↓) in a magnetic field of B = 7.5 Tesla. This provides direct evidence that the gas is spin-polarized and provides a non-destructive technique for measuring the density of H↓. The hydrogen atom has an electronic and nuclear magnetic moment, $g_e\mu_\beta S$ and $g_n\mu_{\beta n}I$, respectively.[1] In a high magnetic field the spin degeneracy is lifted. The atom has four spin states (1-4) and H↓ consists of the two lower states, 1 and 2, so that the magnetization is

$$|\vec{M}| = -g_e\mu_\beta(n_1+n_2)/2 + g_n\mu_n(n_1-n_2)/2 \qquad (1a)$$

$$\simeq g_e\mu_\beta(n_1+n_2)/2 = \mu_\beta n(r) \qquad (1b)$$

Here $n(r) = n_1+n_2$ is the total atomic number density at point r in space and μ_β is the electronic Bohr magneton. The second term in eq.(1a) is negligible since for high temperatures, T >> 54 mK, (the splitting of the hyperfine levels $(E_1-E_2)/K \simeq 54$ mK for B = 10 T), $n_1 \simeq n_2$. In eq.1b we see that the static magnetization is proportional to the local density. The magnetic flux due to a gas of H↓ in a cylinder of volume V containing $N = \int n(r)d^3r = \bar{n}V$ atoms can be measured. Thus as H↓ atoms are introduced into a cell the magnetic flux increases; loss of atoms due to recombination to H_2 reduces the flux since the electron spins pair-off is the singlet state.

2. EXPERIMENTAL TECHNIQUES

The principle difficulty in measuring the magnetic flux due to a gas of H↓ is that this must be done in a field of ∿7-10 T. A sample of about 10^{14} atoms/cm^3, such as in our system, provides an equivalent magnetic field of ∿1 nT (10 μ gauss). This is to be measured in a field of order 10 T, with measurement periods which can be of order 60 min. This means that the magnetic field must be stabilized to order 1 part in 10^{10} for 60 minutes. A superconducting solenoid (scs) with a conventional persistent mode switch (such as ours) has a field decay greater than 10 gauss/hr. Even with a perfect persistent mode switch, field variations can be very large unless the field value is approached in a programmed way.[2] Flux jumps in the scs and other external sources can create large levels of short term noise. This can create a severe environment for use of a sensitive SQUID magnetometer. Finally temperature dependent (nuclear) magnetization arising from construction materials can provide noise that overwhelms the signal due to the H↓ gas. Our design was built to minimize these problems. Instead of a SQUID, a flux gate magnetometer was used. After building and testing the system we found no severe magnetic noise problem to the highest field tested (10 T). The flux gate did not have the required signal-to-noise. We then decided to replace the flux gate with a SQUID (SHE, model 330).

The experimental system is shown in fig. 1.

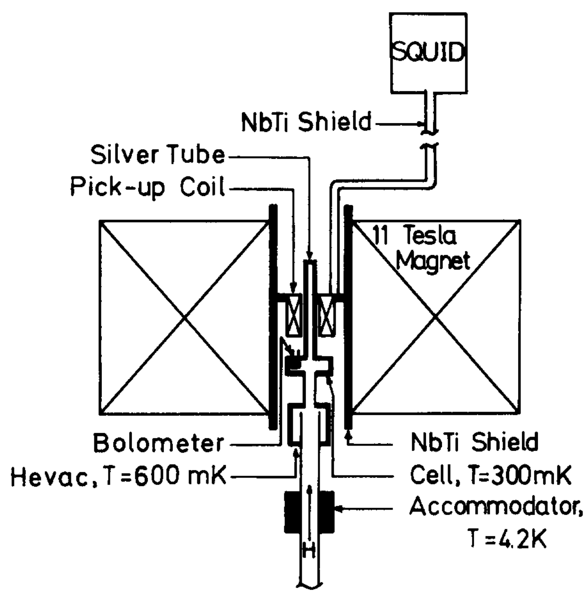

Figure 1. Low temperature region of apparatus used to stabilize and measure magnetization of H↓.

Atomic H↓ is introduced into the cell and stabilized as discussed elsewhere.[3] The cell consists of a tube of silver with id = 3.0 mm, od = 3.7 mm. Silver was used for its high thermal conductivity and low nuclear magnetization. A bolometer was also built into the cell to provide an alternate detector and to enable rapid reduction of the H↓ density to zero to measure the zero of the magnetization.

A pick up (pu) coil to measure the magnetization was wound on an aluminium former, using niomax CN A61/05 (NbTi) wire. The coil consists of four sub coils, designed to have zero mutual inductance with an external field.[4] External field variations were suppressed by approximately a factor 130. The coil was connected by sc wires enclosed in a copper cladded NbTi tube (filled with liquid helium), leading to a SQUID mounted in a NbTi chamber. A persistent mode switch was built into the transformer connecting the pu coil to the squid coil. To further suppress field variations the cell and pu coil were mounted in a NbTi cylinder bored out of a solid rod of $Nb_{0.55}Ti_{0.45}$ supplied by KBI, Inc. and heat treated.[5] This cylinder was clad with copper for uniform cooling to 4.2 K and was provided with a heater to warm it above T_c. The pu coil was rigidly wedged into the NbTi shield which in turn was rigidly placed in the magnet bore, all to suppress vibration in the field.

3. OPERATION AND RESULTS

In zero field the minimum detectable signal of our system was found to be $\sim 3 \times 10^{12}$ atoms/cm^3 in a volume of 0.13 cm^3 corresponding to 4×10^{11} atoms and 3×10^{-3} ϕ_0 in the squid (ϕ_0 is the flux quantum). In 7.5 Tesla the short term noise equivalent signal was $\sim 5 \times 10^{13}$ atoms/cm^3 corresponding to a short term field stability of ~ 1 in 10^{10}. However long term stability of order 1 hour was a few orders of magnitude lower. This can be seen in fig.2 where we show the magnetization (in density units) as a function of time. Here, the zero level is established between points A and B. Filling of the cell begins at B. The initial dip arises from a spurious signal due to heating of the cell. At C the discharge is turned off and at D the temperature is back at its initial value and regulated. The magnetization decays due to recombination, as observed elsewhere by other techniques.[6] After about 40 minutes the remaining atoms are recombined with the bolometer to reduce n to zero at point E. The signal change was too large and rapid for the squid to follow and it comes out of lock. After recovery we have lost our zero of reference, the new zero drifting upwards. This drift was not sufficiently linear in time to enable accurate measurements with a corrected baseline. The main source of drift is decay of the field and variations of the field that occur, depending on how the field was reached before going into persistent mode. Drift originating from temperature fluctuations could be rendered negligible by temperature stabilization. The low frequency drift is stabilized to ~ 1 in 10^8 which is not adequate for accurate measurements of the H↓ density over long period of time.

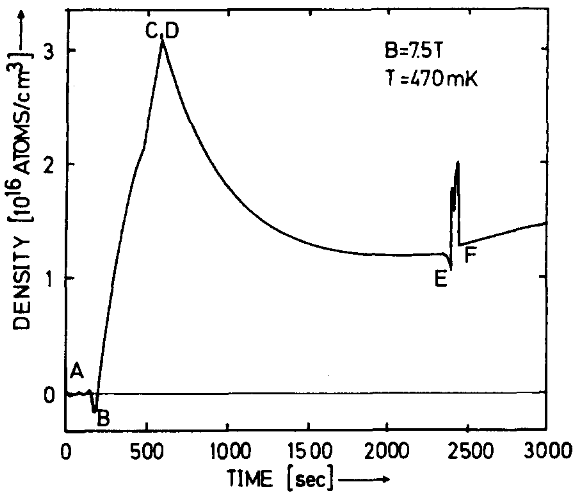

Figure 2. The time dependence of magnetization M of H↓. The signal proportional to $\mu_\beta nV$ is given in units of density, n.

4. DISCUSSION

We have demonstrated that the squid magnetometer can be used as a sensitive accurate short term detector of H↓, and with some straightforward modifications can be used for accurate long term measurements of the static magnetization of H↓. Our system was optimized for a flux-gate magnetometer dominated by noise due to field fluctuations, requiring a pu coil with a small area. Since field noise was not dominant, the sample volume and thus the signal could be increased by about a factor of 10. Persistent mode switches with decay one to two orders of magnitude lower are available. Short term sensitivity can be substantially improved by optimum coupling to the squid. The NbTi cylindrical shield was not quantitatively studied, however it was found to provide effective shielding for all fields, with best results in the low field region.

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