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Low-Field Magnetic Resonance Imaging of Gases

David M. Schmidt* and Michelle A. Espy

Abstract

This is the final report of a six-month, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The main goal of this project was to develop the capability to conduct low-field magnetic resonance imaging of hyper-polarized noble gas nuclei and of thermally polarized protons in water. We have constructed a versatile low-field NMR system using a SQUID gradiometer detector inside a magnetically shielded room. This device has sufficient low-field sensitivity to detect the small signals associated with NMR at low magnetic fields.

Background and Research Objectives

Nuclear magnetic resonance (NMR) spectroscopy and magnetic resonance imaging (MRI) detect the magnetization resulting from the excess population of one nuclear spin state over the other (for spin-1/2 nuclei). This fractional excess, or polarization, is traditionally obtained by placing the nuclei in a magnetic field that slightly reduces the energy of one spin state over the other. At thermal equilibrium this produces a polarization that is proportional to the magnetic field strength and is on the order of 10^{-5} for a field of 1 Tesla and at room temperature. For protons in water this yields a precessing dipolar field of strength about 10^{-8} Tesla that needs to be detected. Traditionally this is detected by a tuned resistive coil that produces a signal that is proportional to the amplitude of the magnetic field and to the precession frequency. This frequency, the Larmor frequency, is proportional to the magnetic field present at each nucleus and for protons is 42 MHz at 1 Tesla. Thus, traditionally the NMR signal goes as B^2, the square of the strength of the magnetic field; one power from polarization and one power from detection. This fact has been the driving force to push to ever higher field strengths so that today large-bore MRI typically uses 1-4 Tesla fields and small-bore spectroscopy uses fields of many tens of Tesla.

Nevertheless, there are many advantages of conducting NMR and MRI in low ($<10^{-2}$ Tesla) fields if one could mitigate the effects of a low signal. The difference in

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relaxation rates of different materials, which produces the contrast in MRI, increases at lower fields. In spectroscopy, the lines associated with nuclear dipole-dipole interactions are easier to measure. These interactions yield more direct information about nuclear distances then chemical shift interactions and are therefore more useful for molecular structure determination. Objects containing metal can be used since the magnetic forces can be easily controlled and the electromagnetic fields can pass much more easily through metal at the lower Larmor precession frequencies (1.2 KHz for protons at the Earth's field of 5×10^{-5} Tesla has a skin depth for typical metals of about 7 mm). Finally, cost decreases and portability increases by eliminating the need for the superconducting magnet associated with high fields.

Our approach to mitigating the effects of low signal traditionally associated with low field NMR is two-fold. First we used superconducting quantum interference device (SQUID) sensors for detecting the precessing nuclear magnetization. With a sensitivity of 10^{-15} Tesla, SQUIDs are the most sensitive magnetic field detectors known. In addition, rather than detecting the time rate of change of the field, they detect the absolute change of the magnetic field so that with SQUID detectors the NMR signal only falls as the strength of the polarizing field rather then the square of the field (as with traditional detection coils). The second part of our two-fold approach is the use of hyper-polarized noble gases. Noble gas nuclei can be hyper-polarized to tens of percent---many orders of magnitude larger than thermal polarization---through laser driven spin exchange [1]. This polarization is independent of the magnetic field strength. Thus with hyper-polarized noble gases and SQUID detectors the NMR signal is independent of field strength.

Importance to LANL's Science and Technology Base and National R&D Needs

A general purpose instrument for conducting low-field NMR and MRI with good signal to noise promises to have a significant impact in a wide range of scientific and technical fields. Eliminating the need for a superconducting magnet would significantly reduce the cost and increase the portability of instrumentation, with applications including portable medical imaging (e.g. for battlefield medicine), bore hole diagnostics and other geophysical remote diagnostics. In addition, the lower frequencies associated with low-field NMR pass much more efficiently through metal, which make it possible to observe NMR and MRI through conductive cavities or walls, a feature that would be useful in non-destructive evaluation. Combining this with the ability to detect and image gas directly with very high signal to noise via NMR would make it possible for the first time to quickly and non-destructively characterize porosity and fractures in materials---even conducting materials. This would have significant uses in materials science, non-destructive evaluation and in modeling the transport of buried hazardous waste. Because the SQUID detectors are broad band and not tuned to a certain frequency the same instrument can be used for detecting a wide range of nuclei---to determine composition---as well as where the different components are located (imaging). In addition, low-field NMR spectroscopy has significant advantages in molecular structure determination with the lines associated with dipole-dipole interactions being better defined [3,4,5].

Scientific Approach and Accomplishments

The low-field NMR apparatus that we built consisted of a static field to polarize the sample being measured, a "spin-flip" field to reorient the spins of the sample prior to measurement, and the SQUID detector, which was the pick-up coil detecting the precession frequency.

We built a precise set of Helmholtz coils that could provide the ~$3x10^{-4}$ T uniform magnetic field, B_0, while operating with existing power supplies. We also built the smaller Helmholtz coils that provided the spin-flip pulse. These latter coils had to fit inside the B_0 pair and accommodate the tail of the dewar where the SQUID was located. Both these coils were built with existing supplies. We characterized both sets of coils and built a tuning circuit to optimize the power output of the spin-flip coil. A function generator and audio amplifier drove the spin-flip coil. Because of the low magnetic fields the spin-flip pulse needed to be of audio frequencies rather than the radio frequencies used in conventional NMR. A picture of this device is shown in Figure 1.

Two different types of SQUID detectors were tested as NMR pick-up coils. Both of the SQUIDs were commercially available, low temperature (liquid helium cooled) devices manufactured by Conductus. The first type of SQUID detector we experimented with had a magnetometer pick-up coil with a ~1mm radius. The second SQUID had a first-order gradiometer as a pick-up coil with a ~5cm baseline and ~1mm radius.

The SQUID electronics were also commercial devices manufactured by Conductus. However, we had to use NIM electronics to develop our own timing system to trigger the spin-flip pulse, the oscilloscope (used for data acquisition), and the SQUID reset. A picture of the electronics and data acquisition system is shown in Figure 2. The very strong spin-flip pulse causes so many flux quanta to pass through the SQUID that the feedback electronics can't keep up and the device becomes "unlocked". Therefore a reset pulse is sent to the SQUID, which effectively holds the device at zero output through the spin-flip pulse, and releases it immediately after the pulse ends.

The majority of our work was done with the SQUID magnetometer as the detector. The inherent sensitivity of the device, defined as the smallest change in magnetic field that the SQUID can resolve in the absence of all external magnetic noise sources, was ~$3x10^{-15}$ T/sqrt(Hz). The sensitivity of the device was also characterized under real experimental conditions inside the magnetically shielded room with the B_0 coil turned on. In this situation it was found that the smallest magnetic field we could measure was on the order of $1x10^{-13}$ T due to all the external sources of magnetic noise present. We calculated that the expected proton signal from water in a $3x10^{-4}$ T field is about $1x10^{-12}$ T. The signal would be several orders of magnitude larger for even a few percent polarized ^{3}He and in principle both water and ^{3}He were within the range of the magnetometer's sensitivity. However, because of the various difficulties discriminating against the high levels of background magnetic noise, we also investigated the first-order gradiometer configuration.

The inherent sensitivity of the first-order gradiometer is $\sim 5x10^{-15}$ T/sqrt(Hz); however the gradiometric configuration is much better at reducing signals from background noise sources and we expect better sensitivity with this device than was achieved with the magnetometer. We are currently in the process of measuring the sensitivity of the first-order gradiometer under real experimental conditions.

In conclusion, we have constructed a versatile low-field NMR system using a SQUID gradiometer detector inside a magnetically shielded room. This device has sufficient low-field sensitivity to detect the small signals associated with NMR at low magnetic fields.

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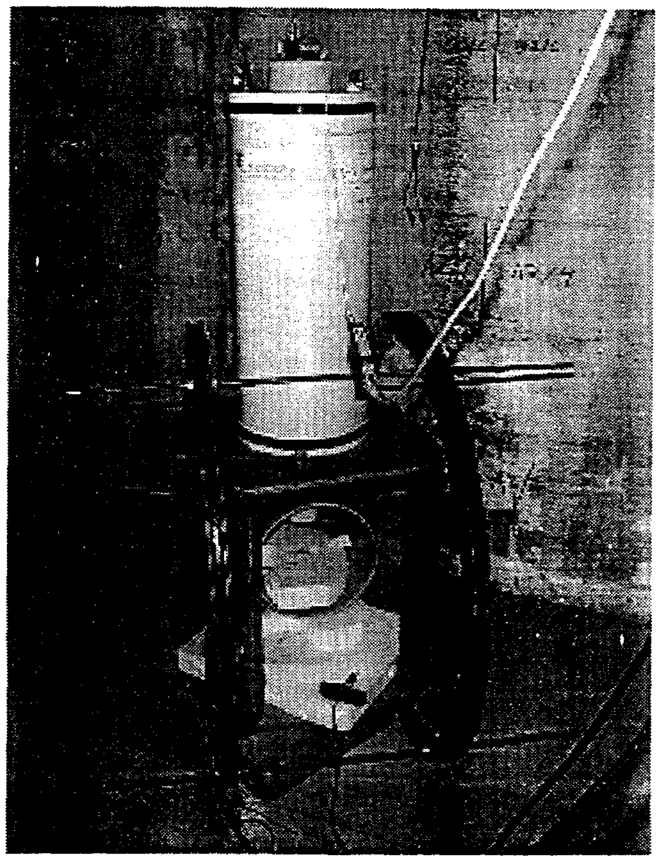

Figure 1. A picture of the low-field NMR device inside the shielded room. The static magnetic field is produced by the large Helmholtz coils while the spin-flipping magnetic pulse is produced by the small Helmholtz coils that are near the center of the setup. The large cylinder is the dewar for the SQUID, which sits at the bottom of the dewar inside the spin-flipping pulse coils.

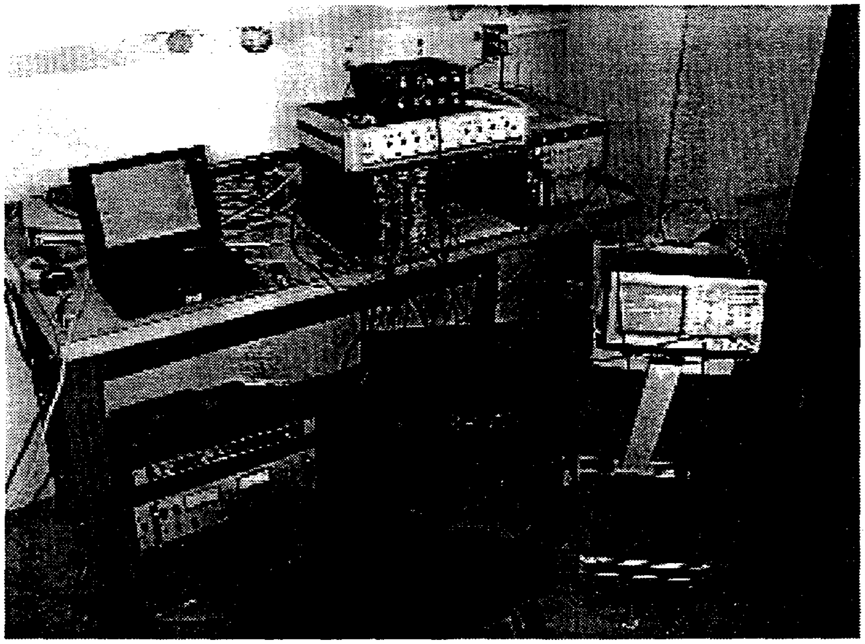

Figure 2. A picture of the electronics used to control and record data from the low-field NMR device. The digital scope was used as the data acquisition system.