Quantum Tunneling of Nanomagnets Using Time-Dependent High Magnetic Fields

A. Raj and H. Nojiri
Institute of Materials Research, Tohoku University, Sendai, Japan

Nanomagnets and research in molecular magnets serve as the foundation for numerous efficacious applications such as supercomputing and novel data storage methods. The purpose of this experiment is to study the properties of nanomagnents by investigating techniques used to control the spin coupling of electrons. A two-level spin system of Cu^{2+} ions doped in $Ca(PO_3)_2$ glass was examined. The use of a glass substrate reduces the propagation of phonons and thus helps to decouple the electrons. Magnetization experiments were conducted at low temperatures such as 4.2 K, 1.7 K, and 0.4 K. The fast sweeping rate (10^5 T/s) of the magnetic field suppresses electron de-coherence. This allows for quantum tunneling to be observed at the zero field. In this experiment, a 3.0% and 7.5% concentration of Cu^{2+} ions were studied using pulsed magnetization measurements for various fields, ranging from 1 T to 10 T, in order to determine the relaxation rate of the material and the energy gap between the excited and ground states. Also, Electron Spin Resonance (ESR) was conducted for the 7.5% Cu^{2+} sample to determine the Landé g-factor, which was calculated to be approximately 2.325. The Bloch equation was used to derive the relaxation rate from the experimental data that showed the expected hysteresis in the magnetization curves. Further tests involving a pulsed field generation of two full cycles will be conducted and analyzed.

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Introduction

Nanomagnets and research in molecular magnets serve as the foundation for numerous efficacious applications such as supercomputing and novel data storage methods.

To observe quantum tunneling at the zero field and study the properties of nanomagnets, minimal spin de-coherence is achieved via:

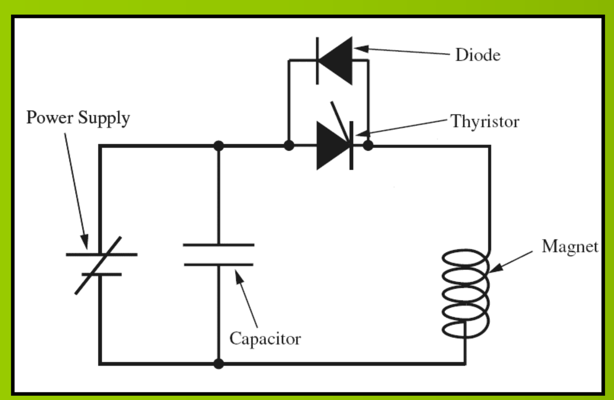
- Quenched cooling - 0.4 K, 1.7 K, 4.2 K
- Fast sweeping of magnetic field - 10^5 T/s

Objective

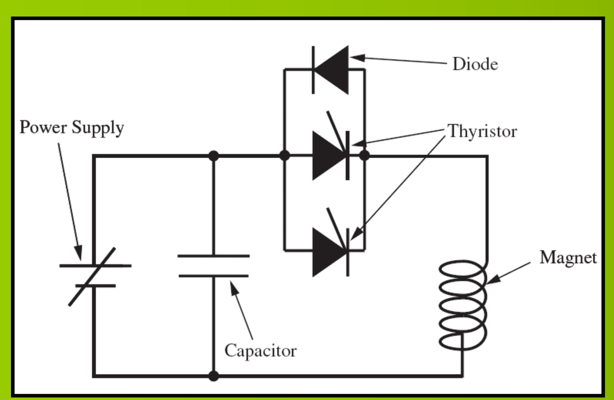
Investigating techniques used to control the coupling of electrons in a two-level spin system of Cu^{2+} ions doped in $Ca(PO_3)_2$ glass.

Methods

Simplified Schematics of Capacitor Bank Circuit

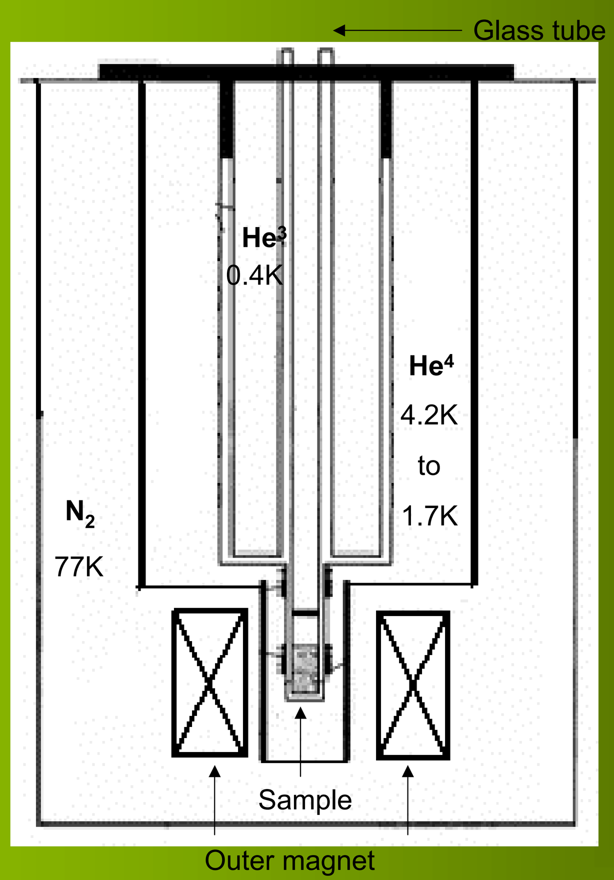


One-Cycle Pulsed Field Generation

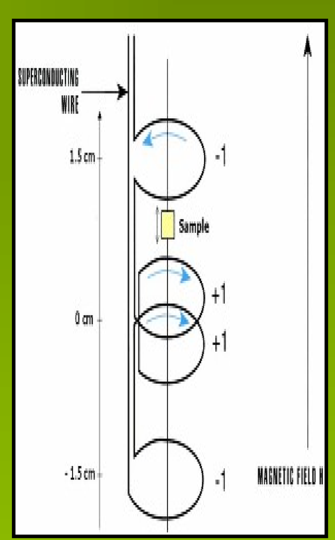


Two-Cycle Pulsed Field Generation

Cryostat Chamber



Pick-up Coil



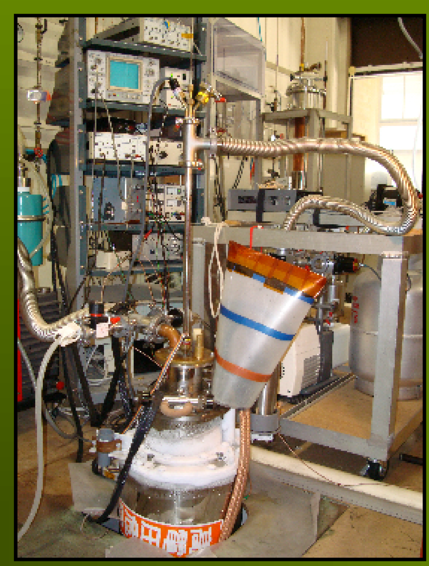
- Prepare sample, attach to glass tube, and insert into pick-up coil
- Fill N_2 and then slowly place holder into chamber for cooling (1 hr)
- Fill He: watch pressure and temperature (begins condensing around 105 kPa)
- Only once He fully condenses, begin pumping He^3 to lower the temperature
- Adjust compensation coil for setting background
- Find optimal position for sample
- Begin time-pulsed high magnetic field tests

Data

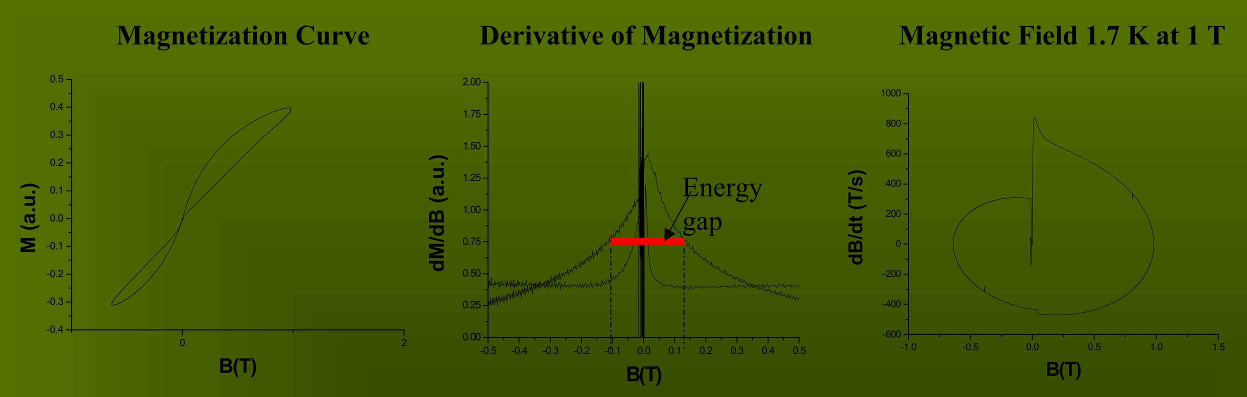
Variables 1) Cu^{2+} ion concentrations: 3.0 % and 7.5 %
2) Time interval between cycles

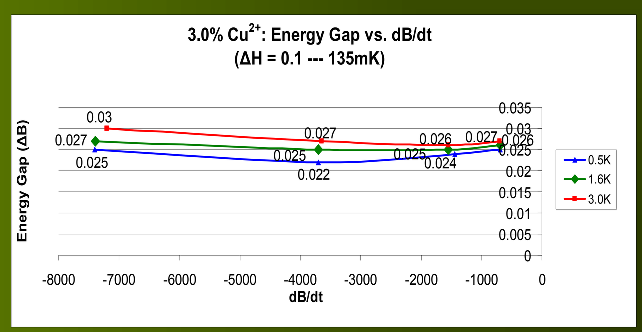
------------------ Magnetization Measurements ------------------

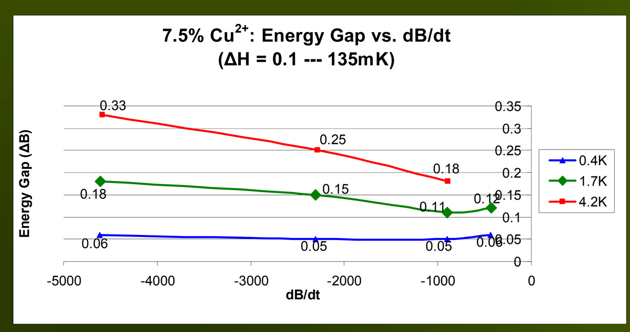
- Temperature – 0.4 K, 1.7 K, 4.2 K
- Field – 1 T, 2 T, 5 T, 10 T

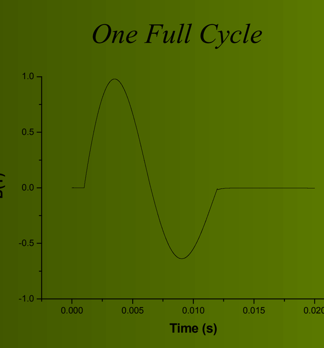


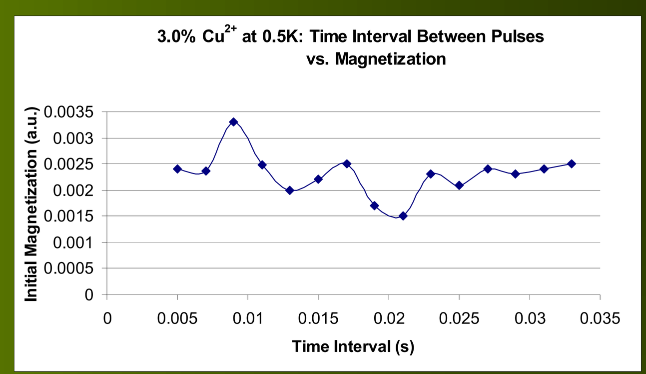
1. Energy Gap

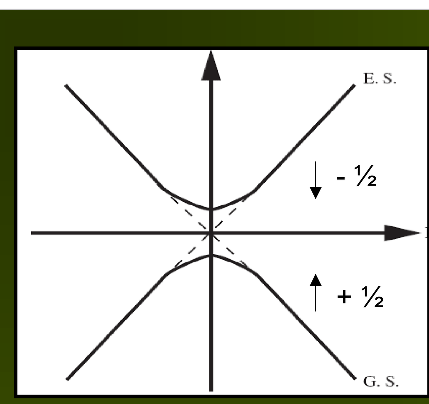




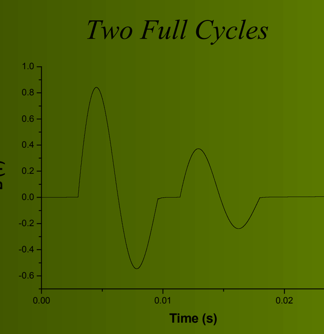






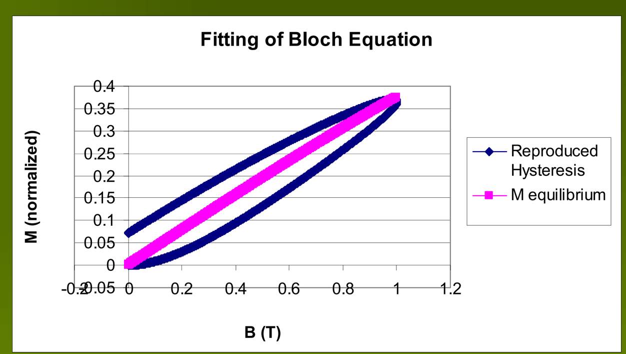


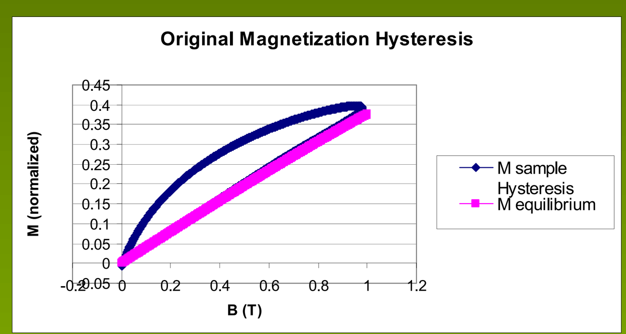
Energy Level with Zero Field Gap



2. Relaxation Rate

7.5% Cu^{2+} at 1.7 K and 1T





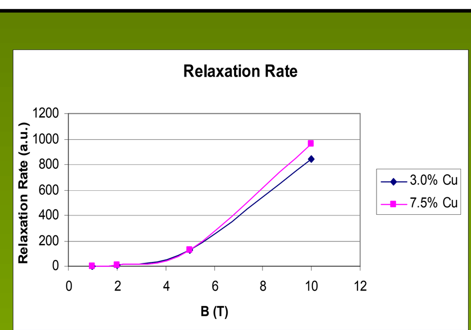
Bloch Equation

$$\frac{d}{dt}M(t) = \frac{1}{\tau(T, B(t))}[M_{eq}(T, B(t)) - M(t)],$$

relaxation rate $1/\tau$

$M_{eq}(T, B(t)) = \tanh[g\mu_B B(t)/(2k_B T)]$

$$\frac{1}{\tau(T, B(t))} = \frac{3(g\mu_B)^3 V_{sl}^2}{2\pi\rho v^5 \hbar^4} B(t)^3 \coth\left[\frac{g\mu_B B(t)}{2k_B T}\right] + R_0.$$



---------------- ESR: Electron Spin Resonance ----------------

- Temperature - 1.45 K, 2.45 K, 2.9 K, 4.2 K, 10 K, 20 K, 30 K, 40 K
- Field – 6 T
- Frequency - 135 Ghz

1. Landé G-Factor

Splitting of energy levels is directly proportional to magnetic field strength

$\Delta E = g_e \mu_B B_0$

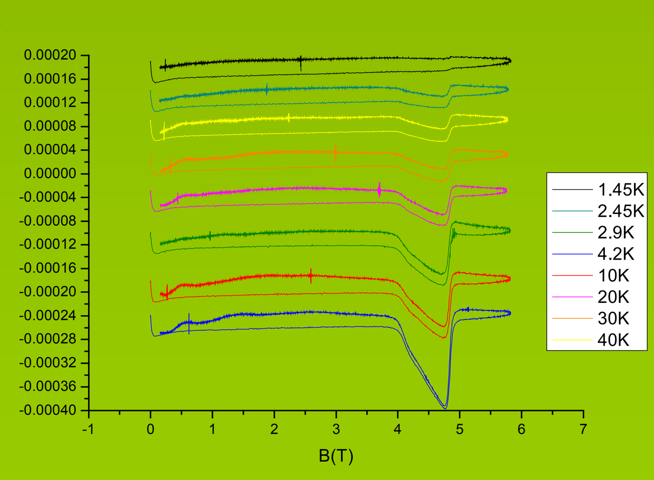
$\Delta E = h\nu$

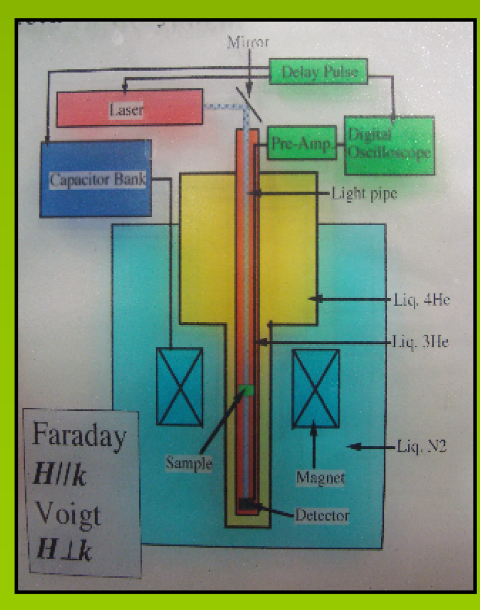
$g_e = h\nu / \mu_B B$

Weighted Average at 4.2 K

B (T)	g_e
4.148	2.325

ESR Curves





Analysis

- 3.0% Cu^{2+} : as magnetic field increases to 10 T, the energy gap is relatively constant for all temperatures.
- 7.5% Cu^{2+} : as temperature reduces to 1.7 K and 0.4 K, the energy gap becomes more constant among the various magnetic fields from 1 T to 10T.
- The difference in energy gaps as temperature decreases is larger for the 7.5% sample than for the 3.0% sample.
- Relaxation "heating": as time interval increases, the sharp initial jump of magnetization disappears. This indicates that the spin polarization of electrons has returned to the equilibrium state.

** Electron spin relaxes from ground state to excited state **

- Relaxation "cooling": rate increases as magnetic field increases for both samples.

** Electron Spin drops from excited state to ground state **

- ESR: peak occurs around 4.148 T independent of temperature. Confirmed the g-value of the sample to be approximately 2.325, which is the expected value based on previous experimentation.

Further Research

Testing various concentrations of Cu^{2+} ions will better indicate the influence of sample composition on quantum tunneling at the zero field. Also, studying different types of materials using high pulsed magnetic fields will allow for further analysis of the properties and trends observed during spin polarization.

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