

Magnetic Ordering in ^3He Nano-Clusters

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Simultaneous measurements of the magnetic susceptibility and pressure have been made in ^3He nano-clusters embedded in a ^4He matrix. Susceptibility measurements, using pulsed NMR operating at 125 or 250 kHz, extend from 0.5 mK to 10 mK. Samples pressures are from 2.88 to 3.54 MPa, for which the clusters either separate as liquid droplets, undergo partial melting as they are cooled further, or remain all solid. For all samples, we find a Curie-Weiss law contribution to the susceptibility χ , which indicates that even the lowest pressure clusters have a solid fraction in the region of the phase diagram where bulk solid is unstable. A possible explanation for this behavior is the strong van der Waals attraction by the much denser ^4He matrix that produces a solid layer of ^3He at the interface.

The susceptibility of the 3.54 MPa sample, which remains all-solid, behaves similarly to that of bulk ^3He for $v=21.3 \text{ cm}^3/\text{mole}$, with a Weiss constant $\theta=-250 \text{ } \mu\text{K}$. It would be useful to study this sample to much lower temperatures to see if ordering occurs near $|\theta|/2=125 \text{ } \mu\text{K}$. For 2.88 MPa, a liquid droplet forms upon phase separation, but as indicated by χ , there is a solid fraction of 0.2. This quantity of solid would occupy only two or three atomic layer at the interface with the ^4He matrix. The temperature dependence of χ yields $\theta=140 \text{ } \mu\text{K}$, indicating a ferromagnetic tendency, similar to 2 D films at some coverages.

At intermediate pressures, χ has a peak near 1.05 mK, as shown in Fig. 1 for $P=3.11 \text{ MPa}$. There is no discontinuity in χ , as is seen in the U2D2 ordered phase of pure bulk solid ^3He . The behavior below the peak is different for 125 and 250 kHz, suggesting

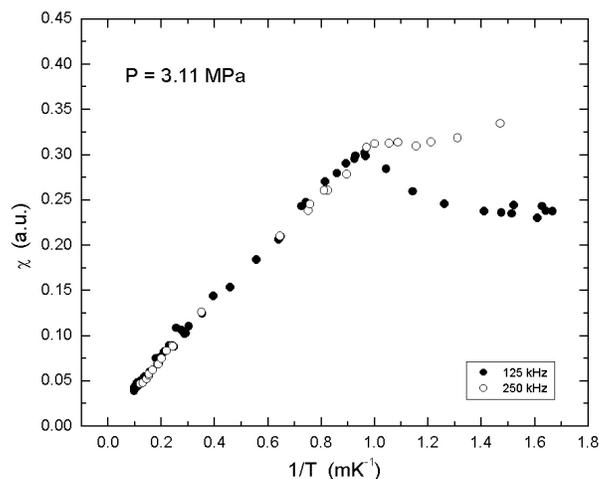


Figure 1. Nuclear magnetic susceptibility as a function of inverse temperature.

that there are two different ordered phases with a critical field of less than 7.8 mT, the field for 250 kHz. In pure bulk ^3He , the critical field separating the U2D2 phase from the high-field phase is 0.45 T. Additional measurements are underway to provide further documentation on the ordered phases of the nano-clusters.

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Field-Induced Spin Diffusion Anisotropy in Dilute Polarized Fermi Liquids

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We are conducting spin transport measurements on very dilute spin-polarized ^3He - ^4He mixtures ($x_3 = 10^{-3}$ - 10^{-4}) in a 15 T magnetic field at temperatures down to 2 mK. For the lowest x_3 and temperature, the ^3He spin polarization approaches 100% in this field. Our main aim is to examine field induced

diffusion anisotropy due to spin polarization. To do this, we are measuring both the transverse spin diffusion coefficient by spin-echo measurements and the longitudinal spin diffusion coefficient by recovery of the magnetization after a large tipping pulse.

For these NMR measurements, we have newly designed and constructed several items: (1) pulsed-NMR electronics that can be used for 10 to 650 MHz (easily extendable to 1 GHz), (2) a low-loss high-frequency coaxial cable from room temperature to the mixing chamber of the cryostat, and (3) a miniature birdcage resonator for ^3He NMR at 500 MHz.

We also designed and constructed a new thermal link to the high field region, and three experimental as shown in the Fig. 1:

- (1) The sample cell contains a composite of silver and platinum power (40 m^2 area), vibrating wire viscometers and an NMR tube. The NMR tube is located at the bottom of the sample cell, and extends into the birdcage resonator. The resonator is thermally isolated from the NMR cell to prevent heat input due to rf pulses. We have been able to apply 50 W NMR pulses with minimal sample heating. The homogeneity of the 15 T magnetic field is 10^{-5} over NMR tube (0.01 cc) and field gradients up to 80 G/cm can be applied. Vibrating wire viscometers were installed in the sample cell to observe changes of quasiparticle scattering processes due to spin polarization. The measurements employed a novel viscometer that minimizes the effects of long mean free path in these very dilute systems.
- (2) A cell containing pure ^3He is used primarily for thermometry, which is difficult in these high-field, ultra-low temperature conditions. A secondary goal of this project is to advance thermometric techniques for very high B/T . The pure ^3He cell contains a viscometer and a Kapton capacitance thermometer.
- (3) The third cell is a ^3He melting-pressure gauge which provides additional thermometry.

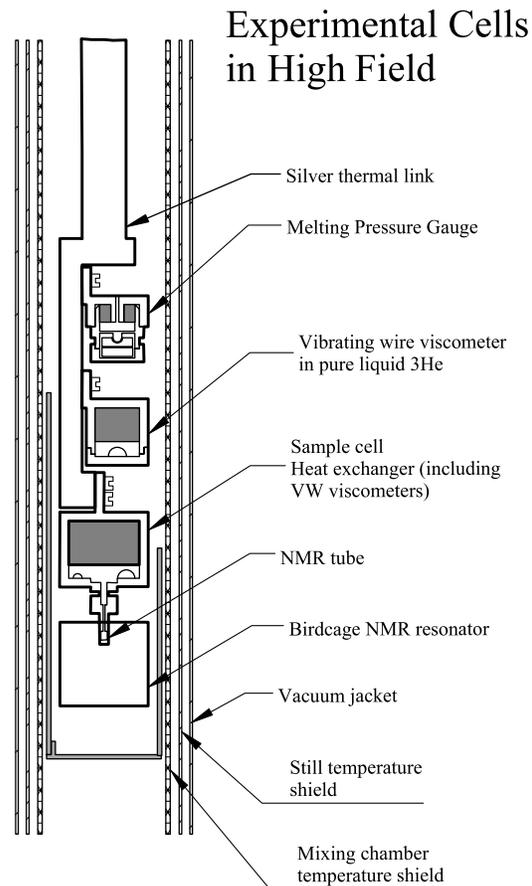


Figure 1. Schematic view of the experimental cells in high magnetic field.

This complex low-temperature and NMR apparatus was constructed and debugged and experimental runs started. Spin transport and viscosity data have been collected for one ^3He concentration ($x_3 = 900$ ppm) and data collection for a second, more dilute concentration is underway.

NMR Studies of Particle Exchange in a Triangular Lattice of ^3He Atoms

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High frequency pulsed NMR measurements have been carried out for a film of ^3He atoms adsorbed on a hexagonal boron nitride (BN) substrate. By carefully controlling the amount of ^3He , it was possible to form a highly symmetric commensurate $\sqrt{3}\times\sqrt{3}$ R30° sub-

monolayer film. The characterization of the film was known from previous isotherm adsorption studies.¹

The nuclear spin-spin relaxation times T_2 for the ^3He atoms were measured for this triangular lattice over the temperature range 0.1 K to 2 K using moderately high magnetic fields so that the contributions to the relaxation rates from components of the spectral density at the nuclear Larmor frequency can be neglected. The values of T_2 are therefore determined by the spectral density at zero frequency and thus directly related to the atomic motion. The T_2 's were measured using a standard $\pi/2$ -- τ -- π NMR pulse sequence. The low electrical conductivity of the BN substrate allows the experiment to be conducted into the UHF frequency range without undue RF power absorption and loss of signal as would occur for the more familiar graphite substrates.

The results are shown in Fig. 1. The solid lines A and B in the figure refer to the two different relaxation mechanisms that occur in this temperature range. At high temperatures the relaxation is determined by the motion of thermally excited vacancies. The relaxation rate $1/T_2 = M_2/x(t)\omega_v$, where M_2 is the second moment due to the interatomic nuclear dipole-dipole interactions and $x(t)$, is the number of vacancies present in thermal equilibrium at temperature T .² ω_v is the vacancy hopping frequency from one lattice site to a neighbor. $x(t) = \exp(-\Phi/T)$ where Φ is the vacancy formation energy, and in this region we therefore expect $T_2 = \exp(-\Phi/T) \omega_v/M_2$ as indicated by the solid line A in Fig. 1. The slope of A in the figure gives the formation energy and since M_2 is known exactly from the atomic separation we are also able to determine ω_v . The best fit to the high temperature data is given by $\Phi = 2.0 \pm 0.2$ K and $\omega_v = 3.4 \times 10^6$ rad/s.

At lower temperatures, the number of thermal vacancies is too small to be effective and the motion is now determined by the quantum mechanical exchange of neighboring atoms. This exchange results from the overlap of neighboring atomic wave functions and is well known in studies of 3D solid helium. The relaxation is now temperature independent as shown by the solid line B in Fig. 1. In this regime, $T_2 = \xi J_{\text{eff}}/M_2$, where J_{eff} is the effective

exchange frequency and ξ is a numerical constant of order unity. The advantage of these high field studies is that it is possible to interpret the data in terms of the motional frequencies without the need for exact models for the spectral density of the motion at high frequencies. With the need to include several different types of exchange motions, 2-particle, 3-particle, up to 6-particle cyclical exchange, it is crucial that the analysis not depend on the details of the NMR motional mechanism. For this reason it is necessary to carry out the experiments for Larmor frequencies high compared to the highest exchange frequency.

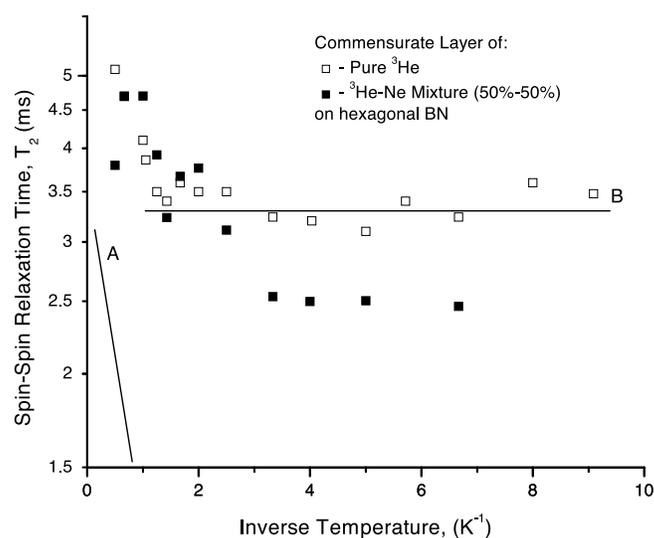


Figure 1. Observed temperature dependence of the nuclear spin-spin relaxation time T_2 for a commensurate triangular lattice of ^3He atoms on BN. Curve A represents a thermally activated atomic motion due to atom-vacancy exchange, and curve B corresponds to quantum mechanical particle-particle exchange.

For the temperature independent value of $T_2 = 3.5 \pm 0.1$ ms., we deduce an effective exchange frequency $J_{\text{eff}} = 5.0 \times 10^5$ rad/s. This is to be compared to values of $J = 30$ MHz for bulk ^3He at the melting curve.

The triangular nature of the ^3He lattice gives us a special opportunity to test the multiple spin exchange model. For this lattice, the dominant exchanges are 2-particle and 3-particle exchange; models of the magnetic behavior suggest that the exchange rates J_2 and J_3 are comparable. Writing out the explicit Hamiltonians for the exchange in terms of J_2 and J_3 and the permutation operators, it is easy to show that $J_{\text{eff}} = |J_2 - 2J_3 + 3J_4 + \dots|$, if one neglects other exchange

frequencies. One can very effectively interrupt the 3-particle and higher processes by random addition of immobile Ne atoms before the adsorption of the ^3He on the substrate. For the addition of 50% Ne, T_2 is observed to decrease by 71%. This is opposite to the classical effect for which the T_2 should increase by a factor of 2 due to the dilution of the atoms ($M_2 \propto x$). This result therefore corresponds to an increase of J_{eff} by a factor of 3.1 just due to the dilution. This would imply that $J_3 = 1.2J_2 \cong 2.10^5$ rad/s. for this oversimplified model. Exact calculations of the relaxation rates for the multiple exchange contributions of J_3 , J_2 , and the other exchange processes are needed for a more accurate interpretation of the data.

One result is clear. It is not possible to understand this effect without invoking the existence of at least two different exchange mechanisms that occur at different rates.

¹ Evans, M.D., *et al.*, J. Low Temp. Phys., **89**, 653 (1992).

² Sullivan, N., *et al.*, Phys. Rev. B, **11**, 1858 (1975).