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OBSERVATION OF SPIN WAVES IN SPIN POLARIZED HYDROGEN

B. R. JOHNSON*, N. BIGELOW, J. S. DENKER, L. P. LÉVY§, J. H. FREED, and D. M. LEE

Laboratory of Atomic and Solid State Physics and Baker Laboratory of Chemistry,
Cornell University, Ithaca, NY 14853, USA

We report the results of continuing experiments on the spin transport properties of a dilute quantum gas, spin polarized hydrogen $H\downarrow$. Spin wave resonances are prominent features of the pulsed Fourier transform NMR spectrum. For small tipping angles, the dependence of the spectrum on polarization and temperature are found to be in good qualitative agreement with theory. Preliminary results are presented on the large tipping angle spectrum, which exhibits a number of features not observed in the small angle spectrum.

For our experimental conditions, $H_0 = 7.7$ Tesla (in the z direction) and $T < 0.8$ K, only the two lowest hyperfine states $|b\rangle = |\downarrow\Downarrow\rangle$ and $|a\rangle = |\downarrow\Uparrow\rangle - \eta|\uparrow\Downarrow\rangle$ of $H\downarrow$ are populated. Here $\downarrow$ denotes the electronic spin and $\Downarrow$ the nuclear spin. The term "spin polarized hydrogen" refers to the electron spin, and means that the upper two hyperfine levels are thermally inaccessible. Throughout the rest of this paper the term "spin" will refer to the nuclear spin, or more precisely to the pseudospin in the $|a\rangle$ - $|b\rangle$ two level system. The admixture η promotes recombination of $|a\rangle$ state atoms into molecular hydrogen, creating a large nuclear spin polarization (1) which in turn produces a large molecular field. The cryostat and spectrometer are identical to the one described in earlier work (2, 3).

Exchange effects have been observed to play a significant role in the spin transport properties of spin polarized hydrogen, $H\downarrow$ (3). The observed effects have been interpreted in terms of collective nuclear spin oscillations in this rarefied quantum gas. For small NMR tipping angles, the equation of motion for the transverse spin density $s_+(\vec{r}, t)$ in the rotating frame is (4, 5)

$$i \frac{\partial s_+}{\partial t} = \delta(\gamma H_0)\, s_+ + i\, D_0 \frac{1 - i\mu P_z}{1 + \mu^2 P^2} \nabla^2 s_+ \qquad (1)$$

where we are using the notation of reference 6. This equation, subject to appropriate boundary conditions, predicts the appearance of discrete resonances in the NMR spectrum at frequencies corresponding to damped standing spin wave modes. For large tipping angles the equation of motion becomes highly non-linear, as discussed by Lhuillier and Laloë (4) and by Lévy and Ruckenstein (5).

Figure 1 shows typical small-angle (≈10°) spectra -- broad resonances with several narrow lines superimposed. Note that as T decreases, causing $|P|$ and presumably (7) $|\mu|$ to increase, the lines become narrower, closer together and more prominent. This is in good qualitative agreement with equation 1 which predicts that the spin wave lifetime should scale as $|\mu P|$. In the presence of a linear field gradient, the separation between lines should scale as $|\mu P|^{-1/3}$. Here we neglect the weak variation of D_0 with temperature (3, 7). The lack of variation of the overall width of the spectrum with T is consistent with confinement of the spin waves by $\delta(\gamma H_0)$, as predicted (5).

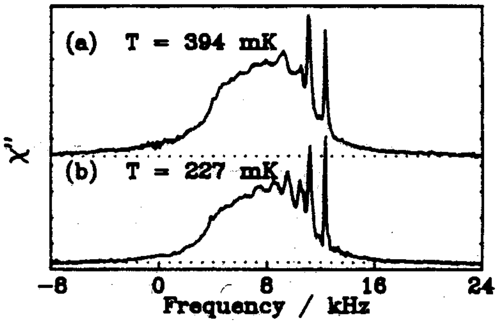

Figure 1. Temperature dependence of small-angle spectum; $n \approx 4 \times 10^{16} cm^{-3}$

Drawing an analogy between equation 1 and the Schrödinger equation, confinement of the spin waves means that the applied "potential" due to $\delta(\gamma H_0)$ is large in comparison to the spin wave "kinetic energy" corresponding to the term containing the Laplacian. The sign of μP_z determines whether the spin wave modes will be confined in the region of most positive or most negative $\delta(\gamma H_0)$. The narrowest lines (which have the smallest "kinetic energy" and the

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*Present address: Department of Physics, University of Massachusetts, Amherst, MA 01003
§Present address: AT&T Bell Laboratories, Murray Hill, NJ 07974

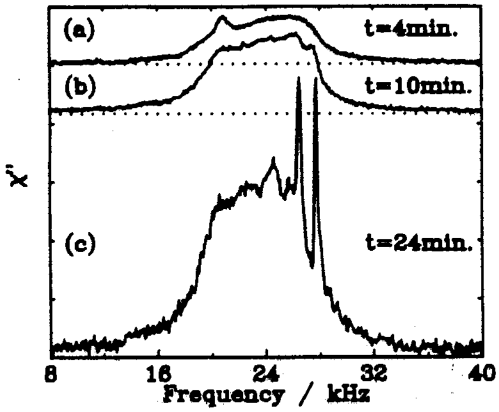

Figure 2. Polarization dependence of small-angle spectrum at T≈400mK. Loading began at t=0 and stopped at t=15min. Polarizations were in the ratio +.1 : −.13 : −.6 (a:b:c).

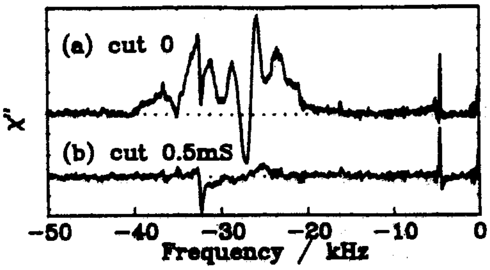

Figure 3. Large tipping angle (≈85°) spectrum. In (b), the first 0.5mS of the FID was deleted before Fourier transforming. T ≈ 395mK, n ≈ 10^{16}cm^{-3}.

longest lifetime) should appear on the high frequency side of the spectrum when μP_z is positive whereas they should appear on the low frequency side when μP_z is negative.

When H↓ atoms are loaded into the cell, P_z is initially positive due to the thermal Boltzmann distribution between the |a> and |b> states, although it soon inverts due to preferential recombination of |a> state atoms. The change of sign of P_z during this time can be verified by observing the sign of the initial voltage of the FID. Spectra obtained under the condition of positive P_z have the lines flipped to the low frequency side of the spectrum; the edge frequencies of the spectrum are not shifted. This is illustrated in figure 2. This result further confirms the applicability of equation 1 and the confinement of the spin waves by $\delta(\gamma H_0)$. The increase in |P| is accompanied by an increased integrated spectral intensity, reflecting the overall increase of magnetization with time.

For large tipping angles the spectrum is markedly different from the small angle spectrum. As seen in figure 3a, the spectrum consists of jagged peaks and deep troughs spread over a frequency range characteristic of the expected inhomogeneous linewidth. In contrast to the small angle spectra, these spectra show no indication that the spin waves are confined near a wall. Although most of the lines are broader than typical lines in the small-angle spectra, we sometimes observe some extraordinarily sharp lines, such as the one at the left of the resonance and the very remarkable line about 20 kHz beyond the right side of the resonance in figure 3a. Sharp lines of this sort are commonly seen in the large-angle spectra, but we are not completely certain what conditions are required to produce them. The 200 Hz linewidth of the peak is instrumentally limited. If the first 0.5 msec of the FID is deleted (to eliminate short-lived phenomena) the peak survives (see figure 3b) with almost the same intensity as in the original spectrum. It is clear that the linearized theory (equation 1) does not apply to these spectra.

In conclusion, exchange effects in a dilute H↓ gas cause damped spin waves to play an important role in spin transport properties. The small NMR tipping angle behavior continues to be in good agreement with the theory. There are remarkable features in the large-angle spectra which may also be explained by molecular field effects, but a better understanding of the full equations (4, 5, 6) of motion of the spin density will be required.

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