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NUCLEAR SPIN RELAXATION TIME OF NORMAL ^3He

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The spin relaxation time T_1 of normal ^3He is calculated for all temperatures $T \leq 2\text{K}$ at two different pressures ($P = 0$ and 27 bar). The calculation is based on a recently developed theory of nuclear spin relaxation via dipole interaction in a Fermi liquid by the present authors. Our results explain the experimental data so far available.

In a recent experiment [1] highly spin-polarized liquid ^3He was produced by rapid melting of the spin-polarized solid. The high spin polarization then decayed within a few minutes. In this contribution we want to show that the nuclear spin relaxation time T_1 of liquid ^3He in this experiment is determined by the purely intrinsic effect deriving from the spin non-conserving nuclear dipole interaction rather than extrinsic effects such as spin relaxation at the walls. Indeed our results agree very well with measurements of T_1 by other authors [2-4] where wall relaxation was supposed to be eliminated.

So far there only exist semi-quantitative calculations of this T_1 for the extreme quantum limit and the classical limit: For a degenerate Fermi gas Ipatova and Eliashberg [5] estimated $1/T_1 \propto (\gamma^2 \hbar^2 n)^2 T^2 / E_F^3$ (particle density n , Fermi energy E_F). For the classical limit there exists the well-known expression by Bloembergen et al. [6] (BPP), namely $1/T_1 \propto (\gamma^2 \hbar^2)^2 n / (Dd)$, where D is the spin diffusion constant and d is defined as "distance of closest approach" of the atoms.

We have recently developed a general description of spin relaxation in terms of the spin density excitation spectrum of the liquid [7], which contains both results as limiting cases. Due to the smallness of the dipole energy in relation to the characteristic energy scales of the liquid, namely the Fermi energy E_F , the thermal energy $k_B T$ and the relaxation energy $\hbar/\tau$, where τ is a typical collision time of atoms or quasiparticles, it is an excellent approximation to calculate the spin relaxation rate in lowest order in the dipole coupling. The relaxation process consists of a homogeneous ($q=0$) spin fluctuation decaying into a pair of inhomogeneous spin fluctuations with equal but opposite momenta, a process which transforms part of the spin angular momentum into orbital angular momentum. This may be expressed by the relation [7]

$$1/T_1 = (\gamma^2 \hbar^2)^2 / (3\pi^2 T \chi(0)) \times \int d^3 q \int d\omega [\chi''(q, \omega) / \sinh(\hbar\omega/2k_B T)]^2 \quad (1)$$

where $\chi(0)$ is the static spin susceptibility and $\chi''(q, \omega)$ is the absorptive part of the dynamic, wavevector dependent spin susceptibility, both divided by $\gamma^2 \hbar^2$. Eq.(1) shows that the spin dynam-

ics only contributes for low frequencies (i.e. $\omega < k_B T/\hbar$) but arbitrary wavevector q . In evaluating (1) two different q regimes have to be distinguished:

1.) For low q , $q < q_0 = 1/\ell$, where ℓ is a mean free path, the dynamics is governed by the diffusion equation and $\chi''(q, \omega) = \chi(0) D q^2 \omega / (\omega^2 + D^2 q^4)$. This yields a contribution to the spin relaxation rate

$$(1/T_1)_{\text{diff}} = (8/3) (\gamma^2 \hbar^2)^2 T \chi(0) q_0 f / D \quad (2)$$

Here we have determined the cutoff wavevector q_0 by requiring $D q_0^2 = 1/\tau$ ($\omega < \tau$ in the diffusion denominator), where τ is related to D , as usual, by $D = \tau / (4m^* \chi(0))$ and where we have assumed a temperature dependence of the effective mass $m^*(T) = \langle p^2 \rangle / (2 \langle E \rangle) = \frac{1}{2} [(p_F^2 + (3mk_B T)^2) / (E_F^2 + (\frac{3}{2} k_B T)^2)]^{1/2}$. While q_0 rather strongly depends on pressure and temperature, f is not as sensitive in that respect ($f = 1 - O(\theta^2) - O[(q_0/2k_F)^2]$, for $T \ll T_F$, where $\theta = \hbar D q_0^2 / (2k_B T)$). In the Fermi liquid regime $(1/T_1)_{\text{diff}}$ is easily seen to vary like T^5 . On the other hand, in the classical limit, where $\chi(0) = S(S+1)n/(3T)$, we obtain the celebrated BPP formula [6]

$$(1/T_1)_{\text{diff}}^{\text{class}} = (\pi/5) (\gamma^2 \hbar^2)^2 n / (Dd(P, T)) \quad (3)$$

which describes the relaxation rate of many classical liquids and which we have here essentially derived from first principle. Note, however that (3) actually contains one significant generalization of the BPP formula: it contains a temperature and pressure dependent length $d(P, T) = (3\pi/10)(q_0 f_{\text{class}})^{-1} \propto \ell$, the mean free path, instead of a constant d ("distance of closest approach" [6] or "atomic diameter" in the case of spherical atoms, i.e. about $1\text{\AA}$ in the case of ^3He) which the BPP formula contains. Indeed, while $d(P, T)$ varies like T^{-2} in the Fermi liquid regime it essentially saturates for $T \geq T_F$. This limiting value of d in the classical regime is about $1.9\text{\AA}$ at $P=0$ and $1.0\text{\AA}$ at $P=27\text{ bar}$. Therefore we see that only at higher pressures (where the "liquid character" is more pronounced than at lower pressures) one has $d(P, T) = d$, i.e. exactly the BPP formula, while at low pressures the characteristic length involved in (3) is by about a factor of 2 higher. It is important to keep in mind that due to the strong temperature dependence at lower temperatures of $d(\propto T^{-2})$ and $T \chi(0) (\propto T)$ the application

of the classical BPP formula to liquid ^3He for temperatures below 0.5K is incorrect and therefore it cannot be used to estimate T_1 .

2.) For $q > q_0$, in the so-called collisionless regime, one may approximate χ'' by the RPA form [8]

$$\chi''(q, \omega) = \text{Im}[\chi_{\text{SC}}^{-1}(q, \omega + i0) - f_0^a(q)]^{-1} \quad (4)$$

where $f_0^a(q)$ is the spin dependent Fermi liquid interaction parameter (wavevector dependent!) as determined by Aldrich and Pines [8] and $\chi_{\text{SC}}(q, \omega + i0)$ is a screened response function (in the region of ω and q we are interested in the backflow term also present in (4) is negligible). We approximate $\chi_{\text{SC}}(q, \omega)$ by the $T=0$ Lindhard function multiplied by a factor $\alpha(q)$ describing the reduced weight of single particle-hole excitations in favor of multipair excitations for larger q -values [8] and by a T -dependent factor $\chi_{\text{SC}}^T(0,0)/\chi_{\text{SC}}^T(0,0)$ chosen such as to yield the experimentally determined spin susceptibility $\chi(0)$. Substituting (4) into (1) one obtains a contribution $(1/T_1)_{\text{RPA}}$ to the spin relaxation rate in the Fermi liquid regime

$$(1/T_1)_{\text{RPA}} = (\pi^5/8)(2\pi\gamma^2\hbar^2n/3)^2(T^2/E_F^3) \times c/[1+F_0^a(0)]^{-3} \quad (5)$$

where $c < 1$ is a dimensionless function of pressure only (via the q -dependent Fermi liquid parameter $F_0^a(q)$); $c=0.33$ for $P=0$ and $c=0.24$ for $P=27$ bar. Hence we see that we recover the T^2 law of Ref. [5] (which is well understood within Landau-theory), but - what is more important - that the prefactor is enhanced by a factor $(1+F_0^a)^{-3}$, which is as large as 55 at $P=27$ bar, because $F_0^a=-0.74$. This enhancement is due to the spin fluctuations as compared to the free Fermi gas. Hence these spin fluctuations increase the relaxation rate at low temperatures much more strongly than assumed so far in the literature.

In general both types of processes, i.e. decay into diffusive modes and into particle-hole excitations, contribute so that the total relaxation rate is the sum of the two rates as discussed above: $1/T_1 = (1/T_1)_{\text{RPA}} + (1/T_1)_{\text{diff}}$. At temperatures below 0.2K the $(1/T_1)_{\text{RPA}}$ always dominates due to its T^2 behavior as compared to the T^5 of $(1/T_1)_{\text{diff}}$. At higher temperatures and pressures (27 bar) the diffusion contribution then smoothly takes over at $T \approx 0.5\text{K}$ and, at $T=1\text{K}$, is about 5 times larger than the RPA-contribution. On the other hand, at higher temperatures and zero pressure $(1/T_1)_{\text{RPA}}$ always dominates and is about a factor 2 larger than $(1/T_1)_{\text{diff}}$ for $0.5\text{K} \leq T \leq 2.5\text{K}$.

In Fig. 1 the results of a numerical evaluation of T_1 are shown for two pressures ($P=0$ and 27 bar). The diffusion constant as a function of temperature was taken from Ref. [9] for $P=0$ and from Refs. [10,11] for $P=27$ bar. For the experimental static spin susceptibility we used the measurements of Beal and Hatton [2] and the Landau parameters were taken from Wheatley's tables in Ref. [12]. Also shown are experimental data for T_1 by Beal and Hatton (BH) [2] (at $P=0.86$ and 28.9 bar), Romer [3] (at saturated vapor pressure) and Amend et al. (AEW) [4] (at 28 bar), as well as those for the relaxation time of the highly spin polarized liquid from Ref. [1] (CFR) at about 23

bar, although the T_1 of this experiment is certainly affected by the high spin polarization.

Considering the uncertainties in our approximations of $\chi''(q, \omega)$ the agreement between the experiments and our results is remarkable - particularly in the regime where the RPA-contribution dominates because there the results sensitively depend on details of χ'' , i.e. on the q -dependence of $\alpha(q)$ and $F_0^a(q)$. If one assumes $\alpha=1$ and $F_0^a(q)=F_0^a(0)$, the rates are by a factor 2-4 larger. Bearing in mind that the above mentioned experimentalists made careful efforts to avoid wall relaxation, the good agreement demonstrates that in liquid ^3He nuclear spin relaxation induced by dipolar interaction indeed seems to be the realistically dominant mechanism at not too low temperatures.

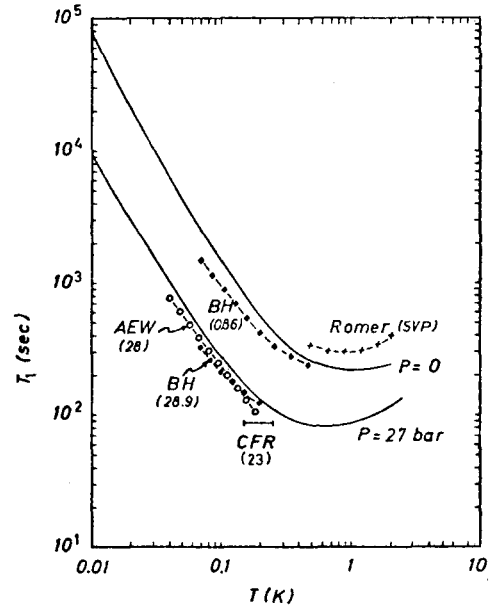


Fig. 1: The calculated spin relaxation time T_1 of normal ^3He as a function of temperature T at two different pressures P (see text).

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