

Viscosity Increase as a Function of Polarization in Liquid ^3He

C. C. Kranenburg, S. A. J. Wiegers, L. P. Roobol, P. G. van de Haar, R. Jochemsen, and G. Frossati
Kamerlingh Onnes Laboratorium, Rijksuniversiteit Leiden, P.O. Box 9506, 2300 Ra Leiden, The Netherlands

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The polarization dependence of the viscosity of spin-polarized liquid ^3He has been determined in the temperature range $75 < T < 300$ mK and the polarization range $\Delta < 0.35$. We find an increase in the viscosity, which can be described as $\eta \propto 1 + \alpha\Delta^2$ with $\alpha = 4.0 \pm 1.5$, at a pressure of 27 bars. This increase is expected from the ratio of the cross sections for s -wave and p -wave scattering. It is rather surprising, however, that there is no temperature dependence of α .

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Polarized liquid ^3He is expected to have remarkable transport properties. In the fully polarized state the strong s -wave scattering is suppressed and only the weak triplet interaction remains, which results in a very long mean free path for the quasiparticles in the interacting Fermi liquid.¹ This means that both the viscosity and the thermal conductivity of the liquid increase dramatically at high polarization. There is no agreement, however, about what the behavior of viscosity is for moderately polarized liquid. Some theories have been developed in order to describe polarized liquid ^3He .¹⁻⁵ The *nearly localized model*³ and the *density functional approach*⁴ have been used to calculate the polarization dependence of the susceptibility. Two models, the *nearly metamagnetic model*^{1,2} and the *paramagnon model*,⁵ have been used to calculate the polarization dependence of both the susceptibility^{2,5} and the viscosity.^{6,7} Hess and Quader⁶ use a polarization-dependent effective interaction, like the nearly metamagnetic model, and an assumption for the spin-flip scattering amplitude as well as the spin-flip phase space to calculate the viscosity. This calculation predicts η to decrease to about 50% of its $\Delta=0$ value at $\Delta=0.35$ before increasing to very large values for $\Delta \rightarrow 1$. This agrees with the experimental evidence for Kopietz, Dutta, and Archie.⁸ A very different behavior is predicted by a recent calculation based on the paramagnon model,⁷ giving a monotonic increase of the viscosity η with the polarization. This is supported by recent work of Vermeulen *et al.*⁹ at a fixed low polarization at one temperature. In this Letter we report our measurements over a wide temperature and polarization range. Our results definitely establish the monotonic increase of the viscosity of liquid ^3He as function of polarization. This supports the paramagnon model,⁷ although there is some quantitative disagreement.

Currently accessible magnetic fields can only obtain very modest polarization in liquid ^3He ($\Delta=0.04$ in 9 T). In order to achieve larger polarizations we have used the rapid-melting technique originally suggested by Castaing and Nozières.¹⁰ Moderately polarized liquid is produced by melting the relatively easily polarized low-temperature solid in a time short compared to the relaxation time

in the liquid.¹¹ The experiments were done in a compression-decompression cell with a flexible plastic membrane. A fixed amount of ^3He could be sealed in the cell by a ruby-tip valve. A small quartz chamber (see Fig. 1) with a volume of ≈ 13 mm³ is connected to the main cell by a small channel (0.4-mm inner diameter, 1-mm length). The quartz cell has been miniaturized to avoid problems with inhomogeneities in temperature and polarization.^{12,13} It contains a very small sliced carbon resistance thermometer ($1 \times 1.5 \times 0.2$ mm³), and an elongated semicircle vibrating-wire viscometer of 1.9-mm diameter which is made of NbTi wire, 50 μm in diameter. The distance between viscometer wire and thermometer is about 0.3 mm. All walls and components in the cell are sputtered with a thin layer of silicon to cover all possible impurities which could influence the magnetic relaxation of the liquid ^3He . The response time of both the thermometer and the viscometer is very short (1–2 s).

The viscometer¹⁴ is operated at resonance, using a feedback loop on the out-of-phase component of the signal. The viscometer is fed with a constant drive current and has a resonant amplitude A , proportional to the quality factor of the vibrating-wire viscometer. The measured amplitude A is determined by the viscous damping of the surrounding liquid and by a contribution of the intrinsic damping of the wire, A_{int} , according to

$$1/A = 1/A_\eta + 1/A_{\text{int}}. \quad (1)$$

The viscosity term, A_η , is proportional to $1/\sqrt{\eta}$ to leading order, in the range of observed viscosities (η is the viscosity).

The polarized solid ^3He is produced by slowly compressing an initially all-liquid sample at 5–7 mK in a field of 9.3 T (Fig. 1). The liquid cools slightly because of the Pomeranchuk effect, and most solid forms at about 4 mK. Only a few percent of solid per hour can be formed in order to get equilibrium polarization.¹³ During the solidification the temperature, pressure, viscometer amplitude, and the average polarization in the little quartz pot as well as in the whole main cell are monitored. When the solid grows in the quartz pot the increase in polarization is seen by an increasing NMR sig-

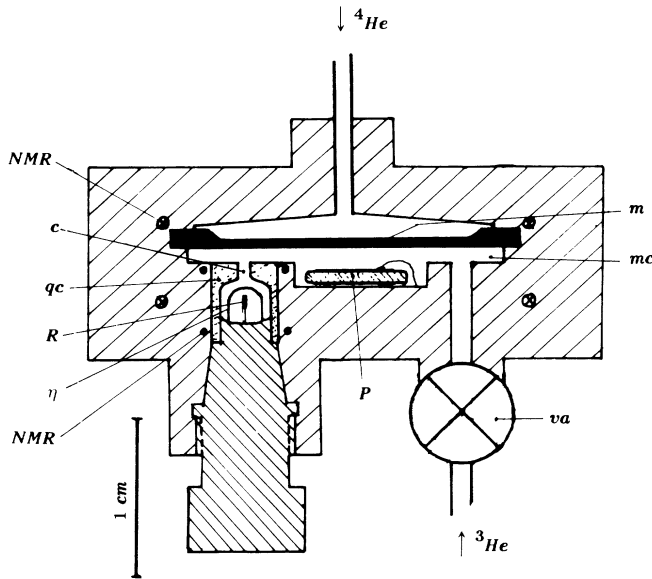


FIG. 1. The compression-decompression cell. qc is the quartz chamber with c the channel, R the thermometer, and η the viscometer; mc is the main cell with P the pressure gauge, m the membrane; va is the valve.

nal. If solid were to grow on the vibrating-wire viscometer, its resonant frequency would be expected to shift downwards (solid formed on top of the wire) or upwards (solid forming at the base of the viscometer wire). The resonant frequency of the viscometer hardly changes while the solid is formed, indicating that the solid is formed along the walls, which is corroborated by the NMR signal growing equally over the total line width. Only 20%–40% of all the ^3He is solidified in order to avoid a very large temperature increase during the rapid melting. Before the melting, the cell is closed with the valve, in order to isolate the ^3He sample from the heat exchanger.

Shown in Fig. 2 are the time traces of the polarization, temperature, and viscometer amplitude, recorded in the little cell with the narrow channel after a typical rapid decompression. The average polarization of the solid-liquid mixture before this decompression is about 25%.

The ^3He pressure was reduced within 15 s from 34 bars to about 25 bars. In Fig. 2 one clearly sees that the enhanced polarization in the liquid persists for several minutes as has been observed before.¹⁵ The relaxation time of the exponential decay was $\tau=280$ s, which is consistent with earlier measurement at this temperature.^{13,16} The temperature increases very quickly from about 5 to 115 mK, and then decreases slowly again (the valve is still closed) while relaxing to the mixing-chamber temperature. From the thermal conductivity¹⁷ and the heat capacity¹⁸ of ^3He we calculate the thermal gradients in the small cell and across the channel. We conclude that the liquid in the small cell is in good

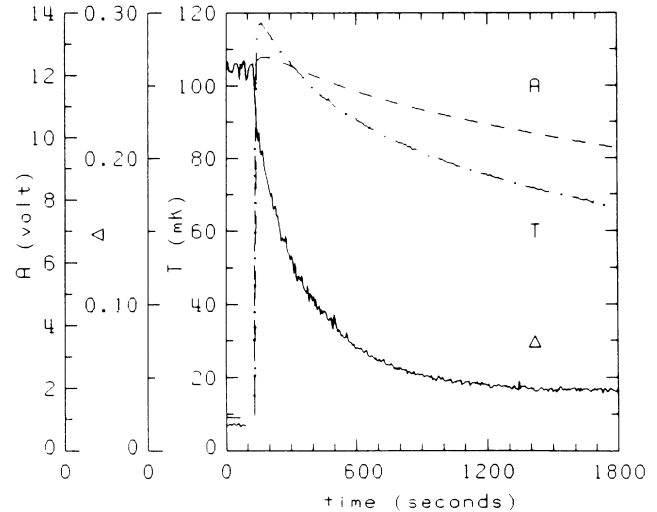


FIG. 2. The viscometer amplitude at resonance A , the polarization Δ , and the temperature T shown as functions of time. The decompression starts at $t=125$ s, and is completed 15 s later, after which the magnetic relaxation takes place.

thermal equilibrium within 50 s after the rapid melting.

Also shown in Fig. 2 is the resonant amplitude of the viscometer. Like the thermometer, it rises very quickly to a maximum just after the decompression, after which the amplitude slowly decreases. Most of the change in viscometer signal is due to the temperature change; only a small fraction of the change is related to the polarization relaxation. In order to divide out the temperature dependence, the viscometer amplitude is recorded at the same pressure, over the same temperature range, while the liquid polarization is in equilibrium with the 9.26-T field ($\Delta \approx 0.037$). In Fig. 3 the viscometer amplitude is shown as a function of the temperature with and without polarization (circles and crosses, respectively). The temperature-dependent viscosity obtained in unpolarized ^3He agrees with earlier measurements.¹⁹

It is clear that the magnetization decreases the resonant amplitude, and thus increases the viscosity. One should realize that the measurement of the circles takes place right after the decompression while polarization relaxes, as in Fig. 2. This is indicated by the arrows in Fig. 3, which show the time elapsed after the rapid decompression.

If we write $\eta = \eta(T)(1 + \alpha\Delta^2)$ and use $A_\eta \propto 1/\sqrt{\eta}$, then

$$\left(\frac{A(\Delta_0)}{A(\Delta)} \right)^2 = \frac{1 + \alpha\Delta^2}{1 + \alpha\Delta_0^2} \approx 1 + \alpha\Delta^2, \quad (2)$$

where Δ_0 is the temperature-dependent equilibrium polarization in 9.26 T.²⁰ In Fig. 4 the result of this analysis is depicted. We find a linear behavior with slope $\alpha=3.3$. It is gratifying to note that the fitted line crosses the horizontal axis very near $\Delta_0^2 = 1.3 \times 10^{-3}$, which cor-

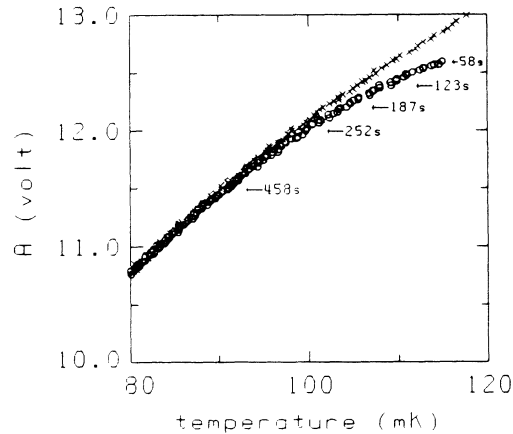


FIG. 3. The amplitude of the viscometer as a function of temperature with an equilibrium polarization in 9.26 T (crosses) and with a relaxing polarization (circles). The arrows indicate the time after the decompression.

responds to the equilibrium polarization in 9.3 T.

We have done a number of decompressions with various initial polarizations and temperatures, and they all give a similar result, as shown in Table I, column 4. Since the resonant amplitude of the viscometer is finite for $\eta=0$ because of intrinsic damping mechanisms, an intrinsic amplitude correction has to be applied. At low temperature $\eta \propto 1/T^2$, and so $A_\eta \propto T$. Using Eq. (1) we plot the inverse amplitude versus the inverse temperature and we find $A_{\text{int}} \approx 23$ V by extrapolation to $1/T=0$. This is to be compared to the value $A_0=87$ V in vacuum where the quality of the resonance is $Q_0=1400$. The normalized values for α are shown in the sixth column of Table I. It is surprising that we see no temperature dependence of the coefficient α within the experimental error (Fig. 4, inset).

To conclude, the monotonic increase of the viscosity η with polarization (at a pressure $P=27$ bars) is in clear disagreement with the experimental result obtained by Kopietz, Dutta, and Archie,⁸ which seems to show a 25% decrease in viscosity for a polarization of $\Delta=0.10$. Although this latter result was supported by a recent calculation by Hess and Quader,⁶ the measured decrease in viscosity could well be caused by thermal gradients, considering the strong temperature dependence of η . The assumption for the spin-flip phase space in the calculation by Hess and Quader⁶ certainly overestimates the spin-flip scattering.²¹ Also their assumption for the polarization dependence of the spin-flip scattering amplitude may not be valid, but this can only be properly evaluated once the phase-space treatment is improved.²¹ Recently a measurement on the viscosity of ^3He was done by Vermeulen *et al.*⁹ at $T=45$ mK, $\Delta=0.039$, and $P=30$ bars with a totally different technique. They find $\alpha=2 \pm 1$, which roughly agrees with our results at higher polarization and temperature. Their analysis de-

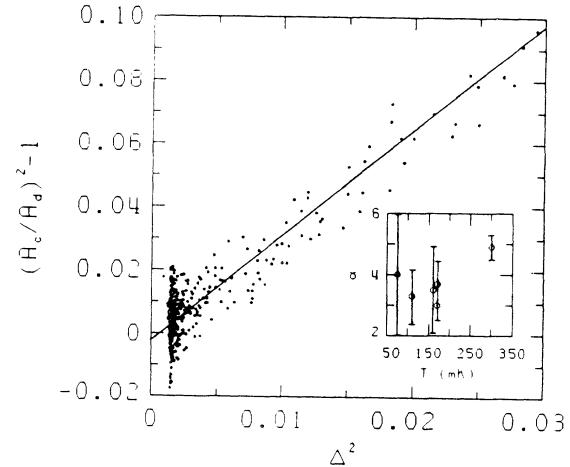


FIG. 4. The normalized amplitude change drawn as $(A_c/A_d)^2 - 1$ vs the polarization squared, Δ^2 . A_d is the temperature dependent amplitude during a fast decompression, and A_c is the amplitude while the ^3He is cooling down. The linear fit of these points gives the coefficient of the polarization dependence of the viscosity, α . Inset: the coefficient α as a function of temperature just after the decompression (T_{start}).

pends rather strongly on a model for heating in the liquid, whereas the intrinsic quality of their vibrating wire in the liquid was not measured. A lower intrinsic quality would raise their value of α . Our measurements are also in qualitative agreement with recent calculations based on the paramagnon theory.^{5,7} Quantitatively this calculation gives too low of a viscosity change. The fact that our results are not obtained in the completely degenerate Fermi liquid, but at $T > 75$ mK ($T_F \approx 200$ mK), will certainly have some effect, but we expect this to be relatively small since we measure η as a function of polarization and not as a function of magnetic field. An increase in temperature will decrease the effect of a fixed field but the effect of a fixed polarization Δ will be much

TABLE I. Coefficient of the polarization dependence of the viscosity. T_{start} , Δ_{init} , and P are, respectively, the maximum temperature, the polarization, and the pressure reached just after the decompression. α is the coefficient of the polarization dependence of η . A_{int} is the intrinsic amplitude (see text). α_{norm} is α corrected for the intrinsic amplitude. The viscosity hardly depends on the pressure.

T_{start} (mK)	nominal P (bars)	Δ_{init} (%)	α	A_{int}	α_{norm}
75	24	22	2	23	4
110	25	21	1.5	24	3.3
160	28	27	1.4	23	3.5
170	29	31	1.3	23	3.7
170	29	30	1.1	23	3.0
300	27	27	2.0	23	4.9

less influenced by temperature.

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