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# Magnetic susceptibility of liquid $^3\text{He}$

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**Abstract.**  $^3\text{He}$  is a model of Fermi liquid, isotropic, its Fermi temperature is attainable and the interaction between atoms can be controlled by changing the pressure on the liquid. In this paper we present accurate cw-NMR measurements of the nuclear magnetic susceptibility of liquid  $^3\text{He}$  as a function of temperature and pressure. The emphasis has been placed in reliable thermometry,  $^3\text{He}$  pressure measurements directly in the cell to increase the measuring range until solidification, and an accurate characterization of the NMR spectrometer. Our measurements give effective Fermi temperatures substantially lower than former results.

## 1. Introduction

One of the most important research subjects in modern physics is the correlated fermions problem. Lev Landau's theory [1] provided a phenomenological framework for the description of the Fermi liquid in terms of quasi-particles, a fundamental concept in modern condensed matter physics. In particular, Landau's theory could successfully describe the quantum fluid properties observed in liquid  $^3\text{He}$  at very low temperatures, establishing a correspondence between the thermodynamic and transport properties of the Fermi gas with those of the interacting system [2]. Liquid  $^3\text{He}$  has been extensively investigated since 1949. The well known Landau parameters were obtained by measuring compressibility, heat capacity, thermal expansion, thermal conductivity, etc. Its nuclear magnetic properties were investigated by NMR techniques, and a strong deviation from the Curie law indicating the onset of the degenerate regime could be observed by Fairbank and collaborators [3]. Many investigations followed these pioneering works. Today, liquid  $^3\text{He}$  is considered as the canonical Fermi liquid, and Landau's theory is firmly established. However, a microscopic theory is still missing, in spite of the considerable amount of work done during the last decades. Predicting, or even calculating numerically the Landau parameters from first principles is still a long term objective. Liquid  $^3\text{He}$ , as a model system, plays an important role, serving as a benchmark for microscopic calculations. For this reason, it is important to have accurate experimental results on its properties. In addition, the coherent quantum states observed in fermionic systems at very low temperatures, like the superfluidity of liquid  $^3\text{He}$ , depend crucially on the Fermi liquid properties. Again, the knowledge of the Landau parameters is essential for a quantitative understanding of these systems.

We present in this article a brief account of the extensive measurements of the nuclear susceptibility of liquid  $^3\text{He}$  performed in Grenoble. The data cover the whole pressure and temperature range. Particular care has been taken to achieve the best accuracy in all

the measured parameters. Substantial deviations have been found with respect to earlier measurements. The consequences are important, as in 1986, when the heat capacity data of D.S. Greywall led to a major change of the accepted values of the Landau parameters and the temperature scale. The Landau parameters inferred from our work, in addition to the improved accuracy, display a very smooth dependence when plotted as a function of the molar volume or pressure. Former data, on the other hand, show a sudden change in slope at intermediate pressures, a feature which caused difficulties in the comparison of the experiments with theoretical works.

## 2. Earlier experimental work and reference experiments

Several articles on the nuclear magnetic susceptibility of liquid  $^3\text{He}$  can be found in the literature. In the sixties, the experiments were limited to rather high temperatures [4, 5, 6], and their accuracy was poor: discrepancies of more than 15% were common. The measurements performed in 1970 by Thompson et al and Ramm et al [7, 8] were considered for many years as the reference measurements for the magnetic susceptibility of liquid  $^3\text{He}$  and the related magnetic Landau parameters. In 1991 Nacher et al observed inconsistencies between a measurement of the nuclear susceptibility of liquid  $^3\text{He}$  and the pure liquid  $^3\text{He}$  reference data extrapolated to zero pressure [9]. Soon after, in 1992, Hensley et al published new data of the susceptibility of liquid  $^3\text{He}$  which agreed well with the 1970 results [10].

However, in measurements of the nuclear susceptibility of liquid  $^3\text{He}$  confined in aerogel performed in Grenoble during the PhD thesis of Chen et al. [11], the bulk liquid  $^3\text{He}$  contribution was found to be clearly at variance with earlier measurements of this magnitude. This led us to reinvestigate the magnetic properties of bulk liquid  $^3\text{He}$ . Our first results [12, 13] confirmed the existence of a large discrepancy with ref. [7, 8]. A large inconsistency was also observed by H. Bozler and coworkers [14, 15] using SQUID techniques.

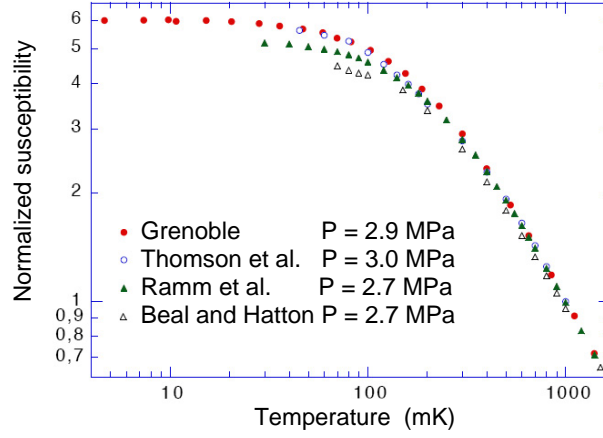
## 3. Experimental results

Our objective was to measure the nuclear magnetic susceptibility of liquid  $^3\text{He}$  in the temperature range 5 mK - 2 K, for all pressures from the saturated vapor pressure to solidification. For this purpose, a high power and very low temperature dilution refrigerator (built in the laboratory) was used.

Substantial efforts were devoted to establishing high quality thermometry, in the framework of a European research program, in liaison with metrological institutions. A sophisticated thermometric set-up, including a high accuracy melting curve thermometer, a superconducting fixed points device SRD1000, a Coulomb Blockade thermometer, and several carbon thermometers for temperature regulation and control, were attached to the mixing chamber of the refrigerator. The sample pressure was determined by a cryogenic pressure gage (similar to a melting curve thermometer); this allowed us to measure the pressure at low temperatures even above the minimum of the melting curve, where the liquid sample is isolated by a solid  $^3\text{He}$  plug.

The experimental cell is made out of Stycast 1266, and the radio-frequency coil is wound directly onto the cell. The liquid is confined in a volume of 2.7 mm diameter, and the length seen by the radio-frequency is on the order of 1 cm. Platinum wires of diameter 25  $\mu\text{m}$  ensure the thermalization within the main volume, while sintered silver heat exchangers are used in the reservoir placed outside the radio-frequency field, connected to the filling capillary.

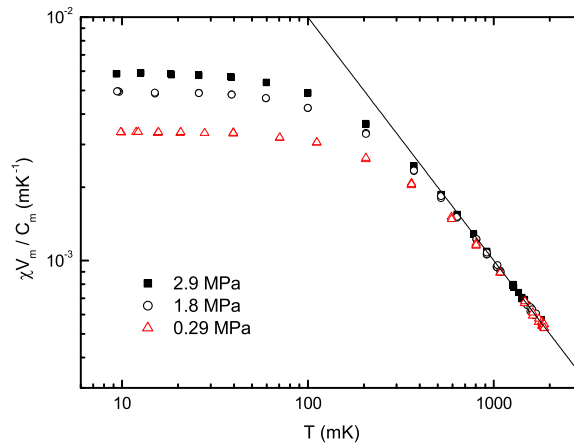
The NMR measurements were performed at a frequency of 750.15 kHz, in a magnetic field of 23.1 mT provided by a superconducting magnet. The NMR lines (in-phase and quadrature signals) were recorded automatically as the magnetic field was swept by a computer controlled system. Typical results are shown in figure 1, together with the results of other works.



**Figure 1.** Normalized susceptibility of bulk liquid  $^3\text{He}$  as a function of temperature, at pressures around 2.9 MPa. The graph shows the large deviation observed between different sets of data (see References). Note that our results extend to lower temperatures and that the measured low temperature susceptibility is substantially larger than reported in previous works.

The calibration of the spectrometer sensitivity was done by determining the Curie constant of liquid  $^3\text{He}$  for temperatures above 1 K at different pressures, and also with solid  $^3\text{He}$  at a (melting curve) pressure of 3.2 MPa between 165 and 520 mK. The determination of the Curie constant was made with an uncertainty of 0.5%. Note that in addition to the large pressure dependence of the molar volume, the latter also displays a small temperature dependence. Corrections have been made in order to accurately determine the molar susceptibility from data obtained at constant pressure.

From the susceptibility measurements one can obtain the effective Fermi temperature  $T_f^{**}$ , which is a measure of the temperature below which degeneracy effects are noticeable.  $T_f^{**}$  is smaller than the Fermi temperature  $T_f^*$ , in the ratio of the susceptibility enhancement with



**Figure 2.** Magnetic susceptibility of bulk liquid  $^3\text{He}$  (normalized by the molar volume and the Curie constant) as a function of temperature, for three pressures: 0.2898, 1.811 and 2.906 MPa. The error bars are smaller than the size of the points on this graph.

respect to the ideal Fermi gas of the same density:  $\frac{\chi_{0,m}}{\chi_{0,m}^{id}} = \frac{T_f}{T_f^{**}}$

The effective Fermi temperatures obtained in this work are substantially smaller than those reported in previous works. Our data for the saturated vapor pressure, for instance, yield  $T_f^{**}=329$  mK, to be compared to the currently accepted value of 359 mK [7, 8]. At higher pressures, the discrepancy is even larger. Our results for the three pressures of figure 2 (0.2898, 1.811 and 2.906 MPa), are respectively 291, 202, and 170 mK.

We believe that the discrepancies observed between different authors are due to the considerable difficulty of the measurements. Although it may look simple to measure the magnetic susceptibility as a function of temperature and pressure, various problems arise when all quantities must be determined with an accuracy on the order of a percent. The nuclear susceptibility is small, especially at high temperatures (above 1 K) where a calibration of the NMR spectrometer is made in the Curie regime of the susceptibility. At millikelvin temperatures, the Kapitza resistance induces a decoupling from the liquid  $^3\text{He}$  and the heat exchangers, necessarily placed outside the NMR radio-frequency coils. Note that radio-frequency leakage was common in old NMR spectrometers, and that the flat susceptibility of liquid  $^3\text{He}$  below 100 mK makes it difficult to notice a heating effect. In pulsed-NMR measurements, it was also difficult to check that the free induction decay time remained constant, therefore affecting the extrapolation of the signal to the origin of time. At intermediate temperatures, the thermal diffusion is poor. It is difficult to design a cell adapted to measurements in a large temperature range. Finally, measuring accurately the temperature from a few mK to several K is a challenge.

#### 4. Conclusion

We have measured the magnetic susceptibility of bulk liquid  $^3\text{He}$  as a function of pressure, in all the pressure and temperature range of interest. Our results have been carefully checked by making several independent NMR and thermometry measurements, in different set-ups [12, 16]. Due to their accuracy, our data lead to a determination of the effective Fermi temperature, an essential parameter in the physics of this model Fermi liquid. In particular, with a careful analysis [16] we could derive the Landau parameter  $F_0^a$  for liquid  $^3\text{He}$  as a function of molar volume, and the new results are in excellent agreement with density functional theory. A detailed account of the experimental and theoretical results will be published elsewhere [17]

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