Thermodynamics and Transport in Spin-Polarized Liquid ^{3}He : Some Recent Experiments

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Chapter 1

Introduction

Strongly correlated fermionic systems are common in nature, ranging from condensed matter physics (heavy fermions systems, high critical temperature superconductors,...) to nuclear physics (nuclear matter) and astrophysics (neutrons stars), or, very recently, atomic physics (ultracold degenerate Fermi gases). Among these systems, liquid ^{3}He is probably the simplest stable example one can dream of : it is a pure system, with no underlying lattice, and the interactions between the spin $\frac{1}{2}$ atoms are simple and accurately known, consisting mainly in hard core repulsion at short distance and weak long range attraction, as described by the Aziz potential [Aziz *et al.* 1979]. Since its first liquefaction in 1950, ^{3}He has been experimentally studied in great detail, the thermodynamic and transport properties having been measured over the whole range of temperature and pressure (<3 K, and 0-30 bar) in the normal phase as well as in the superfluid phases. As such, liquid ^{3}He is an ideal ground to test our understanding of strongly correlated fermions.

At low temperature (T <200 mK), Landau theory offers a satisfying phenomenological description, but, due to the many-body nature of the problem, Landau parameters cannot be rigorously derived from a first principles calculation. This led to the development of a variety of models, trying to account for the value and the density dependence of Landau parameters. In particular, two opposing views picture ^{3}He as being close to a ferromagnetic instability ('nearly ferromagnetic' model) or to a Mott localization transition ('nearly localized' model). Both provide a more or less satisfying description of the properties of the unpolarized liquid (see [Bonfait *et al.* 1990] for a review). Another issue is the description of ^{3}He beyond the Landau Fermi liquid regime. Close to the critical point, the experimental transport properties resemble those of a quantum gas of hard spheres [Wilks 1967]. The transition regime, from 200 mK to 2 K, has been little studied theoretically, most often at a qualitative level only (see [Lhuillier 1991] for a review).

In the low temperature, degenerate, regime, the properties of liquid ^{3}He are expected to be quite sensitive to the spin polarization as a consequence of Pauli principle. The theory of thermodynamics and transport phenomena in spin-polarized liquid ^{3}He within the framework of the Landau theory have been reviewed by [Meyerovich 1987]. Beyond the Landau theory, Castaing and Nozières suggested in 1979 that the effects of polarization should allow to test the 'nearly ferromagnetic' versus the 'nearly localized' pictures [Castaing and Nozières 1979]. More generally, the extra control parameter provided by the spin polarization could open to a new realm of properties -including the possibility of new phases [Bashkin 1984b, Lhuillier and Laloë 1979, Stringari *et al.* 1987, Pickett 1989]- against which different theories could be tested.

These possibilities were the initial motivation for producing and studying spin-polarized liquid ^{3}He. As the equilibrium polarization is quite small in currently available static magnetic fields, one has to use to out-of-equilibrium methods. Castaing and Nozières thus proposed in 1979 to obtain transiently polarized liquid by melting a strongly polarized ^{3}He solid [Castaing and Nozières 1979]. This rapid melting technique was soon demonstrated by a number of groups [Schumacher *et al.* 1979, Chapellier*et al.* 1979, Bonfait *et al.* 1984, Dutta and Archie 1985]. The first experiments conducted using this method have been reviewed in the 1990 review paper of [Bonfait *et al.* 1990]. At that time, there was a contradiction between the polarization dependence of the melting pressure, which suggested the occurrence of a metamagnetic transition, in agreement with the 'nearly localized' picture, and that of the sound velocity, which showed no anomaly. The difficulties of interpretation associated with the two-phase coexistence in the first type of experiment led the Grenoble group to undertake a measurement of the magnetization curve in a fully liquid sample, where the polarization can be determined unambiguously. This measurement rested on an elaboration of the rapid melting technique, where the polarized ^{3}He is obtained inside a silver sinter heat exchanger. This was an experimental breakthrough, as this modification allowed to obtain strongly polarized ^{3}He at controllable temperature and pressure, opening the way to measurements which would have been impossible otherwise. It is the purpose of the present paper to describe these experiments, which study the polarization dependence of thermodynamic (effective field, specific heat) and transport (viscosity, thermal conductivity) properties. Their results provide a new ground to test the different theoretical descriptions of liquid ^{3}He. The thermodynamic measurements rule out any metamagnetic transition and show that the 'nearly ferromagnetic' and 'nearly localized' pictures are probably too extreme. The transport measurements give surprizing results. On the one hand, the polarization dependence of the viscosity resembles that predicted for a dilute gas of fermions (lack of density dependence at low temperature, persistence of the effect beyond the degenerate regime), which we did not expect for a dense liquid. On the other hand, the polarization dependence of the thermal conductivity is found much weaker than predicted for a dilute gas of fermions.

We have chosen to give a self-contained presentation of our experimental results and their theoretical context. It is our belief that such a synthesis might be useful beyond the field of liquid ^{3}He physics. For example, the Hubbard model discussed here is relevant to recent work on ^{3}He films [Casey *et al.* 2003], and applies as well to the case of cold bosons [Greiner *et al.* 2002] or fermions [Modugno *et al.* 2003] in optical lattices. Also, the transport mechanisms in liquid ^{3}He might have some relevance in the new field of strongly interacting cold fermions gases, in these special circumstances where the s-wave and p-wave scattering cross-sections would be simultaneously large [Regal *et al.* 2004]. However, it should be stressed that our presentation of the theoretical background mainly focuses on the two 'extreme' points of view represented by the 'nearly ferromagnetic' model and 'nearly localized' model. Other relevant approaches (e.g. density-functional calculations Barranco *et al.* 1996, Gatica *et al.* 1998, induced interaction model [Sanchez-Castro and Bedell 1989b], ...) are only mentioned in the context of our experimental results.

Although we will not discuss them, we would finally like to mention a number of other recent developments in the field of spin-polarized pure and dilute ^{3}He. For pure liquid ^{3}He, these are the study of the vapor pressure [Villar *et al.* 2000b] and the analysis of the melting of polarized solid ^{3}He [Marchenko *et al.* 1999]. For spin-polarized ^{3}He-^{4}He mixtures, we quote the recent viscosity measurements by [Owers-Bradley 1997], [Woerkens, PhD Thesis 1998], [Akimoto *et al.* 2002], and the measurement of the osmotic pressure of saturated ^{3}He-^{4}He mixture [Rodrigues and Vermeulen 1997]. Finally, a good deal of work deals with the transverse spin dynamics in polarized Fermi systems: The non-linear phenomena induced by the dipolar or demagnetizing fields have been studied by a number of authors ([Nacher and Stoltz 1995], [Fomin 1997a], [Owers-Bradley *et al.* 2000], [Villar and Nacher 2000a], [Nacher *et al.* 2002], [Krotkov *et al.* 2002]). The possible damping of spin waves at zero temperature is also a subject of present theoretical ([Meyerovich 1985], [Mullin and Jeon 1992], [Meyerovich and Musaelian 1993], [Fomin 1997a], [Mineev 2004]) and experimental ([Wei and Candela 1993], [Ager *et al.* 1995], [Roni and Vermeulen 2000], [Buu *et al.* 2002c], [Akimoto *et al.* 2003]) controversy.

The outline of this paper is as follows : we first present the initial theoretical issues by describing the Landau approach, the 'nearly ferromagnetic' and 'nearly localized' pictures, both for the unpolarized and spin-polarized liquid ^{3}He (chapters §2 and §3). Next, we describe in chapter §4 the various techniques used to polarize liquid ^{3}He, putting the emphasis on the method of rapid melting inside a silver sinter. The success of this method relies on the combination of a small Kapitza resistance of the silver sinter, and a relatively long magnetic surface relaxation time. As silver sinters are widely used in the low temperature community, we chose to describe in detail the measurements of these quantities in the separate appendix §A.

Chapter §5 presents the first experiment that we performed, that is the determination of the susceptibility up to an effective field of 200 T, and an analysis of its results in relation to chapter §3. The next three chapters concern the measurements of the viscosity (§6), the thermal conductivity (§7), and the specific heat (§8) of the polarized liquid. All these measurements use the same experimental set-up, based on a vibrating wire viscometer. Operating this viscometer required to open a small gap inside the sinter. The influence of this gap on the polarization and temperature gradients inside the cell is of central importance for a correct interpretation of our experimental results. However, the corresponding discussion is rather technical. This is why we have specifically devoted two appendixes (§B and§C) to these problems. Finally, appendix §D gives the theoretical background necessary to the discussion of our transport measurements.