CHAPTER 13

Spin-Polarized Phases of ^3He

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Helium Three
Edited by
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1. Introduction

Recently, a new branch of physics has been rapidly developed – the physics of spin-polarized quantum systems. In this branch, the studies of spin-polarized ^{3}He Fermi systems, ^{3}He↑, take an important place. The interest in the investigation of ^{3}He↑ is caused by several reasons. First, during the last decades a substantial advance has been achieved in attaining ultralow temperatures and high magnetic fields. The combined effect of these two factors revealed the appearance of a large number of new, sometimes quite unexpected, phenomena. In this field, ^{3}He is one of the most important subjects to study since ^{3}He is the main heat-transfer agent or the working medium and is unavoidably used in all apparatuses working at temperatures below 1 K. From this point of view, the study of ^{3}He↑ seems to be quite essential for ensuring a further progress in low-temperature techniques.

Second, different low-temperature phases of helium represent unique systems where important macroscopic quantum phenomena of a fundamental interest are exhibited. In helium such phenomena are usually exhibited in the most clear and pronounced form and are accessible to a consistent theoretical and experimental analysis. Therefore, studies on helium systems (including ^{3}He↑) may also be promising for understanding and simulation of phenomena in other quantum systems.

Third, the interest in the physics of magnetic phenomena is now shifted towards research on nuclear magnetism, and ^{3}He is a rare example of a pure nuclear magnetic material accessible to experiments. Although ^{3}He represents the simplest nuclear exchange paramagnet (in all phases without magnetic ordering), magnetic properties of different phases of ^{3}He turn out to be quite nontrivial.

Actually, the majority of interesting unusual properties of ^{3}He are related to the existence of nuclear spins in ^{3}He and are consequences of complicated magnetic (mainly exchange) processes in the different phases of ^{3}He. The aim of the present review is to describe, where possible from a unified point of view, the physical effects which are due to the partial or total spin polarization of different phases of ^{3}He. It turned out that the spin polarization results not only in the substantial change of properties of the traditionally studied ^{3}He phases, but also in the possibility of appearance of quite new, unusual, phases of ^{3}He↑. Some of these new phases do certainly exist in the ^{3}He↑ magnetic phase diagram, and the question about the existence of others is still open. In what follows, we describe practically all phases of ^{3}He↑, except A- and B-phases of superfluid ^{3}He, the antiferromagnetic phase of solid ^{3}He and the majority of two-dimensional helium systems.

Properties of different phases of ^{3}He↑ have many common features. As we shall see below, magneto-kinetic effects and the spin dynamics are, at least qualitatively, virtually the same in all phases. The propagation of the high-frequency spin waves in dilute Boltzmann ^{3}He↑ gas can most easily be explained on the basis of the Fermi liquid approach, although at first glance such a description can be formally applied to helium systems only in the case of normal Fermi liquid ^{3}He or in the case of degenerate ^{3}He–He-II solutions. The properties of the vacancy ferromagnetic phase of solid ^{3}He should mostly resemble the completely polarized dilute solution of ^{3}He in superfluid ^{4}He. The effect of the magnetic field on the transverse zero sound in liquid ^{3}He is similar to the damping of the high-frequency spin–sound oscillations in dilute ^{3}He–He-II solutions, etc.

Until recently, it has been assumed that the spin-polarization effects in ^{3}He lacked special interest. The point is that the switching on of a strong external magnetic field H seemed to be the only available and direct method of spin polarization of different phases of ^{3}He (the so-called "brute force technique"). In this case, the degree of spin polarization is determined by the value of the parameter $\beta H/E$, where $\beta \sim 0.08\,\text{mK/kOe}$ is the ^{3}He nuclear magnetic moment and E is the characteristic energy of the particles. In the presently available fields, $H \lesssim 100\,\text{kOe}$, the value of βH does not exceed $10\,\text{mK}$, and such a direct method of spin polarization can only be effective, even at extremely low temperatures, $T < 10\,\text{mK}$, for solid ^{3}He (the Néel temperature is of the order of $1\,\text{mK}$) or for dilute solutions of ^{3}He in superfluid ^{4}He for which the Fermi energy is small due to the smallness of the ^{3}He concentration. It has been assumed that

(1) for dilute ^{3}He–He-II solutions the spin polarization only results in a trivial insignificant change in properties,

(2) for the solid ^{3}He experiments in high fields and at low temperatures do not promise fundamentally new effects and are technically very complicated, and

(3) for all other phases a possible weak spin polarization leads only to insignificant small corrections of the order of $\beta H/E$ to the system parameters. All these assumptions turned out to be invalid. First, even for very dilute ^{3}He–He-II solutions, the spin polarization results in fundamentally new, large and measurable effects. Second, for many phases of ^{3}He even the insignificant spin polarization may result in quite essential effects. Third (which is probably the most important), new alternative methods of spin polarization have been developed for ^{3}He. These methods are based on the fact that the depolarization time for the ^{3}He spin system in most of the ^{3}He phases is very long, and it may

be possible to create long-lived quasi-equilibrium states of ^{3}He↑ in which th degree of spin polarization is governed not by the value of an external magneti field, but by the prehistory of the system.

There exist two mechanisms of depolarization in ^{3}He: the magnetic dipole-dipole interaction of ^{3}He nuclear spins and the depolarization on the cell walls The dipole interaction is very weak (the characteristics time is of the order o $\tau_d \sim \hbar E r_0^6 \beta^{-4} \sim 10 E r_0^6\,\mathrm{s/K\AA^6}$, where r_0 is the average distance between ^{3}H particles) and the corresponding depolarization processes are often ineffective The depolarization on the walls is usually more efficient and has a characteristic time L^2/Dw, where D is the (exchange) spin diffusion coefficient and L is the size of the cell. The ^{3}He accommodation coefficient with respect to the spin on the walls, w, can be substantially decreased if one uses some special protective coatings which increase the depolarization time up to tens of minutes or even to several hours. Now there exist reliable methods to polarize dense liquid ^{3}He (for $T \lesssim 10\,\mathrm{mK}$, and polarization up to 30–50%, the depolarization time is of the order of ten minutes), using the fast melting of polarized ^{3}He crystals in fields below 100 kOe, and to polarize ^{3}He gas (for $T \sim 1\,\mathrm{K}$, and polarization up to 70%, the depolarization time about sixty hours), using optical pumping at room temperatures. These methods of ^{3}He spin polarization are discussed in more detail in the appropriate sections of this chapter. In principle, similar methods can allow one to polarize also some other phases of ^{3}He, e.g., ^{3}He–^{4}He mixtures. The majority of results described here are valid both for equilibrium and for long-lived quasi-equilibrium polarized ^{3}He↑ systems. Therefore, it is sometimes convenient to choose as thermodynamic variables not N_3 and $\boldsymbol{H}$ (where N_3 is the number of ^{3}He atoms per unit volume), but the pair of variables N_3 and $\boldsymbol{M}$ (where $\boldsymbol{M}$ is the magnetic moment per unit volume) or, in case one is interested in processes without changes in the direction of magnetization $\boldsymbol{M}$, the pair of variables N_+ and N_- ($N_\pm$ are the numbers of ^{3}He atoms per unit volume with the spin projections $\pm\frac{1}{2}$ on the axis $\boldsymbol{e} = \boldsymbol{M}/M$ chosen as the z-axis; $N_+ + N_- = N_3$, $\beta\boldsymbol{e}(N_+ - N_-) = \boldsymbol{M}$).

It is clear that a completely consistent microscopic description can be developed only for rarefied phases of ^{3}He which are the subjects of the first sections of this chapter. The theory has the simplest form for degenerate rarefied polarized systems (section 2). However, for many of the most pronounced effects of polarization in dilute systems, the requirement of degeneracy of a gas is not very essential. Therefore, polarization phenomena at arbitrary degrees of quantum degeneracy for ^{3}He systems are considered in section 3. Of course, the majority of analytical results here are derived in the limiting cases of completely degenerate or Boltzmann systems. The following section (section 4) is devoted to the effect of the spin polarization on the superfluid properties of degenerate rarefied ^{3}He Fermi systems. Finally, the last two sections contain a description of the low-temperature properties of the dense phases of ^{3}He↑.

Although the field seems to be quite narrow, quite a large number of experimental and theoretical papers on the properties of the $^3He\uparrow$ systems have been published during the last years. Therefore, due to the limitation of space for this chapter, many of the results are either only briefly mentioned or are not included at all in the text. The selection of the material for this chapter has been guided mainly by the desire to present a qualitatively uniform description of the polarization phenomena in quite different phases of $^3He\uparrow$. For instance, we practically do not mention the results of a large number of papers on the numerical analysis of the ^3He ground-state properties. Some earlier information on the properties of $^3He\uparrow$, obtained up to 1980, can be found in "Spin-polarized quantum systems" (1980) and in a review article by Bashkin and Meyerovich (1981).

2. *Degenerate polarized Fermi gas*

2.1. *Dilute ^3He–He-II solutions*

A system of impurity ^3He particles dissolved in superfluid ^4He represents a most convenient subject for study of the properties of a gas of uncharged fermions in a wide temperature range. After the discovery (Edwards et al. 1965) of the finite solubility of ^3He in superfluid ^4He down to zero temperature, the study of liquid ^3He–He-II solutions has been of particular concern. Such a solution was the first of all helium systems investigated at high degrees of spin polarization. This section describes the properties of a dilute spin-polarized solution; however, as we will see below, the results can easily be generalized, practically without modification, to other dilute Fermi gases.

Now we shall briefly outline the basic properties of dilute ^3He–He-II solutions (for more details see Radebaugh 1968, Ebner and Edwards 1971, Khalatnikov 1971, Eselson et al. 1973, Baym and Pethick 1978, Ghozlan and Varoquaux 1979, Bashkin and Meyerovich 1981, and Meyerovich 1987). At sufficiently low temperatures, the contribution of phonons and rotons, which exist both in pure ^4He and in the solution, is negligibly small, and the thermodynamics of the solution is governed mainly by the excitations in the ^3He impurity system. For instance, at a temperature of 0.7 K and a ^3He concentration 0.5%, the phonon contribution to the normal density amounts up to about 1% of the contribution from the ^3He impurity. Since ^4He in its ground state represents a liquid characterized by a macroscopic wave function, an isolated ^3He impurity atom, according to Landau and Pomeranchuk (1948), is delocalized in superfluid ^4He and behaves as a peculiar impurity quasi-particle with an energy spectrum $\mathscr{E}(\boldsymbol{p})$. At low momenta p, the spectrum $\mathscr{E}(\boldsymbol{p})$ is quadratic in p and according to experimental data has a minimum at $p = 0$

characterized by several unknown parameters, and our real understanding of the situation will improve only after systematic experiments on depolarization time.

7.3. Concluding remarks

Most of the polarization effects in the thermodynamics, kinetics and spin dynamics discussed in this chapter have much in common for the various low-temperature spin-polarized phases of ^{3}He↑. These effects are due, as a rule, to similar changes in the effective interaction of single-particle Fermi exitations in exchange systems upon their spin polarization. Many of the phenomena considered above have been elucidated both theoretically and experimentally, but some of the problems are still under consideration.

In this chapter, I have tried to discuss the polarization phenomena in all possible bulk phases of pure ^{3}He↑ and ^{3}He↑–^{4}He mixtures with the exception of the A- and B-phases of pure superfluid ^{3}He. In superfluid ^{3}He, the order parameter is so complicated that even a mere listing of interesting magnetic properties of ^{3}He-A and ^{3}He-B discussed in the literature would require more attention than was possible in this chapter. Some of these properties are discussed in other chapters of this book.

In this chapter, I have also not considered different two-dimensional ^{3}He↑ systems: the surface impurity states of ^{3}He↑ in ^{3}He↑–^{4}He solutions, ^{3}He↑ and ^{3}He↑–^{4}He films, adsorbed ^{3}He↑ systems on regular (e.g., grafoil) and disordered substrates, solidified boundary ^{3}He↑ layers near solid surfaces, etc. Many of the polarization properties of these two-dimensional systems have very much in common with the bulk systems considered in this chapter. However, in many cases the dominant role in many of the phenomena in question is played, for 2D systems, by the very specific two-dimensional features of interaction, transport phenomena, fluctuations, localization effects, etc. Therefore, the results for such systems were not included into this chapter. Needless to say, that the studies of spin-polarized two-dimensional quantum systems are still in an initial stage, and it is practically impossible to cover the corresponding material within a systematic general review.

8. Summary

This chapter reviews theoretical and experimental data on the effect of spin polarization on the physical properties of different low-temperature phases of pure ^{3}He and ^{3}He–^{4}He mixtures. Thermo- and hydrodynamics, transport properties, spin dynamics, high-frequency effects and the superfluidity of spin-polarized helium systems are discussed. Virtually all bulk liquid, solid and gas

hases of $^3He\uparrow$ and $^3He\uparrow$–^4He mixtures are discussed, except for ^{3}He-A and He-B. The majority of the effects considered are due to the influence of spin olarization on the density of states and the effective interaction of single-article Fermi excitations (^{3}He quasi-particles or vacancies). It is shown, that for ll ^{3}He phases the spin polarization results in the interesting, sometimes very rge effects accessible for observation. Such effects for different helium phases e discussed, whenever possible, from a unified point of view. Both equilibrium nd quasi-equilibrium polarized helium systems are studied and methods of spin olarization are described.

cknowledgements

he author would like to express his deep gratitude to A. Andreev, E. Bashkin, u. Kagan, F. Laloë, and L. Pitaevskii for numerous useful discussions on the rious stages of this work.

This work was started in the Institute for Physical Problems (Moscow, SSR), and was finished at the University of Rhode Island; I would like to ank all my numerous European and American colleagues who helped and pported me during the transition period.

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