SPIN POLARIZED HELIUM-3, A PLAYGROUND IN MANY DOMAINS OF PHYSICS

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Résumé - On présente dans cet article une revue des différentes méthodes utilisables pour polariser le spin nucléaire de l'hélium-3. On discute tout particulièrement ces techniques en relation avec la production de cibles d'hélium-3 polarisé pour des expériences de physique nucléaire : diffusion d'électrons ou de protons, polarisation de faisceaux de neutrons. On met l'accent sur le développement des nouveaux lasers à solide de puissance maintenant utilisés pour le pompage optique de l'hélium. Certaines applications à la physique atomique et à la statistique quantique sont également mentionnées. On décrit pour terminer une expérience récente montrant que la conductivité thermique du gaz d'hélium-3 à basse température dépend de la polarisation nucléaire. Ceci est une conséquence de l'indiscernabilité quantique des particules qui joue un rôle important dans les collisions binaires et donc modifie les propriétés de transport du gaz.

Abstract - This article gives a survey of the different methods which can be used to polarize the nuclear spin of helium-3. These techniques are particularly discussed in relation to the production of polarized helium-3 targets for nuclear physics experiments, such as electron or proton scattering and neutron spin filters. Some emphasis is given to the development of new powerful solid state lasers now used for helium optical pumping. Applications to atomic physics and quantum statistics are also mentioned. A recent experiment is finally described which shows that the heat conductivity of the helium-3 gas at low temperature depends on the nuclear spin polarization. This is a consequence of the quantum indistinguishability of the particles which plays a large role in binary collisions, thus influencing the transport properties of the gas.

I - SEVERAL FIELDS OF PHYSICS MAKE USE OF SPIN POLARIZED HELIUM

I.1 In atomic physics

In atomic physics the helium atom has been extensively studied in the last decades : it is one of the simplest existing atoms and the wavefunctions for a two electron particle are relatively well known [1]. Spectroscopic measurements of high accuracy, making use of optical pumping and magnetic resonance techniques, were performed on the ground state and the excited states of both helium-3 and helium 4 isotopes, providing a value for α , the fine structure constant [2] and several tests of Quantum Electrodynamics. This field was first revived by the use of single frequency tunable lasers and Doppler free spectroscopy methods. Enhanced precision is now expected from

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the newly developed techniques of cooling and trapping atoms using laser beams [3]. In this way a beam of metastable helium atoms was recently transversely cooled down to 2 μ Kelvin [4].

Atomic physics studies dealing with polarized helium atoms extend to surface physics. Polarized metastable helium atoms incident on magnetized surfaces yield secondary electrons, the polarization of which probes the local density of occupied surface electronic states [5]. In the same way the relaxation rate of helium-3 atoms on a surface can be used to measure the adsorption energy of helium on various substances or study the formation of ^3He – ^4He films. Let us also mention that, as soon as they were discovered, the methods for spin polarizing helium were applied to measuring very small fluctuations of magnetic field of the earth, caused by winds in the magnetosphere, by geomagnetic activity or by man-made disturbances [6]. The helium magnetometer has been adopted by the U.S. Navy two decades ago and its sensitivity and performances are expected to improve from the newly developed compact lasers which can optically pump helium [7]. Note that a magnetometer was launched in space in 1973 to probe the field of Jupiter and Saturn and it still returns data some 17 years later [8].

1.2 In quantum statistics

The possibility of cooling polarized helium-3 atoms, either by optical or by conventional refrigeration techniques, opens up also new perspectives in quantum physics. When the atomic de Broglie wavelength becomes large compared to the range of the interatomic potential, spectacular changes in the macroscopic behaviour of the helium-3 fluid occur as a consequence of the polarization of the nuclear spin, in spite of the smallness of the nuclear magnetic moment. These effects are subtle consequences of the indistinguishability of the particles and of the symmetrization principle in quantum mechanics [9]. One expects changes of the transport properties of the gas, such as the viscosity, the heat conduction or the spin diffusion, as a function of M, the degree of nuclear spin polarization, which can be treated as a new thermodynamical variable [10]. Similarly the phase diagram of helium-3 is expected to change with spin polarization at very low temperature, the melting pressure decreases with M, the saturating vapour pressure increases, the critical temperature for superfluidity raises.

When the richness of the domain of quantum statistics dealing with polarized helium-3 atoms was first realised in the earlier eighties, our group at E.N.S. started a program for producing large values of the polarization M by optical pumping of the gas. We were thus induced to build tunable infrared lasers at the appropriate wavelength (1.083 μm). Combined with cooling techniques for the polarized helium-3 gas, optical pumping allowed us to show the existence of collective oscillatory modes, the transverse spin waves [11], to modify the heat conductivity of the gas [12] and to produce polarized helium-3 liquid, a fascinating new quantum fluid [13].

1.3 In nuclear physics

Polarizing helium-3 nuclei is also of much concern for nuclear and high energy physics, as already realized several decades ago [14]. Actually the helium-3 nucleus can be considered as a good approximation of a free neutron, from the point of view of nuclear targets. The reason is that the two protons are predominantly in a s-state, whereas the unpaired neutron carries 90 % of the spin of the nucleus. Scattering electrons or protons from helium-3 nuclei should thus bring informations about refined details of the 3 body wavefunction of the nucleus, as well as about the magnetic and electric structure of the neutron, as pointed out by several speakers at this conference [15] and demonstrated by a recent experiment at Bates [16]. The possibility of easily reversing or destroying the helium-3 polarization by NMR pulses gives much flexibility to these experiments where asymmetries in scattering amplitudes are measured. Let us also mention the use of spin polarized helium-3 targets as spin filters for neutron beams. The method is based on the very spin dependent cross-section for the reaction :

where neutrons in a spin state opposite to that of the ^3He targets are transiently absorbed to a resonant state of the ^4He nucleus with a huge absorption cross-section of 3000 λ Barns, where λ is the neutron wavelength in $\text{\AA}$ [17] [18]. This technique should apply well to very cold neutron beams of wavelength below 1 $\text{\AA}$, for which conventional polarization by reflection from magnetic crystals is rather unefficient. This was illustrated by early experiments in Los Alamos [19].

This article first reviews the possible means of producing spin polarized helium-3 and discusses the various experiments now in progress to achieve large densities as well as large polarizations. The subject of spin polarized quantum fluid is briefly reviewed at the end.

II - HOW TO POLARIZE HELIUM-3 NUCLEI ?

Several methods can be used to obtain a significant nuclear polarization in gaseous or liquid helium-3. The simplest idea in principle is to use the so-called "brute force technique" where the fluid is submitted to a high magnetic field at low temperature. It is well suited for helium-3 in its condensed form. Alternatively one can operate the optical pumping techniques discovered by Kastler in 1954 [20], which apply well to helium in its gaseous phase. We here compare the expected results.

II.1 Brute force methods

α) Dilute phases of helium

For gaseous helium-3 brute force techniques are not very efficient. In this case the nuclear polarization M increases monotonically with the ratio B/T (B is the magnetic field, T is the temperature). For instance at $B = 10\text{T}$, M reaches 0.8 % at $T = 1\text{ K}$ and 4 % at 0.2 K. At lower temperatures the vapour density falls down to ridiculously low values. However let us mention another system which shows many similarities with helium-3 gas and is much easier to polarize by brute force : the solutions of helium-3 diluted in superfluid helium 4. At low enough temperature the helium-4 solvent behaves like "massive vacuum" showing no entropy, viscosity or heat conductivity. Diluted in it, the helium-3 atoms behave like an isolated gas of quasi-particles, provided their concentration is less than 6 % . This gas can be cooled to temperatures arbitrarily low. Thus it becomes substantially polarized for temperatures below T_F (Fermi temperature), where T_F increases with the ^3He concentration x as $x^{2/3}$. For instance for $x = 10^{-4}$, $B = 10\text{T}$ and $T = T_F = 5.6\text{mK}$, one calculates $M = 85\%$ [21]. These solutions can be used for applications where a large amount of helium 4 nuclei is not a problem. They also provide a nice tool to study quantum Fermi gases below the degeneracy limit.

β) Dense phases of helium

For all the experiments where pure helium is required, one can think of applying brute force methods to the dense phases of helium-3. In the case of pure liquid helium-3 they are still less efficient than for the gas, because this liquid is a Fermi degenerate system of relatively low magnetic susceptibility below 0.4 K, corresponding approximately to its Fermi temperature. For example, at $B = 10\text{ T}$ and $T = 0.2\text{ K}$, M would only equal 2 % in the liquid and would not increase much at lower temperature. Only when applied to solid helium-3 are brute force methods useful. Solid helium can be obtained at low temperature by compression to about 36 atmospheres. At a temperature of 10 mK in a field $B = 10\text{ T}$ the ordering of the nuclear spins in the solid reaches 80 % . Following an idea suggested in 1969 [22], several groups have shown that polarized liquid can be transiently created by a fast decompression, resulting in melting the solid [23] [24]. Initially the liquid polarization M can reach 50 % . However M quickly decreases under the action of the dipole-dipole relaxation in the liquid phase. Relaxation times T_1 are of order 5 minutes at 0.5 K and depend on temperature.

II.2 Optical pumping methods

α) some historical remarks

Optical pumping is an alternative method which allows playing with the internal variables of the atoms, such as their electronic orbital moment L , their electronic spin S and, through hyperfine interaction, their nuclear spin I . It results from a transfer of angular momentum from polarized light to atoms, through the process of photon absorption and reemission by spontaneous emission [20]. The rich field of atomic physics opened up by this discovery is for instance covered in reference [25]. The first experiments were performed on an atomic beam of Na, with densities of the order of 10^8cm^{-3} .

It was thought initially that the method could only apply to very dilute media, first because of the optical thickness of the absorbing medium, second of the relaxation processes due to collisions of the oriented atoms with the walls of their container. The latter difficulty was partially overcome by the use of buffer gases, slowing down the diffusion of the pumped atoms to the walls, and by appropriate films coating the inside of the container. The method could thus be extended to vapours of mercury, alkalies and many other atoms, with densities reaching 10^{10} cm^{-3} , still limited by the absorption of the pumping light when density increases.

β) the case of helium-3

When the nuclear orientation of helium-3 with optical pumping was discovered, it became clear that it was a very good case for obtaining relatively large densities of polarized gas. Two reasons to this. First the nuclear relaxation time T_1 of helium-3 can be extremely long; T_1 values up to several days have been measured in the absence of field gradients; the nucleus is very well shielded from the outside perturbation by the two electrons of the atomic close shell. Second helium-3 ground state atoms can be indirectly polarized through collisions with other atoms submitted to optical pumping, the density of which can be much lower than the density of the helium buffer. For instance it was discovered in 1960 that spin exchange collisions between pumped Rb and ^3He lead to a slow build-up of nuclear polarization of helium 3 [26].

At about the same time (1963) a group in Texas found another idea, making use of helium 3 atoms excited to the 2^3S_1 metastable state by a weak discharge. These metastable atoms are optically pumped using light at $\lambda = 1.08 \mu\text{m}$ corresponding to the $2^3S_1 - 2^3P$ transition (see figure 1). This results in a nuclear polarization of the reservoir of helium 3 ground state atoms through the so-called metastability exchange collisions [27].

Both methods were constantly improved in the last two decades and now benefit from the new generation of solid-state lasers. The spin exchange technique was pushed to impressive limits by groups in Princeton and Harvard. It allows high polarization at relatively large pressure of helium-3 gas, at the expense of time constants as long as several hours for reaching an equilibrium [19]. Recently T. Chupp reported M values of order 60 % at a helium pressure of 3 atmospheres [28]. They were achieved by optical pumping of Rb atoms at density of $6 \times 10^{14} \text{ cm}^{-3}$, using 3 W of continuous power at 795 nm emitted by a Ti sapphire laser excited by a 20 W Ar^+ laser. The pumping time is about 7 hours; this requires a careful selection of the glass for the container, which should not relax the nuclear polarization of atoms colliding with the walls.

The polarization technique through optical pumping of helium metastable atoms gives about the same polarization values. It applies to much lower pressure but requires shorter time constants. The cell contains nothing but helium. Several ideas are currently being tried to increase the pressure. This method is described in more details in the next two-sections.

III - OPTICAL PUMPING OF HELIUM THROUGH ITS METASTABLE STATE

The optical pumping is applied to 2^3S_1 metastable atoms created by a discharge in the helium-3 gas. The density at which the pumping is efficient is set by the requirement of an homogeneous weak discharge in the gas and a long life time of the metastable atoms. This corresponds to number densities ranging from $3 \cdot 10^{15}$ to $3 \cdot 10^{17} \text{ cm}^{-3}$, the optimum being close to $3 \cdot 10^{16} \text{ cm}^{-3}$. The density of the metastable atoms is of order 10^{10} cm^{-3} . Until recently the optical pumping was performed with discharge lamps, which did not allow nuclear polarization larger than 20 % [29]. Great improvement came from the design of powerful solid state lasers generating the desired wavelength $\lambda = 1.083 \mu\text{m}$, corresponding to the $2^3S - 2^3P$ transition on which the pumping process occurs (see figure 2).

III.1 Tunable lasers at $1.08 \mu\text{m}$

The advantage of lasers over lamps for pumping helium metastable atoms is not only the larger power available but also their narrow band and tunability, which allows selecting pumping on only

one component of the fine and hyperfine structure of the 2^3S-2^3P transition (usually the $2^3S_1(F=1/2)-2^3P_0$ component is chosen) [30]. Colour center lasers using $(F_2^+)^*$ center in NaF were first developed for this purpose. These lasers operate at liquid nitrogen temperature and require non trivial know-how for producing the crystals [31]. They were then replaced by neodymium lasers of the YAG type, which show several advantages : the crystals do not deteriorate in time and they can be excited not only by expensive gas lasers but also by diode lasers or by discharge lamps. Several matrices doped with Nd^{3+} ions were successfully considered : $LiNbO_3 - MgO$ [32], $YAlO_3$ (also called YAP) [33]. Another possibility is $LuAlO_3$ which exhibits an emission peak exactly centered at $\lambda = 1.08 \mu m$ [34] ; however this material is yet difficult to find.

Lamp pumped YAP lasers show many similarities with commercial YAG lasers. They can deliver up to 100 W at the peak of their gain curve, which does not quite coincide with the helium wavelength ; tuning them to $\lambda = 1.083 \mu m$, on the side of their emission band, requires some skill ; 2 Watt of useful power can thus be produced [35]. $LiNbO_3$ lasers were only tried in excitation by Kr^+ gas lasers ; the difficulty for obtaining long rods of this material, as well as its poor thermal properties, make it rather unattractive for lamp pumping and strong emission.

So far the most convenient material is LNA ($La_{1-x}Nd_xMgAl_{11}O_{19}$) [36]. With a large doping level of Nd (15 %) its main emission band peaks at about $1.08 \mu m$ and it can easily be tuned to $1.083 \mu m$. The latest version of this laser in lamp pumping is shown in figure 3 [37]. The optical resonator has been designed to take into account the thermal focusing problems due to the heating of the crystals by the lamps. The long LNA rods are now commercially available. They must be excited at moderate lamp power to avoid cracking the crystals, which exhibit relatively low and anisotropic heat conductivity. Operated well below the destruction threshold, they show no sign of deterioration after working for several years. The solid etalons in the cavity shown in figure 3 are used for tuning and restricting the emission bandwidth ; when tilted they introduce walk-off losses in the cavity and several ideas are currently tried to reduce them [38]. So far these lasers can deliver 3 Watt of continuously tunable power at $\lambda = 1.083 \mu m$ within a bandwidth of 2 Ghz.

There is some hope to further increase this output power by improving the crystal quality and eventually by turning to diode pumping of the rods, which would suppress the heating problems and increase the excitation efficiency. Alternatively, codoping LNA with Cr and Nd might be a possibility to better use the available power from the pumping lamps [39] and newly discovered laser materials are still to be tried.

Let us finally mention simple versions of these lasers, which can be operated at low cost for some applications where only moderate powers are required, such as probing the polarization or cooling and trapping atoms. Longitudinal pumping of a small LNA crystal by a diode array, can provide up to a 30 mW of useful single frequency power [7] [40]. Other possibilities could be the Nd doped fiber lasers, the integrated $LiNbO_3$ wave guide lasers or the semiconductor lasers operating at $1.083 \mu m$.

III.2 Nuclear polarization of helium-3 gas

The optical pumping and detection schemes are shown in figure 2. The helium-3 gas is excited by a weak RF discharge which produces the metastable 2^3S atoms. The cell is immersed in a magnetic field $\vec{B}_0$; the value of B_0 is not critical and a field of a few Gauss is convenient. The only drastic requirement is the homogeneity of B_0 : to avoid nuclear relaxation the field gradients must, in practice, be kept smaller than 1 mG/cm over the entire volume where the helium-3 atoms are confined. The laser beam propagates along the direction of the $\vec{B}_0$ field. A high degree of circular polarization is required for the laser, especially at high pumping power [41]. Several methods can be used to measure the nuclear polarization M, such as NMR probing or optical detection [42]. The latter method gives a continuous reading of M, is not destructive and often conveniently used when there is a discharge in the helium cell. Its principle is to monitor the degree of circular polarization of the light emitted by the discharge, as shown in figure 3a. The detection signals have been calibrated in several ways [42] ; their calibration was recently rechecked by comparison with NMR proton signals ; it is now believed to be accurate to better than 5 % [42].

Figure 4 shows the build-up of a polarization signal in a $100cm^3$ cell filled with 0.8 torr of pure helium-3 when irradiated with the laser of figure 3. The mode structure of the lamp pumped

LNA laser seems well adapted to pumping helium-3 atoms in the gas phase. Its width of 2 Ghz corresponds to the coexistence of several transverse as well a longitudinal modes of the laser. It approximatively matches the Doppler profile of the metastable helium atoms to be pumped. This means that the laser simultaneously excites several atomic velocity classes, the number of which is even increased by mirror M, shown in figure 2, which reflects the laser beam back into the cell.

The time constant required to reach the equilibrium for the nuclear polarization shortens with increasing laser power : with 1 Watt it takes only 5 secondes to reach $M \sim 72\%$. Figure 5 shows the M values obtained as a function of the laser power at a pressure of 0.8 torr. The crosses are experimental results and they can be well fitted by calculations of the kinetics of the optical pumping process [30]. The theory takes into account not only the coupling between 2^3S and 2^3P atomic states due to absorption and emission of photons, but also the metastability exchange collisions between 2^3S and 2^3S states, which couple the nuclear orientation of the metastable atoms to the ground state atoms, while the electronic spin orientation of the metastable atom is unchanged by the collision process. The coupling between the populations of the metastable level and those of the ground state is thus non linear, except at very low polarization. Consequently, after a linear increase, the curve of figure 4 becomes sensitive to non linear effects which reduce its slope. Although an infinite laser intensity would lead to a value of M very close to 100 %, only $M = 76\%$ could be obtained so far in pure helium-3.

Significantly higher values could be registered in mixtures of ^3He and ^4He , as shown by the squares in figure 5. These are preliminary results obtained in our group by pumping the metastable atoms of helium-4 and relying on metastability exchange collisions between different isotopes to polarize the helium-3 nuclei. The laser is more efficiently absorbed by the cell when tuned to the D_0 line of helium-4 (see fig. 1) and it excites more velocity classes of the metastable atoms, as discussed in the article in preparation [44]. For instance, with 0.2 torr of helium-3 diluted in 0.6 torr of helium-4, a nuclear polarization M of 80 % was measured by NMR.

In pure helium-3 about the same values of M are found between 0.2 and 2 torr. At lower pressure the fast diffusion of the metastable atoms towards the walls of the container makes their lifetime too short for an efficient pumping. At high pressure other processes such as metastable ionization and 3 body collisions limit the density of the 2^3S atom, which does not increase linearly as a function of pressure. The proportion of pumped atoms becomes insufficient to achieve high M values.

IV - INCREASING THE DENSITY OF OPTICALLY PUMPED HELIUM-3

For many applications, especially in nuclear and high energy physics, optical pumping of helium through its metastable state provides targets of too low densities, which imply prohibitive counting times. However such a target was first used in 1962, as soon as the method was invented, for an experiment in which a beam of α -particles was scattered from helium-3 nuclei [45]. Other similar experiments with protons were tried elsewhere [46] [47] but the pressure of the target was obviously insufficient. In the early seventies a group in Toronto started a program to compress the polarized gas with a Toepler pump [48]. They reached a pressure of 1 atmosphere with a nuclear polarization of 3 %, limited by wall relaxation problems. Similar compression techniques, using a piston of liquid gallium were tried elsewhere with encouraging results [49]. Alternative methods to increase the density are cryogenics : cooling one part of the cell to low temperature is a way to concentrate the polarized gas, and eventually to liquefy it. A promising attempt to this was made in 1967 by Mc Adams who dynamically polarized liquid helium-3. A droplet with M of order 0.1 % was thus obtained [50].

Both ideas have been recently reconsidered under the strong demand for good nuclear targets as well as the progress allowed by lasers. We now discuss the state of the art for these evolving techniques.

IV.1 Compression of the polarized gas

In 1988 a group in Germany decided to study compression techniques for reaching high densities of polarized gas at room temperature. They started with a Toepler pump, following the

example of reference [48]. The sketch of their set up is shown in figure 6. It is an all-glass apparatus in which a mercury piston is actionned periodically to compress gas from the optically pumped cell (bottom part of figure 6) into the storage cell (top part of figure 6). The piston contains 2 liters of mercury moved by the pressure of an external inert gas reservoir, regulated by a set of electrovalves. It is linked to the storage cell by a small tube containing a mercury valve on top of a section of sinter glass. As soon as the pressure of the compressed helium-3 gas becomes equal to that of the valve, it opens and admits the gas in the storage volume ; then the valve closes. The mercury level is lowered while fresh helium-3 gas is optically pumped again. The time constant for a cycle is of order 1 minute. The storage cell is leaking through a capillary tube calibrated so that a convenient pressure equilibrium is reached in each part of the apparatus. Promising results were recently obtained which will be soon published [51]. The pumping cell contains 1 liter of helium-3 gas at a pressure of 1 torr polarized to 50 % by an LNA laser excited by an Ar^+ laser and emitting 300 mW of power. After about 1 hour a polarization equilibrium is reached in the storage cell filled at a pressure of 1 bar. This polarization is monitored by NMR and evaluated to be of order 30 % . To account for the polarization loss in the compression cycle, several causes of relaxation have been identified so far, which will hopefully be suppressed in the new version of the experiment. Furthermore turning to a powerful lamp pumped laser should increase the initial polarization. Other compression pumps, both tight and non relaxing but avoiding the use of mercury, are currently being investigated [52].

IV.2 Cryogenic methods

It is also possible to optically pump ^3He at room temperature, as described in section III, and to transport the nuclear polarization by spin diffusion to a region at low temperature. Actually this method was first developed by our group when we started to study the quantum statistical properties of spin polarized ^3He in the 2K range (see section V). It was adapted to the requirements of an external nuclear target by groups in Caltech and MIT and recently used for an electron scattering experiment at Bates [16].

α) Cooling the polarized gas

The principle of the experiment, already described in reference [53], is sketched in figure 7a which shows the set-up used in 1985 to observe spin waves in the cooled polarized gas [11]. The upper cell at room temperature sustains a discharge and is optically pumped by the laser beam. The lower cell is cooled by a liquid helium bath. The thermal shields and foam insulation are used to control the temperature gradients along the tube connecting the two cells. In its cold part the glass vessel is internally coated with a film of solid hydrogen, which minimizes the nuclear spin relaxation of helium-3 atoms at the walls. Under the best conditions it is possible to transfer the spin polarization of the upper cell to the cold region without significant loss.

This method has been adapted to the design of the nuclear target developed at Caltech (see figure 7b) [54]. In that case the lower cell is made of copper attached by epoxy to the glass upper cell, which is pumped by a YAP laser. It is operated at 17 K and the cold part of the apparatus is coated internally with solid nitrogen against wall relaxation. The polarization is evaluated to be of order 30 % in a helium-3 gas at a number density of 10^{18}cm^{-3} .

β) Condensing polarized liquid

We mentioned in section II.1 β the possibility of producing polarized helium-3 liquid by fast decompression of solid magnetized by brute force methods. Similarly it is possible to obtain polarized liquid helium-3 by fast cooling of optically oriented gas [13]. The method is an extension of that described above for the gas, except that the temperature of the cryogenic bath is lower, of order 400 mK, and thus requires the use of a helium-3 refrigerator. Highly polarized liquid in equilibrium with the pumped gas is not easily obtainable, because the intrinsic relaxation time T_1 , of a few minutes in the liquid phase, is too short. The method described in reference [13] is to first maintain the temperature of the lower bath above liquefaction, between 1 and 2K, so as to reach an equilibrium for the spin polarization, and then to quickly lower the temperature of the pumped helium-3 bath to condensate the cold gas. It was shown that one thus obtains a thick film nucleated on the cell walls, the polarization of which can initially reach 50 % , before it decays through intrinsic relaxation in 4 to 5 minutes. Similar experiments had already been performed in 1967 [50]. Figure 8 shows an example of the free induction decay signals recorded after liquefaction : two different frequencies are present. The quickly decaying one is unambiguously

attributed to the liquid phase. The origin of the shift is nothing but the strong demagnetizing field created by the liquid itself. The value of the shift gives an absolute calibration of the liquid polarization (roughly 1 kHz corresponds to $M \sim 30\%$).

This method provides small samples of polarized liquid (a fraction of a cubic millimeter) because of intrinsic limitations which have their source in the intensity of the pumping laser. On the other hand the nuclear polarization is probably homogeneous, which is not always the case in the fast melting method. Such samples are well suited to study the quantum properties of the liquid-gas equilibrium curves, for which interesting predictions have been made on the quantum dependence of the saturating vapour pressure upon magnetization [55]. Experiments along these lines are in progress. They are expected to bring quantitative informations on this Fermi liquid, such as its binding energy per particle.

IV.3 Perspectives for nuclear targets

The dense phases of helium-3 would make ideal targets if they could be polarized efficiently and in continuous operation. These requirements are indeed fulfilled for solid helium-3, but the experimental conditions are difficult : very low temperature (in the mK range) and high magnetic field (several Tesla). In particular for experiments in which charged particles will be scattered from the target, the presence of a large field might cause unwanted deviation of the beam ; in addition the heat deposited by the beam in the target would prevent operation of the cryostat at such low temperature. Polarized liquid helium-3 is also very appealing for a nuclear target. However the two methods described above are "one shot" ; they do not provide a steady sample, and the polarization dies away in a time much too short for most nuclear physics experiments. Yet let us mention that the technique of condensing the optically polarized gas was never thought of with a target goal in mind. Some ideas could be tried, such as the dilution of ^3He in ^4He and a more appropriate design of the double cell geometry. Experiments of that sort are under construction in our group for the study of the transport and equilibrium properties of highly polarized and concentrated solutions of ^3He in superfluid ^4He .

So far only gaseous helium-3 targets have been built. The densities obtained by the spin exchange method are already quite large and do not require further enhancement. The record was recently obtained at Triumph, where a target of density close to 10^{20}cm^{-3} was polarized up to 65 % and used in a proton scattering experiment [56]. All glass double cell versions of these targets have been designed for electron scattering experiments, where Rb atoms are confined by temperature gradient out of the region crossed by the beam [57]. The spin exchange technique seems also very adequate for neutron spin filters and should be chosen for the "troisième souffle" generation of experiments with polarized epithermal neutrons at ILL [58].

The optical pumping of pure helium-3 provides clean samples, the pressure of which has to be increased for external targets. The mechanical compression of the gas is a method which has already proved to work and should be now developed and eventually simplified by avoiding the use of mercury as a piston. The cryogenic method has produced a target already used in a successful experiment ; some further progress could still be made, for instance by operating at liquid helium temperature instead of 17 K, which would substantially increase the helium-3 gas density.

As for the future internal targets to be adapted to storage rings, several proposals have been made based on leaking cells with flowing gas optically polarized by one or another method. The orders of magnitude are discussed in reference [14] and in recent proposals. The reachable densities seem to be ultimately limited by the available laser power in both cases, which do not allow polarizing more than 10^{18} atoms per second so far.

V - HEAT CONDUCTIVITY OF SPIN POLARIZED GASEOUS HELIUM-3

As already mentioned in section I.2, even if it is dilute and non-degenerate, spin polarized gaseous helium-3 exhibits interesting properties related to quantum statistics, enhanced if the temperature is low enough. Colliding particles in the same spin state are indistinguishable and proper symmetrization of the wave functions lead to an effective scattering cross section which

depends on the spin polarization. Figure 9 illustrates this idea. It pictures a head-on collision between two helium-3 atoms, represented by their associated wave packets. If these two fermions are in the same spin state, an interference pattern builds up when the wave packets overlap. There is a dark fringe at the center, called the "exchange hole", of order λ_D , the de Broglie wavelength. On the other hand if the two particles are distinguishable by their spin state, no interference takes place. There is an analogy between the phenomenon shown in figure 9 and interferences obtained with polarized light in optics. Suppose that two laser beams, circularly polarized and originating from the same source, overlap on a screen. If they both carry right handed polarization fringes are observed, whereas if one is right and the other left handed, no fringes are visible.

Let us further discuss the collision between two atoms shown in figure 9. If the temperature is low enough for the exchange hole to be larger than the range of the interatomic potential, the interaction between the two atoms is inhibited. Thus for an ensemble of particles contained in a vessel the mean free path is changed by the polarization, as well as the transport properties of the gas.

We designed an experiment to measure the changes of the heat conductivity of gaseous helium-3 with polarization M . It was carried in the temperature range 1.3 - 4.2K, where λ_D is of order 5 to 10 Å, which is larger than the range of the helium-helium potential of typically 3 Å. This experiment is described in some detail in reference [12]. Basically the set-up is similar to that of figure 7a. The low part of the cell is a cylinder, the upper plate of which is kept at low temperature by a pumped helium-4 bath, as shown in figure 10. The outside of the cell is surrounded by a good vacuum. The bottom plate of that cell can be heated up with an electrical power $\dot{Q}$. Thus a temperature difference $T_2 - T_1$ appears between the upper and bottom plates, which is measured by sensors R_1 and R_2 of figure 10. If one ignores the heat propagation through the cell walls, the thermal impedance of the gas is given by :

$$T_2 - T_1 / \dot{Q} = \frac{\ell}{SK}$$

where S is the area of the horizontal plates and ℓ their spacing. K is the heat conduction coefficient of the gas, to be measured as a function of M , the gas polarization monitored by the NMR pick-up coils shown in figure 10.

References [10] and [59] predict a dependence of the form :

$$K(M) = K(0) \times \frac{1 - \xi_1 M^2}{1 - \xi_2 M^2}$$

where ξ_1 and ξ_2 are coefficients calculated from collisional integral using a phase shift expansion. This equation reduces within a good approximation to :

$$K(M) - K(0) = K(0) [\xi_2 - \xi_1] M^2$$

for values of M below 30 % , which was always the case in practice.

Experimentally we have observed that, for a given value of $\dot{Q}$ and a fixed temperature T_1 of the cryogenic bath, temperature T_2 varies significantly with M , reflecting the changes of $K(M)$ with M . The quadratic dependence of $K(M)$ with M was checked and in figure 11 are plotted the measured values of $[K(M) - K(0)]/M^2$. The scatter in the data points gives an idea of the experimental error, the main cause of which comes from the estimation of the change of the temperature difference $T_2 - T_1$ when M is destroyed. It is of the order of 15 % above 2.2K, but only 5 % below the superfluid transition, due to the better temperature stability. Figure 11 also shows the results of the recent calculations of reference [59]. Slightly different predictions are made above 2K, according to the number of terms in the Sonine expansion used as a trial function in the calculation of K . The scatter of the data in that temperature region does not allow to reliably discriminate between the two curves of figure 11. Altogether the quantitative agreement between the experimental results and theory is good, especially below 2K.

The understanding of the transport properties of spin polarized quantum gases is a difficult challenge for theorists. Recently several groups have contributed to this field using a microscopic

approach to the problem [60] [61]. Experiments with polarized helium-3, both in the gas phase as reported here, or in $^3\text{He}-^4\text{He}$ solutions [62] [63], have been carried out to verify these predictions. Much is yet to be elucidated in this domain, especially at very low temperature in the degenerate regime of the quantum fluid.

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Figure 1 : Level scheme of the $2^3S_1 - 2^3P$ transition in helium.
 a) The nine lines of ^3He .
 b) Relative position of the ^3He and ^4He spectra.

Figure 2 : Set-up for optical pumping of helium-3. $\lambda/4$ is a quarter wave plate circularly polarizing the laser beam. The optical detection includes a photomultiplier P.M., an interferential filter F.I., a lens L and a circular analyser (polarizer P and quarter wave plate $\lambda/4$).

Figure 3 : Lamp pumped LNA laser
 M_1 and M_2 : mirrors
 E and E' : solid etalons

Figure 4 : Build-up of nuclear polarization in optically pumped helium-3.

Figure 5 : Nuclear polarization M obtained by optical pumping in gaseous helium-3, as a function of laser intensity at $\lambda = 1.08 \mu\text{m}$. The dots refer to pure ^3He at a pressure of 0.8 torr, the squares to a mixture of ^3He (0.2 torr of ^3He and 0.6 torr of ^4He).

Figure 6 : Compression of helium-3 gas with a Toepler pump. The gas is optically polarized by a laser at 1.083μ in the lower cell. It is compressed to the storage cell by a mercury piston actuated by ^4He gas.

Figure 7a : Double cell used to produce polarized helium-3 gas at low temperature for experiments on quantum fluids at ENS.

Figure 7b : Cryogenic helium-3 target build-up at CALTECH for nuclear physics experiments.

Figure 8 : Free induction decay signal observed by NMR detection of polarized helium-3 at 0.4 K. The fast decaying signal corresponds to the liquid phase, the long lasting one to the gas phase.

Figure 9 : Wavepackets associated with two helium-3 atoms undergoing a collision. During the collision they overlap. If the atoms are in the same spin state, the density of the wavefunction oscillates, whereas no interference occurs if they are in opposite spin states.

Figure 10 : Bottom part of the cell used to measure heat conductivity of polarized helium-3. The bottom plate is heated electrically. Sensors R_1 and R_2 measure the temperatures of the end plates of the cylinder filled with helium-3. NMR coils monitor the spin polarization.

Figure 11 : Changes of the heat conductivity coefficient $\kappa(M)$ with polarization M of the helium-3 gas, plotted as a function of temperature T . The lines are theoretical results taken from reference [59].