

Nuclear Structure Studies with Low Temperature Technique (I)

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Abstract

The theory of quantum mechanics states that for any system there are a set of discrete physical states, quantum states, which corresponds a particular energy level of the system. The lowest energy the system can have, corresponding to its ground state, is not necessarily zero, but depends only on the precise microscopic nature of the system under consideration. At the absolute zero of temperature all systems will be in their lowest energy state (zero point energy) and as the system is warmed from 0K, the higher energy states become occupied. The probability of occupancy of the excited states relative to that of the ground state is proportional to the absolute temperature. Therefore we can obtain nuclear dipole and quadrupole moment very accurately at ultra low temperature (<15mK) by NMR and from the destruction of anisotropy. The former is called LTNO/NMR and the latter is called LTNO (Low Temperature Nuclear Orientation). In this paper we discuss and introduce only an experimental apparatus with results of cooling power test, a helium dilution refrigerator, which can reach 8mK, and an actual technique for the experiment, a theory and results will be presented in another papers.

1. Introduction

To understand LTNO it is important to understand the relevant properties of liquid and solid matter involved in the attainment of low temperatures. Therefore in this paper these aspects of the work will be explained. Additionally experiments at low temperatures make no sense at all without good thermometry but this, itself, will be another topic so it will be discussed in another paper.

2. Properties of liquid ^3He and ^4He

There are two stable isotopes of liquid He, namely, ^3He and ^4He . ^3He is a fermion and obeys Fermi-Dirac statistics while ^4He is a bose particle and obeys Bose-Einstein statistics. When pure samples of the two isotopes are cooled, both liquify and remain liquid down to the very lowest temperatures under their saturated vapour

pressures. This occurs since both isotopes experience extremely weak Van der Waals binding forces that arise from the fluctuating polarisation charges induced in the electron shells of adjacent atoms.

Suppose an atom in the liquid as a free particle located in a k -space formed by the adjacent atoms. Since they have the small atomic mass m , they have a large quantum mechanical zero-point energy, E_0 ,

$$E_0 = \frac{h^2}{2mr^2} \quad (1)$$

where $r = (V_m/N_A)^{1/2}$ is the distance between the atoms, V_m the molar volume and N_A is the Avogadro's number. As the zero-point energy is inversely proportional to the mass of the atom, ${}^3\text{He}$ is relatively more affected, leading to a molar volume of $\sim 40\text{cm}^3$ compared to $\sim 28\text{cm}^3$ for ${}^4\text{He}$ though the atoms are the same size. Also ${}^3\text{He}$ has a higher vapour pressure than ${}^4\text{He}$ at the same temperature. The different statistics for the boson ${}^4\text{He}$ and for the fermion ${}^3\text{He}$ give rise to substantial differences in their low-temperature behaviour. The helium liquids are called quantum liquids because of the strong influence of quantum effects on their properties. ${}^3\text{He}$ fermi particles cannot undergo the analogue of a Bose momentum condensation into a superfluid state as the bosons ${}^4\text{He}$ do at the so called lambda transition temperature, T_λ .

Figure 1 shows several of the remarkable features of helium isotopic liquid mixtures. Pure liquid ${}^4\text{He}$ becomes superfluid at 2.17K and this transition temperature is depressed when it is diluted with liquid ${}^3\text{He}$. Eventually, superfluidity ceases to exist for ${}^3\text{He}$ condensations, $x_3 > 67\%$. At this concentration and at a temperature of 0.87K the λ -line meets the phase separation line. If a He mixture with $x_3 > 6.5\%$ is cooled down below 0.87K the heat motion of the ${}^4\text{He}$ content has almost completely disappeared, and its entropy and specific heat are very much less than those of ${}^3\text{He}$. Hence, ${}^4\text{He}$ in the solution behaves only as a background fluid, in which the ${}^3\text{He}$ atoms move about rather as a gas of atoms in a vacuum. The mixture will eventually separate into two phases - one rich in ${}^3\text{He}$ and the other rich in ${}^4\text{He}$, and the interaction between them will be weak. The dilute ${}^3\text{He}$ atoms behave like a perfect fermi gas and the ${}^3\text{He}$ rich phase will float on top of the ${}^4\text{He}$ rich phase as the density of ${}^3\text{He}$ is lower than that of ${}^4\text{He}$. If the temperature is decreased to close to absolute zero, the ${}^3\text{He}$ rich liquid becomes pure ${}^3\text{He}$. However, the concentration of ${}^3\text{He}$ in the dilute phase has a constant value of 6.5% at saturated vapour pressure even at 0K . This finite solubility is of utmost importance for ${}^3\text{He}/{}^4\text{He}$ dilution refrigeration technology.

An ${}^3\text{He}$ atom passing from the concentration phase to the dilute phase will result in cooling because the specific heat of a ${}^3\text{He}$ atom is larger in the dilute phase than in the concentrated phase. Because of this solubility of ${}^3\text{He}$ in ${}^4\text{He}$ a cooling power will decrease only with T^2 and not exponentially as in the evaporation cooling

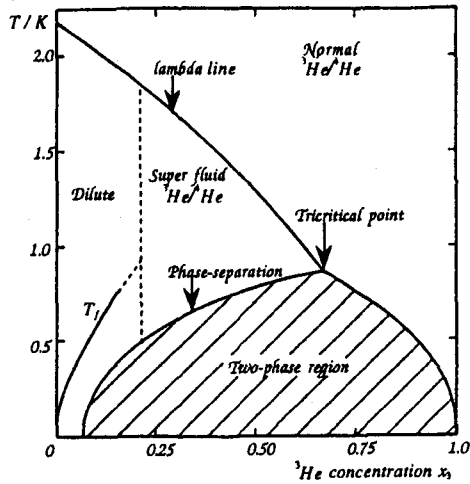


Fig 1. Phase diagram of liquid ${}^3\text{He}/{}^4\text{He}$ mixtures at Saturated vapour pressure^[1].

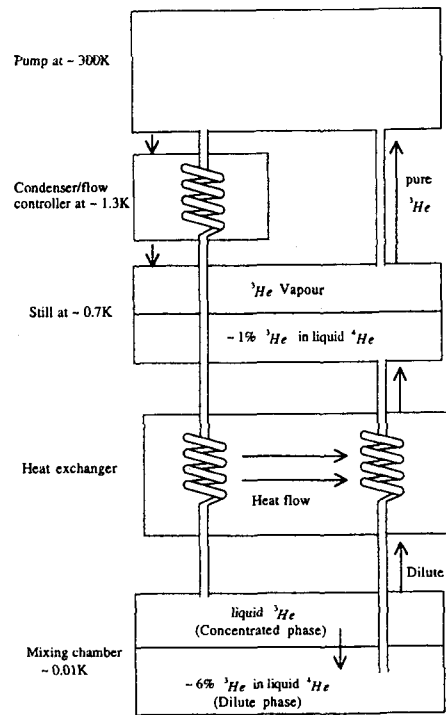


Fig 2. A schematic layout of a dilution refrigerator.

process. Due to the substantial difference the vapour pressures of ${}^3\text{He}$ and ${}^4\text{He}$ at the same temperature, circulation of almost pure ${}^3\text{He}$ can be achieved. An osmotic pressure will drive the ${}^3\text{He}$ from the mixing chamber up into the still if they are at different temperatures in a cryogenic apparatus.

3. Continuous operation below 10mK

The evaporation of low boiling point liquids is the usual method of maintaining a low temperature. A temperature bath between 4K - 5K can be easily obtained on liquid ${}^4\text{He}$ in dewar. The same liquid, evaporated at a lower pressure by using a pumping system, can maintain a lower temperature since the saturated vapour pressure decreases with temperature, and the size of the pumping system is limited, there is a lowest accessible temperature. For ${}^4\text{He}$ this is ~1K and ${}^3\text{He}$ is ~0.3K. To obtain steady temperatures down to a few mK the essence of the method is to dilute a ${}^3\text{He}/{}^4\text{He}$ mixture. A schematic view of the main features of a conventional continuous operation ${}^3\text{He}/{}^4\text{He}$ dilution refrigerator is shown in fig 3.

In stable operation, the concentrated phase boundary must lie in the mixing chamber which is the coldest part of the refrigerator. The dilute phase in the mixing chamber is connected to the still via a series of heat

exchangers. The still is pumped by a large diffusion pump backed by a sealed rotary pump. By pumping the still, ^3He is caused to cross the phase boundary from the concentrated phase to the dilute phase producing cooling. An optimal circulation rate of ^3He in the system is produced by an electric heater which maintains the still at a temperature $\sim 0.8\text{K}$. ^3He from rotary pump exhaust re-enters the cryostat after removing any air that may have leaked into the circulating tube by passage, through liquid nitrogen traps (called cold traps). The ^3He is re-cooled to $\sim 1.2\text{K}$ by thermal contact with a pumped ^4He pot and is then liquified in the condenser which comprises a fine capillary tube of high impedance which is needed to keep the pressure of the ^3He sufficiently to occur. The ^3He is cooled to $\sim 0.8\text{K}$ by passage through a wrap around heat exchanger on the still, and then returns to the mixing chamber through a concentric tube continuous heat exchanger and a few sintered silver step heat exchangers, where cooling is performed by the out-going ^3He of the dilute phase. The efficiency with which the returning ^3He can be pre-cooled before entering the mixing chamber is one of the limitations on the base temperature attainable.

The conventional cryostat design consists of an Inner Vacuum Can (IVC), a main liquid ^4He bath of capacity $\sim 30\text{l}$, and an Outer Vacuum Can (OVC). There is a radiation shield maintained at 77K by a liquid nitrogen reservoir within the OVC. The IVC, which contains the dilution unit, is maintained at a pressure of $<10^{-6}\text{torr}$ during stable operation, with the main helium bath acting as a 4.2K radiation shield. Additional reduction in radiation heating of the dilution unit is achieved by the 0.8K shield that is attached to the still. The still, 25mK plate and mixing chamber temperatures can all be monitored during circulation using resistors. In normal operation, the temperature can be measured by use of a standard nuclear orientation thermometer soldered to a copper cold finger, which is screwed to the base of the mixing chamber to ensure good thermal contact.

4. Top loading dilution unit

The top loading facility allows a sample at room temperature to be loaded directly into a cold dilution refrigerator without warming the refrigerator above 1K and cooled to base temperature within a few hours. The cold finger is mounted onto a long vacuum insulated top loading syphon and this is then lowered into the central access tube of the cryostat, through a vacuum lock and sliding seal arrangement, until the sample holder is just above the 1.2K pot. Liquid ^4He is then transferred from the main liquid ^4He bath through the top loading syphon to a small chamber at the bottom of the syphon cools the sample holder by conduction.

The top loading tube is fitted with a series of moveable baffles which act as radiation shielding during the normal operation of the refrigerator after top loading system has been removed.

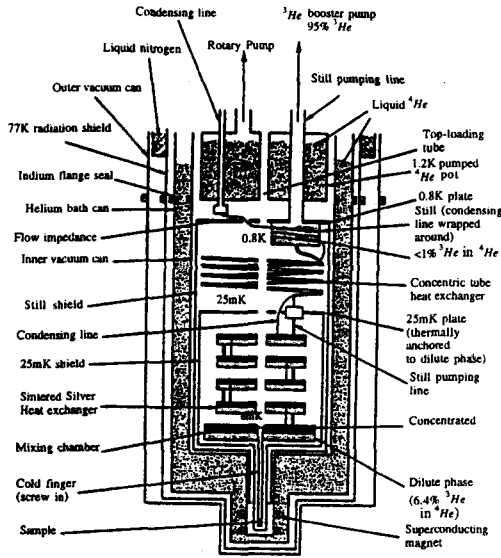


Fig 3. Schematic view of the conventional Oxford $^3\text{He}/^4\text{He}$ dilution refrigerator showing the main features necessary for continuous operation at temperature down to $\sim 6\text{mK}$ ^[1].

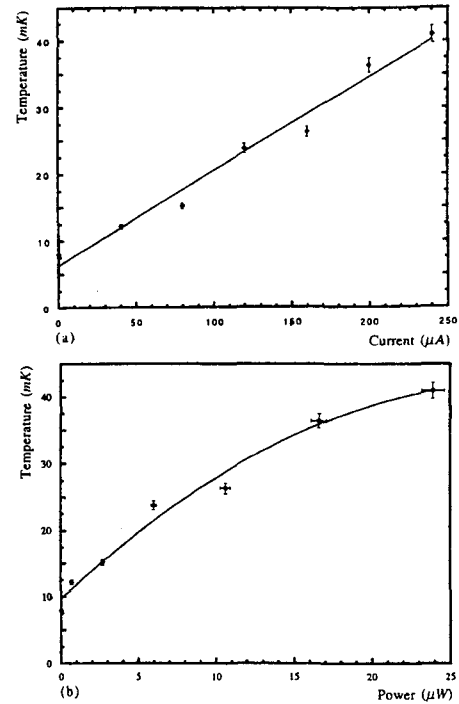


Fig4. Cooling power of the Oxford refrigerator (a) the mixing chamber temperature is plotted against the current in the mixing chamber resistor (b) against cooling power.

5. The cooling power test and results

The Oxford Instruments model 300TL is used for the cooling power test. The cooling power is given by^[2]

$$\dot{Q} = \dot{n}_3(107 - 24)T^2 = 84\dot{n}_3T^2(\text{W}) \quad \text{for } T < 0.1\text{K} \quad (2)$$

It is desirable to vary the temperature of the mixing chamber, and hence that of the sample. This can be done by passing current through a 415Ω resistor, thermally attached to the mixing chamber. If the external heating of the mixing chamber is denoted by \dot{Q} , then from the cooling power of the refrigerator as a function of temperature, it can be shown that^[2]

$$\dot{Q} = C(T_{mc}^2 - T_{base}^2) \quad (3)$$

where T_{mc} is the temperature of the mixing chamber and T_{base} is the minimum temperature that can be attained. C is a constant for a particular set of refrigerator operating conditions. (3) can be rewritten as

$$T_{mc} = \left(\frac{\dot{Q}}{C} + T_{base}^2 \right)^{1/2} = T_{base} \left\{ \frac{R_{mc}}{C} \left(\frac{i}{T_{base}} + 1 \right) \right\}^{1/2} \approx i \left(\frac{T_{mc}}{T_{base}} \right)^{1/2} \quad \text{for} \quad \left(\frac{T_{mc}}{T_{base}} \right)^{1/2} \gg 1 \quad (4)$$

For the Oxford refrigerator, the ^3He circulation rate for optimum performance is $\sim 400 \mu\text{mols/s}$ and base temperature can be obtained as low as $\sim 5\text{mK}$. Plots of T_{mc} against current I , and T_{mc} against cooling power \dot{Q} are shown in fig 4. The experimental points have been fitted using (4), giving the values

$$C = 0.0206(1)\mu\text{W} \quad T_{base} = 6.3(1)\text{mK} \quad (5)$$

The cooling power at 25mK is $\sim 10 \mu\text{W}$ using the parameters in (5), which agrees with the specifications quoted by Oxford Instruments. From these results, a required temperature can be achieved by choosing the appropriated current for the mixing chamber heater.

6. Discussion

At very low temperature the energetically lower states, m -substates in the case of magnetic interactions, must be unequally populated according to the Boltzmann distribution, and so their splitting should be at least comparable to the available thermal energy kT .

The method of Low Temperature Nuclear Orientation (LTNO) involves the "brute-force" orientation of the static electric or magnetic moments of the nucleus with an external magnetic field, and this method are used to study the hyperfine interactions of radioactive isotopes and the angular distribution of their decay products.

We will present more detailed experimental techniques and results in the next papers.

References

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