NUCLEAR MAGNETIC RESONANCE
IN FLOWING SUPERFLUID $^3$He-A

By

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Flow in superfluid $^3$He has been produced in a channel connecting two Pomeranchuk cells by compressing or decompressing one cell while the pressure in the other cell was regulated to maintain constant temperature. Transverse nuclear magnetic resonance in the liquid in the 1.5mm diameter channel was observed in a field of 14.7mT oriented at several angles to the channel. Marked changes occurred in the presence of flow, including structure and satellite signals, step changes in signal amplitude at particular velocities and rapid attenuation beyond some critical velocity. Assuming the normal fluid at rest and using known superfluid fractions, the critical velocities were between 0.14mm/sec at the lowest temperatures and 0.64mm/sec near the transition temperature.
CHAPTER I

INTRODUCTION

General Introduction

The superfluid behavior $^3$He was suspected more than a decade before being observed in the laboratory. Bardeen, Cooper and Schrieffer (1957) had successfully described superconductivity in terms of a condensation of Cooper pairs of electrons into a single quantum state. Pitaevskii (1959) realized that a similar kind of pairing might occur in $^3$He and Anderson and Morel (1961) and Balian and Werthamer (1963) described some properties of two theoretically interesting model phases containing condensed Cooper pairs of $^3$He atoms. The pairs in each of the proposed phases possess non-zero relative angular momenta as a consequence of the hard-core repulsion between two atoms of $^3$He, in contrast to the zero angular momenta of pairs of electrons in superconductors. The wavefunction for a state containing such pairs is anisotropic and the properties of the superfluid were expected to be anisotropic as well. The anticipation of such unusual behavior for the superfluid stimulated a considerable amount of theoretical investigation as well as some unsuccessful experiments aimed at observing superfluidity. After two new phases in $^3$He were reported (Osheroff, Richardson and Lee, 1972a; Osheroff, Gully, Richardson and Lee, 1972b) it soon became clear that these were probably the predicted phases.
The remainder of this chapter will discuss some selected results from previous experiments in order to form a basis for a description of the author's own research. The extensive review by Wheatley (1975) is highly recommended as a survey of the experiments on superfluid $^3$He before 1975, including a large body of work outside the scope of this introduction.

Various workers have contributed to mapping the phase diagram shown in Fig. 1, which indicates the values of temperature, $T$, and pressure, $P$, for which the two superfluids exist. For a given pressure, the line $T_C$ designates the temperature at which the liquid, upon being warmed, undergoes a second order transition from one of the superfluid phases into a non-superfluid state named the normal Fermi liquid. The phase called $^3$He-A is stable for conditions of $T$ and $P$ between $T_{AB}$ and $T_C$ while the other of the two new phases, $^3$He-B, is the more stable state over the remainder of the region to the left of $T_C$. The transition between the two superfluid phases is first order. The measured properties of $^3$He-A have been found to be in good agreement with those calculated for the model proposed by Anderson and Morel (1961) and later expanded upon by Anderson and Brinkman (1973a). Much of the behavior of $^3$He-B can be explained in terms of the model of Balian and Werthamer (1963), but there are some troublesome discrepancies.

Fig. 1 includes lines of transition temperatures, $T_{AB}$, for two different magnetic field strengths, $B=4.9\text{mT}$ and $B=34.9\text{mT}$. That the transition temperature is dependent upon magnetic field is expected since $^3$He nuclei have magnetic moments; however, it is unusual for such small fields to produce such dramatic changes.
Fig. 1. Phase diagram of $^3$He near the superfluid transitions. (After Wheatley, 1975).
A large shift in the perpendicular nuclear magnetic resonant (NMR) frequency, $v_p$, of $\textsuperscript{3}$He-A liquid was discovered by Osheroff, Cully, Richardson and Lee (1972b). For most materials, the NMR frequency in the liquid state is nearly equal to the Larmor frequency for the isolated atoms, $v_L = \gamma H_0 / 2\pi$, where $\gamma$ is the gyromagnetic ratio for the atom and $H_0$ is the magnitude of the static magnetic field. The NMR frequency of a solid is also very nearly equal to $v_L$ and Osheroff et al. found this continues to hold for $\textsuperscript{3}$He even for solid temperatures below $T_C$. However, the resonant frequency of $\textsuperscript{3}$He liquid in the A-phase obeys the equation

$$v_p^2 = v_L^2 + v_{\text{shift}}^2(T).$$

$v_{\text{shift}}(T)$ is approximately proportional to $(T_C - T)$ but it is practically independent of $H_0$, unlike $v_L$, for example. The values of $v_{\text{shift}}(T)$ fall in the range from zero at $T = T_C$ up to about 100KHz at the coldest temperatures at which the A-phase exists. The shift in the perpendicular resonant frequency disappears in the B-phase.

Leggett (1973) and Anderson (1973b) soon proposed mechanisms to explain this unique shift and eventually a very successful theory was developed. Takagi (1975) and Fetter (1975) have extended the theory to include the influences of walls and hydrodynamic flow in determining the NMR frequency for a wide range of experimental conditions. The experiment to be described later in this dissertation was initiated as a search for the predicted frequency shifts resulting from flow.

In superfluid $\textsuperscript{4}$He, heat flow and hydrodynamic flow have been found to be intimately related. A study of heat flow in superfluid $\textsuperscript{3}$He by Johnson, Kleinberg, Webb and Wheatley (1975) revealed a similar
relationship. They maintained a constant rate of heat input at one end of a small diameter cylindrical tube filled with $^3$He. The opposite end of the tube was kept at constant temperature while the temperature difference between the ends of the tube was recorded. This was repeated for many temperatures of the cold end. When Johnson et al. compared the results for two different tube diameters (2mm and 3mm) they found the temperature difference varied as the inverse fourth power of the tube diameter. Furthermore, there were large and abrupt changes in the temperature difference at several temperatures.

These effects can be conveniently interpreted in terms of the two-fluid model, in which one of the two interpenetrating fluids is assumed to have quite ordinary properties; in particular, it has finite viscosity and finite entropy. It is therefore called the normal fluid. The other component fluid, the superfluid, has no viscosity and no entropy. The two fluids can move relative to each other with only weak interactions between them.

The fraction of the fluid which is superfluid depends on temperature as well as direction, which is one consequence of the anisotropy of the wavefunction for the Cooper pairs. The directional dependence can be accommodated by expressing the superfluid density as a tensor quality. However, in many situations an average of the tensor components is sufficient. Several experiments (Kojima, Paulson and Wheatley, 1974, 1975; Yanof and Reppy, 1974; Osheroff and Corruccini, 1975) have yielded similar values for the ratio of the average density of the superfluid, $\bar{\rho}_s$, to the total density of the liquid, $\rho$. It was found that the expression $\bar{\rho}_s/\rho = 0.6(1-T/T_c)$ fits their data well. This same functional form is expected from
theoretical considerations.

In the experiment of Johnson et al., the observed relationship of heat flow to the tube diameter becomes plausible if the heat is viewed as having been transported by hydrodynamic flow of the two fluids. When heat was absorbed at the source, the entropy of the liquid increased by conversion of superfluid to normal fluid. The normal fluid flowed to the cold end of the tube where more superfluid was created by a reduction in the entropy of the liquid. Superfluid then moved upstream against the direction of flow of normal fluid to complete the cycle. The measured dependence of the temperature difference on the tube diameter was that which would have been expected in circumstances where Poiseuille's law applied for the viscous flow of the normal fluid.

The sharp increases of the temperature differences as Johnson et al. raised the temperature can also be explained as a flow related phenomenon. As the temperature of the liquid increased, the amount of superfluid decreased. Therefore, it was necessary for the velocity of the superfluid, \( v_s \), to increase in order to sustain a constant rate of replacement of the entropy-carrying normal fluid. The step changes in the temperature differences were interpreted as being caused by \( v_s \) exceeding critical velocities, \( v_{s,crit} \). Analogous critical velocities have long been observed in a wide variety of experiments on superfluid \(^4\)He, in which case they are considered to be threshold velocities for the formation of vortices. It is probable that a similar explanation is appropriate for the critical velocities found by Johnson et al.

In the experiments to be described in this dissertation, dramatic reductions in the amplitude of the NMR absorption signal for \(^3\)He-A
were detected as the velocity of superfluid flow exceeded threshold velocities in the range 0.14 mm/sec to 0.64 mm/sec. These velocities are comparable to the critical velocities in the heat flow experiments of Johnson et al. It is possible that the effects which appeared in these two experiments can be attributed to the same underlying cause.

A Brief Survey of the Microscopic Theory of the Superfluid Phases of $^3$He

Devising a complete theory for liquids is a difficult problem because the atoms comprising the liquid interact very strongly with their neighbors. For a system of identical Fermions, as for example, $^3$He, Landau (1956) developed a powerful technique for overcoming some of the difficulty. Rather than attempting to deal with the atoms themselves, an equal number of weakly interacting quasiparticles is introduced. Each of these quasiparticles may be thought of as a $^3$He atom and its surrounding cloud of neighboring atoms. Dragging this cloud around causes a quasiparticle to respond in the manner of a Fermion with effective mass several times that of an isolated $^3$He atom. The introduction of the effective mass is sufficient to describe most of the effects of the frequent collisions of atoms. The quasiparticles act as almost free particles, although Cooper showed that there is an important class of interactions between quasiparticles. Calculations of the kinetic coefficients and quasiparticle lifetimes must, of course, consider collisions of the quasiparticles.

Being Fermions, the quasiparticles occupy all of the available energy levels of the system up to the vicinity of the Fermi energy although at finite temperatures some energy levels just below the
Fermi energy will be left vacant by the thermal excitation of some particles into levels just above the Fermi energy. It is the quasiparticles with energies in this region which can find it energetically advantageous to form Cooper pairs by becoming bound by the otherwise insignificant attractive interactions between the quasiparticles. In addition to their being in levels near the Fermi energy, Cooper (1956) showed that the essential requirement for the formation of these pairs is that the two particles have linear momenta which are equal in magnitude, but opposite in direction. The condensation of many Cooper pairs into a single quantum state is the source of the superfluid properties.

Usually the Cooper pairs of electrons in superconductors are bound in a quantum state for which the orbital angular momentum, $\lambda$, is zero. However, the interaction in $^3$He is repulsive for the small separations which are most probably in an $\lambda=0$ state, so instead the pairs form in states with $\lambda=1$. To preserve the antisymmetry of the wavefunction for the pair when its members are interchanged, its total spin angular momentum, $S$, must be unity, allowing three possible spin states, $S_z=1,0,-1$. Depending upon the experimental environment of the sample, the pairs may have only one, two, or all three of these values of $S_z$. This is not to be interpreted as meaning several kinds of Cooper pairs may be present simultaneously. Rather, the wavefunctions of the single kind of pairs is a superposition of the appropriate spin states.

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$^1$Other small values of $\lambda>1$ are also possible, but the calculated properties for states with $\lambda=1$ compare well with experimental observations.
The ABM state (Anderson and Morel, 1961; Anderson and Brinkman, 1973a) is the one that is most important in what is to follow. Only two spin states are included in the pair wavefunction for it, namely those with $S = +1$ and $S = -1$.

Interactions of the very weak nuclear magnetic moments of paired quasiparticles cause the energy of the pairs to depend on $J$, the quantum number for total angular momentum. The lowest energy state is that with $J = \ell$, which classically corresponds to the directions of $\ell$ and $S$ being perpendicular. However, all Cooper pairs must be in the same quantum mechanical state and, therefore, have the same value of $J$. Alteration of the spin state of one pair is not possible; either the pair must be broken at considerable expense in energy or else the spin state of all pairs must change in unison.

Leggett (1973, 1974) considered the effect of the correlation of spins on the NMR frequency. He showed that the coherent torque produced by this correlation is the origin of the frequency shift of the perpendicular nuclear magnetic resonance in the A-phase. Values of the shift calculated from his theory are in excellent agreement with those obtained from experiments over a wide range of conditions provided the A-phase is identified with an ABM-like state. Leggett also predicted the existence of another nuclear magnetic resonance at the frequency, $v_{\text{shift}}(T)$. This resonance is called the longitudinal resonance since it is observed in the unusual geometry in which the $H_0$ and $H_1$ are parallel. The existence of the resonance has since been demonstrated (Bozler, Bernier, Gully, Richardson and Lee, 1974; Osheroff and Brinkman, 1974; Webb, Kleinberg and Wheatley, 1974).
The Predictions of Takagi and Fetter

After Leggett published his theory for NMR in stationary superfluid $^3$He, Takagi (1975) and Fetter (1975) extended the theory to make quantitative predictions of the effect of hydrodynamic flow on NMR in bulk samples. Their results indicate that the NMR frequency should shift by an amount which depends on the relative velocity of the normal and superfluid components of the liquid, the strength of the static magnetic field and the relative orientation of the directions of flow and the magnetic field.

The following discussion will be brief and qualitative (the reader is referred to the excellent review of Leggett (1975) as a basis for the detailed theoretical background required for a satisfactory understanding of Takagi's and Fetter's theories). No attempt will be made to distinguish the work of the two authors in most instances since both were considering the same influences on the resonant frequency although their mathematical approaches to the problem are different. A fuller description of the frequency shifts can be obtained by consulting the works of both authors. The discussion will be limited to the A-phase.

The orientation of the spin and orbital angular momenta of Cooper pairs is subject to many influences. Two of these are important in the bulk fluid. External magnetic fields tend to align the magnetic moments of the nuclei and, therefore, the spins along the direction of the field. Flow of the superfluid through the normal fluid tries to align the orbital angular momentum of the pairs parallel to the direction of flow (Glassgold and Sessler, 1961). Except for special cases, these two effects will be in competition. The orientations of
spin and orbital angular momenta are coupled by the dipole-dipole interaction so it also enters the calculation. Given the velocity, \( \vec{v} \), and the magnetic field, \( \vec{H}_0 \), the equilibrium state can be found by minimizing the free energy. The NMR frequency can then be found from Leggett's equations.

The contributions to the free energy density by the external magnetic field and the relative flow velocity, \( v \), are proportional to the squares of \( H_0 \) and \( v \), respectively, while the dipole-dipole energy is a constant. The three energy terms are equal when the magnetic field and velocity have characteristic values \( H_C \approx 2 \text{mT} \) and \( v_C \approx 1 \text{mm/sec} \), according to rough estimates by Takagi.

Takagi has given an explicit function describing the perpendicular NMR frequency for the special case of the limit \( H/H_C \to +\infty \). He finds

\[
\nu_P^2 = \nu_L^2 - v_0^2 \cos 2 \theta_L
\]

where

\[
\cos 2 \theta_L = \frac{[\cos 2 \psi - (v_C/v_s)^2] / [1 + (v_C/v)^4 - 2(v_C/v_s)^2 \cos 2 \psi]^{1/2}}{
}
\]

\( \psi \) is the angle between vectors \( \vec{H}_0 \) and \( \vec{v} \), and \( \theta_L \) is the angle between \( \vec{H}_0 \) and the direction of the orbital angular momentum vector, \( \vec{\ell} \). A graph of \( (-\cos 2 \theta_L) = (\nu_P^2 - \nu_L^2) / \nu_L^2 \) is displayed in Fig. 2 for several velocities. The strong dependence on \( v \) is immediately evident. If one interprets critical velocities observed by Johnson et al. as upper limits on \( v \), it will be seen that for a given temperature the change of the NMR frequency in the presence of flow relative to its value for \( v=0 \)

\footnote{The notation used by Takagi has been changed to be consistent with that employed in this dissertation.}
Fig. 2. \((v_p^2 - v_L^2) / v_i^2\) versus the angle \(\psi\), computed from the predictions of Takagi (1975) for several values of \(v / v_c\).

Takagi's results apply for the special case in which \(H_C < H_0\).
is very small. For example, the natural linewidth of the perpendicular resonance can be estimated from measurements by Bozler, Bernier, Gully, Richardson and Lee (1974). Assuming the resonance to be centered at $500KHZ$, the predicted, flow-induced shift is roughly 1% of the natural linewidth, even at the lowest temperatures in the A-phase.

Fetter's analysis was basically capable of treating all combinations of $\vec{H}_0$ and $\vec{v}$, but he concentrated on obtaining explicit formulas for the case of small velocities in the presence of weak fields. He found

$$ \nu_P^2 = \nu_L^2 + \nu_\perp^2 (1 + \cos^2 \phi) $$

where

$$ \sin^2 \phi = \frac{1}{\eta} [1 + (1 - \frac{1}{\eta} \cos \psi) / (1 - \eta \cos \psi + \frac{1}{\eta} \psi^2)] $$

Here $\eta = 2(v_s^2/v_C^2) / (H_0^2/H_C^2)$. A plot of $(1 + \cos^2 \phi) = (\nu_P^2 - \nu_L^2)/\nu_\perp^2$ appears in Fig. 3 for several values of $\eta$. The percentage shift is larger in the low-field and low-velocity limit than for the case considered by Takagi.
Fig. 3. \( \frac{v_p^2 - v_L^2}{v_L^2} \) versus the angle \( \psi \), computed from the predictions of Fetter (1975) for several values of \( \eta \). These results apply for the special case in which \( H_c \gg H_o \) and \( v_c \gg v_s \).
CHAPTER II
APPARATUS

The apparatus to be described was designed specifically for the study of the effects of flow on the NMR signal for $^3$He. A brief introduction to it will be given before an expanded discussion of its important components.

Cooling of the $^3$He into the superfluid phases was accomplished in a pair of Pomeranchuk cells of the type described by Kummer (1975). In this kind of cell, the necessary volume changes are achieved by varying the $^4$He pressure applied to the outside of a thin cylindrical diaphragm which encloses the $^3$He. The two cells were connected in the manner shown in Fig. 4. Liquid could be forced to flow along the channel by varying the $^4$He pressure in the lower cell at a controlled rate while maintaining constant $^3$He pressure in the upper cell through adjustment of its $^4$He pressure.

The r-f coils for observing nuclear magnetic resonance in the flowing $^3$He were imbedded in the epoxy walls of the horizontal section of the channel joining the cells.

The pair of Pomeranchuk cells and connecting channel were precooled to 15mK by a conventional $^3$He-$^4$He dilution refrigerator, which also served as a thermal guard during the adiabatic compressions.
Fig. 4. Schematic diagram of the flow apparatus. (a) Flow channel, 1.5mm diam, 10mm long; (b) NMR saddle coil; (c) capacitive pressure gauge.
The Channel

The 1.5mm diameter channel through which the sample flowed was cast in a block of 100A (FURANE PLASTICS) epoxy. Casting had two important advantages. It produced walls that were smoother than if they had been machined. It also enabled the NMR coils to be placed very close to the channel by imbedding them in the epoxy walls. In this way the filling factor for the rf-coils was substantially improved.

The horizontally oriented channel was connected to the Pomeranchuk cells by two 37.5mm long vertical brass tubes. These 2mm i.d. tubes carried the flowing liquid to the main channel while allowing NMR to be conducted in a region free of inhomogeneities produced by the superconducting materials used in the construction of the Pomeranchuk cells. Brass was chosen as the material for the tubes as it was strong, non-magnetic and yet it had better thermal diffusivity than epoxy, for example.

Flow Control System

It was necessary to regulate and measure the velocity of $^3$He through the channel. Direct measurement of the velocity would have been difficult. Instead, the volume rate of transfer of $^3$He from one Pomeranchuk cell to the other was determined and the velocity was calculated from this and the known diameter of the main channel. The number obtained in this way, assuming that the velocity was uniform throughout the channel and that the normal fluid and superfluid were moving together, will be called the bulk velocity, $v$. Regulation of
the velocity was also accomplished indirectly by controlling the system volumes.

The cylindrical diaphragm type of Pomeranchuk cell proved to be very satisfactory for these experiments since changes of the volume of the $^3$He space can be accurately and easily determined with this design. Volume changes are proportional to changes in the pressure difference across the diaphragm. The required constant of proportionality is essentially a spring compliance and in the case of one of the cells, it had been accurately measured by Kummer (1975).

The rate of change of $^4$He pressure in the lower Pomeranchuk cell was controlled by a needle valve in the line between the cryostat and a source of helium at a suitable pressure. A differential pressure gauge across an impedance in the line indicated the rate at which $^4$He was being admitted to the Pomeranchuk cell and, therefore, the speed of flow of $^3$He through the channel. Another needle valve venting into the inlet of a vacuum pump permitted reversal of the direction of $^3$He flow by withdrawing $^4$He from the cell.

The system $^3$He pressure was regulated by automatic adjustments of the $^4$He pressure in the upper Pomeranchuk cell. The adjustments were made in response to error signals derived from a bridge which compared the capacitance of a Straty-Adams (1969) pressure gauge to a precision reference. The error signals drove a heater which varied the temperature within a reservoir of $^4$He gas and, therefore, the pressure of the gas. The feedback loop was completed when the pressure changes were communicated to the $^4$He liquid in the Pomeranchuk cell to adjust the volume of the $^3$He. The $^4$He reservoir was located in a liquid nitrogen bath to increase its $^4$He capacity and to reduce the response
time for pressure changes.

Pomeranchuk cooling had a valuable advantage for this experiment; regulating pressure was sufficient to regulate temperature. The pressure control system described above was sufficient to maintain a desired temperature with variations of about one microkelvin.

Pressures were found from a measurement of the capacitance of the $^3$He pressure transducer. The capacitance of this transducer was calibrated at a series of known pressures at the beginning of each run. Temperatures could be obtained from the measured relationship of temperature and pressure along the melting curve of $^3$He (Halperin, Archie, Rasmussen, Buhrman and Richardson, 1975a; Halperin, 1975b; Kummer, 1975).

**NMR Apparatus**

As mentioned, the rf-coils for NMR were cast into the walls of the channel, as close as possible to the $^3$He in order to improve the signal-to-noise ratio by maximizing the filling factor. For the same reason, these coils were in the form of a rectangular saddle pair wrapped around the bore of the cylindrical channel. Each coil was wound with 100 turns of 0.025mm diameter enamelled copper wire, yielding about 110$\mu$H inductance for the completed pair. All joints in these wires were silver-soldered, if they were in the vicinity of the NMR sample, as part of the effort to maintain sufficient homogeneity of the steady magnetic field.

There was an additional 1.5mm diameter solenoidal coil of the same wire, connected electrically in series with the saddle pair. This coil surrounded a small sample of stationary $^3$He located in a blind
pocket which opened to the main channel at a point quite near the saddle rf-coils. The signal from this coil was intended to be a reference against which the signal for flowing liquid could be compared. In this way it should have been possible to discern real differences in the NMR signals for static and flowing $^3$He from spurious effects such as viscous heating and frequency drift in the electronics. The signals from the saddle coils and the stationary liquid coil were to be separated by the different resonant frequencies for the $^3$He located in different parts of the steady magnetic field. Unfortunately, the signal for the stationary liquid was too small and at a frequency too little removed from that for the flowing liquid; however, a similar arrangement in an earlier version of the apparatus yielded much of the desired information.

Both rf-coils were oriented to produce vertical $\vec{H}_1$ fields. In this way a pair of superconducting Helmholtz coils located in the $^4$He bath could be rotated about the vertical axis of the cylindrical tail of the cryostat to orient the direction of the steady magnetic field, $\vec{H}_0$, to any desired angle, $\psi$, relative to the direction of flow, without upsetting the perpendicular orientation of the rf-fields and the steady magnetic field, $\vec{H}_0$. The angle, $\psi$, could be varied by operation of controls external to the dewar and coupled to the Helmholtz coils by flexible shafts and a series of gears.

Most of the data were obtained for a steady field of 14.7mT. The field was homogeneous to one part in $10^4$ over the region of the NMR sample, as determined from the width of the resonance line for solid $^3$He.
The resonances were observed by a frequency-swept circuit of the Rollin type. Sweeping frequency was chosen over field sweeping to avoid eddy current heating in the metal parts of the Pomeranchuk cells. The Rollin circuit was selected as the simplest configuration in which good electrical isolation of the oscillator and resonance coils is possible. Marginal oscillators were tried and rejected since they are prone to serious frequency pulling by the strongly absorbing $^3$He solid resonance.

The rf-generator for the Rollin circuit was a Wavetek Model 131 function generator which was chosen because of the ease with which a very linear frequency sweep and uniform rf-output voltage could be obtained from it. Another function generator, a Hewlett-Packard model 3300A, provided the symmetrical triangular ramp required to frequency modulate the rf-generator. The rf-tuning components and high source impedance for exciting the NMR coil were combined in a homemade module which linked the NMR coil, the rf-generator and the preamplifier. This preamplifier was a Princeton Applied Research model CR4 which was modified to extend its high frequency response to beyond $1.5 \text{MHz}$ and to somewhat reduce the $1/f$ noise which set the principal limit on the sensitivity of the NMR system. The detector for recovering the absorption signal was another homemade module. In addition to a full-wave diode detector, it included a small broad-band amplifier. This was required since the CR4 preamplifier was incapable of producing an output signal whose voltage amplitude was large enough to overcome the forward voltage drop of the rectifier diodes. An additional set of modules contained a low-pass filter and a narrow-bandwidth parallel-tee filter for rejection of mains frequency noise.
The NMR absorption signal was always displayed on an oscilloscope. Often the amplitude of the signal was read visually, directly from the oscilloscope, but in some cases Polaroid photographs were made in order to obtain information on changes of frequency or shape of the signal. Two other electronic instruments aided in measuring the signals; a peak detector monitored by a digital voltmeter was found to be valuable in obtaining higher resolution in measuring the peak heights while an integrator was useful in studying the effects of flow on the total, integrated absorption instead of the amplitude.
CHAPTER III

PROCEDURE

Flow Control

The preliminary steps before an experiment were very similar to those detailed by Kummer (1975). The only significant deviation from his method was that the two Pomeranchuk cells were present instead of his one, and both were compressed simultaneously until reaching the superfluid phase transition. When the transition was reached, closure of a single valve divided the pressure regulator from the flow regulating controls.

For most experiments, a fairly standardized procedure was followed. After observing the NMR signal at zero velocity, the flow rate was increased to some value, \( v \). This was maintained long enough for the signal characteristics to stabilize and for the desired measurements to be completed. The flow velocity was then returned to zero while the signal was briefly observed, after which the liquid was made to flow in the opposite direction, at \( -v \). Finally, the velocity was again brought to zero, for the beginning of a new cycle at a different flow rate.

The procedure offered a number of advantages; it allowed us to detect and correct for any counter-flow introduced by the presence of thermal gradients, it created a similar past history for each measurement to avert irreproducibility related to hysteresis effects and finally, it was more compatible with technical limitations on the integrated volume of fluid which could be transferred from one
Pomeranchuk cell to the other.

As stated previously, flow rates were monitored by a differential pressure gauge connected across a fixed impedance in one of the \(^4\)He flow paths. It was necessary to calibrate this. Fortunately, Kummer (1975) had obtained accurate data relating the variation of the pressure difference across the diaphragm of one of the Pomeranchuk cells to the variation of the internal volume of the cell. In calibrating the differential pressure gauge, a fixed differential was established while the \(^4\)He pressure in the Pomeranchuk cell was recorded and the internal \(^3\)He pressure was kept constant by the regulator. The product of the time derivative of the \(^4\)He pressure and the calibration constant provided by Kummer then gives the time rate of transfer of \(^3\)He from one Pomeranchuk cell to the other. Since the diameter of the channel was known, finding the flow velocity was trivial.

Data Acquisition

A large portion of the NMR data was obtained from direct visual readings of the rectified and filtered rf-signal, as displayed on the oscilloscope. This had the advantage of immediately revealing any irregularities in the absorption signal. However, the data acquired from the electronic peak detector and digital voltmeter were preferred in cases where greater resolution in the signal amplitude was required.

In the early searches for frequency shifts, many Polaroid photographs were analyzed with a magnifier and finely engraved reticle. Some peak heights were also obtained from photographs, but the method was slow and cumbersome except for observations of complex shape distortions of the signal or of transient phenomena.
CHAPTER IV
RESULTSS

Introduction

The experiment was begun as a test of the theories of Takagi and Fetter. However, the preliminary attempts to find the shifts were impeded by effects which severely distorted and attenuated the NMR absorption peaks in flowing $^3$He-A. Instead of continuing the search for the shifts, attention was soon turned to these complex, competing effects.

The first of the effects is the occurrence of small, transient satellite peaks scattered on the low frequency side of the main liquid absorption peak. The other effect is abrupt decreases in the amplitude of the main peak itself as the velocity of flow increases beyond one or more characteristic velocities. Sometimes there were several, step-like decreases in amplitude and there always was a final reduction of the amplitude to a small fraction of that for stationary liquid.

These effects could occur simultaneously, and when they did, the satellite peaks generally interfered with accurate measurements of peak height variations.

Satellite Peaks

Examples of the satellite peaks are shown in Fig. 5, which is a photograph of NMR absorption spectra for $^3$He-A at various flow velocities. The velocity was zero for the lowest of the traces and
Fig. 5. Examples of satellite NMR signals at $\psi=45^\circ$. $\nu_0$ for the lower trace and increases to $\nu_0 0.014\text{mm/sec}$ for the top trace. The oscillator frequency is 482.71kHz at the left and 483.89kHz at the right.
increased for successive traces. The velocity, $v$, for the uppermost trace was 0.014 mm/sec.

There was other evidence that it was the flow of liquid which induced the satellites beyond the absences of satellites in spectra such as the lowest example in Fig. 5. The most convincing of this evidence came from the early version of the apparatus with a successful coil for observing NMR in static liquid. The liquid in this coil was contained in a short, cylindrical chamber which was open at only one end. This end opened into the main channel as close as possible to the coils for flowing liquid. Other than the coils themselves, the same electronics monitored the signals from the two coils. Furthermore, the signals were being observed within a fraction of a second of each other. While satellites often were present on the absorption peak for the liquid in the flow channel, they were never on the peak for the static liquid. In addition, they were not seen when the liquid was in either the normal Fermi liquid phase or the B-phase. It thus seems certain that the satellites are a property of flowing $^3$He-A, and not, for example, an artifact of the electronics.

If a satellite had been observed at some frequency it was unlikely for a satellite to be found at the same frequency even on the next sweep. The duration of each frequency sweep was 3 sec with successive sweeps being in opposite directions. It was, therefore, possible for two observations at a frequency near the extremes of the sweep range to be separated by considerably less than 3 sec. The change in position or perhaps even the complete disappearance of a satellite on this time scale suggests that they were associated with phenomena which were themselves varying substantially in time intervals of this order. Each
The satellite peaks were observed during numerous compressions at $\psi=45^\circ$ as well as the single compression for $\psi=0^\circ$. Satellites were not found at $\psi=90^\circ$ even though many data were accumulated at this angle on several different days. A possibly related fact which will be expanded upon later is that the satellites were almost exclusively at frequencies lower than the frequency of the main liquid resonance.

While the number of satellites varied widely, their heights and widths were quite uniform. They were narrow compared to what would be expected if the phenomenon which caused them extended over a large fraction of the region of the channel sampled by the NMR coil. Otherwise, the inhomogeneities of the magnetic field would have spread them over a wider range of frequencies. An alternative interpretation is that the phenomenon lasted only long enough for a small range of frequencies to have been swept.

Since the satellites were effectively noise when measurements of the height of the main NMR absorption peak were being attempted, methods of eliminating them were sought. It was found that prolonged flow at high velocities was sometimes beneficial. Oscillating the temperature also helped. However, this was done by perturbing the pressure regulator, which induced some flow, so the improvement could have resulted either from the flow or directly from the temperature excursions. It is possible that the reduction in the number of satellite signals was caused by some modification of the solid $^3$He which inevitably accumulates on the channel walls; however, the NMR signal for the solid was not visibly altered in either shape or size.
by the procedures for elimination of satellites so the changes in solid
distribution must have been small and localized.

**Effects of Flow on Signal Amplitude**

Flow-induced attenuations of the signal amplitude were present
under a wide range of experimental conditions. Fig. 6 is an example of
this effect. Each of the peaks is a record of a single frequency sweep
while the velocity was being maintained constant. Successive sweeps
were displaced horizontally as the velocity was increased in approxi-
mately equal steps between steps. The sequence was begun at \( v=0 \) for
the upper left trace and ended at the lower right trace where
\( v=0.022 \text{mm/sec} \). Arrows have been added to the photograph to mark the
locations of step decreases in signal amplitude. The velocities at
which the amplitude decreased sharply will be designated critical
velocities.

Graphs of peak height as a function of velocity for two different
temperatures appear in Fig. 7. The invariance of the positions of the
features for the two directions of flow indicates that counterflows
caused by thermal gradients were an insignificant contribution to the
net velocities.

There are two kinds of step-wise amplitude decreases apparent in
Fig. 6 and Fig. 7. The large, final decrease was always observed.
Small step-decreases, such as that in the low temperature data in
Fig. 7, were less predictable. They sometimes occurred at any
temperature in the A-phase. Occasionally there were as many as three
of these, yet often there were none. They seemed to be related to
another effect, namely, metastability of the peak height for \( v=0 \). The
Fig. 6. Examples of decreasing signal amplitude as flow velocity is increased. Successive sweeps are displaced from upper left to right with flow increasing in approximately equal increments, \( v = 0.01 \text{mm/sec at upper right and 0.022mm/sec at lower right. Steps occur at arrows.} \)
Fig. 7. Typical behavior of signal height versus bulk velocity. Steps in height occur at the breaks in the curves. △, (1-T/T_c)=0.062; ○, (1-T/T_c)=0.184. Open and closed symbols refer to flow in opposite directions. Vertical scale is different for the two sets of data.
height usually was the same before and after the liquid had been flowing, even if the peak was depressed during the flow. However, sometimes it changed. Less frequently, changes occurred spontaneously while the liquid remained stationary for a time. When it was suspected that these peak heights were clustering around several discrete values, histograms of the heights at zero velocity were prepared. The histograms confirmed the suspicions. Moreover, the most probable of these peak heights were roughly equal to the peak heights for the plateaus between the steps in graphs like that in Fig. 7.

The final decrease of the signal amplitude was more reproducible than the small steps. There were definite trends in the manner in which the critical velocity varied with temperature. In Fig. 8, the bulk velocities\(^1\) at the final steps have been plotted versus the reduced temperature\(^2\), \((1-T/T_C)\). Most of these data are for \(\psi=90^\circ\), where the steps were best defined because of the lack of satellite peaks at this angle. The points for the final steps, those designated by the solid symbols, fall along segments of several straight lines passing through the origin. Since the superfluid fraction is

\[^1\]The term bulk velocity, \(v\), will be defined to mean that uniform velocity at which all \(^3\)He in the channel, whether normal fluid or superfluid, and regardless of its proximity to the walls, would have been moving to attain the known rate of transfer of \(^3\)He through the channel. Assuming the normal fluid is actually stationary, it is related to the superfluid velocity by the equation \(v = \frac{v_s}{\rho_s}\).

\[^2\]There are some differences in the temperature scales which are in common use in this range. Presentation of data on a scale of reduced temperatures allows easier comparison of results from various experiments because the transition temperature, \(T_C\), then has the same value, zero, on all of the scales. It is also advantageous in that several quantities of theoretical interest such as the density of Cooper pairs and the superfluid density are proportional to \((1-T/T_C)\).
Fig. 8. Bulk critical velocities versus (1-T/T_c). Δ, ψ=45°; ○, ψ=90°. Closed symbols indicate the final step in signal height; open ones indicate an additional step at lower velocities.
proportional to the reduced temperature, the superfluid velocity, $v_s$, along any straight line through the origin is a constant, assuming the normal fluid is stationary (Because of its viscosity, time constants for the normal fluid to come to rest after being set in motion are calculated to be ~ 100 msec, much shorter than the time taken in a measurement). The values of $v_s$ range from 0.14mm/sec to 0.64mm/sec for the line segments marked in Fig. 6(b).

The manner in which the peak amplitude falls off as the velocity increases beyond the final critical velocity is different for high temperatures than at low temperatures. As in the examples shown in Fig. 6, near $T_C$ there is a prolonged decrease of the signal amplitude as the velocity increases. In contrast, the signal drops rapidly at low temperatures. Other features of the peaks were also temperature-dependent. At temperatures well below $T_C$, for velocities beyond critical the signal was attenuated without any apparent change of shape and at high enough velocity the signal eventually disappeared almost entirely. A careful search for a change of amplitude of the absorption at the location of the solid signal revealed no change. Neither was it possible to detect even the small shifts in the baseline which would have been expected if the liquid signal simply spread over a moderately wide range of frequencies. However, if the signal had become sufficiently broad, it would not have been detected. The absorption peaks at high temperatures not only persisted for velocities well beyond critical, they broadened and skewed toward lower frequencies as the velocity increased. The broadening compensated for the loss of amplitude so that the integrated signal did not decrease until the velocity greatly exceeded those required to significantly depress the signal amplitude.
CHAPTER V
DISCUSSION

Frequency Shifts

The effort to find NMR frequency shifts of the kind predicted by Takagi and Fetter was frustrated by the low critical velocities. These limited flow velocities so that any shifts were not sufficiently large to permit any real frequency shifts for the bulk flow of liquid to be delineated from artifacts. These artifacts included drifts in the electronics and small, thermally-induced frequency shifts. However, if the predictions are correct, the shifts are almost certainly large enough to measure even at velocities considerably below the observed critical velocities. The required frequency stabilities are well within the capabilities of modern electronic techniques. Furthermore, the use of a separate coil for simultaneously recording the resonance for stationary liquid would reduce the demands for frequency stability as well, in the manner described in CHAPTER II. Ideally, each coil should have a separate amplifier and detector, but both coils should be operated from the same swept-frequency generator. If the magnetic field were trimmed to place the resonances of both samples of liquid at the same frequency the immunity to drifts would be improved. If zero crossings of the derivative spectra were compared, the sensitivity to frequency shifts would be high. The ultimate limitation on the procedure will be the considerable natural width of the resonance lines in the presence of the intrinsic noise of any electronic system.
Signal averaging would be of some benefit, but it is questionable whether steady flow velocities can be maintained for long enough times to average more than a few frequency sweeps.

Even though shifts were not detected in the flowing bulk liquid, they may have been an important contribution to the effects which were observed. Confidence in any interpretation of these effects in terms of frequency shifts would be increased if the theories of Takagi and Fetter were verified at least for low flow velocities.

Speculations on the Origin of the Observed Effects

More than one mechanism may be required to explain all the effects which appeared in flowing superfluid $^3$He. It is probable that some progress can be made by appealing to what is known about superfluid $^4$He, which has been studied extensively over many years. However, $^3$He and $^4$He differ in an important way; $^4$He nuclei have zero spin angular momenta and, therefore, they have no magnetic moments. There are several consequences of this single difference;

1) $^3$He is the only known superfluid which can be studied by means of NMR. The NMR rf-field may function as more than a tool for observation. It may extensively modify the way $^3$He responds to flow.

2) The superfluids themselves are different for $^3$He and $^4$He because they are comprised of Fermions and Bosons, respectively. Thus, $^4$He lacks Cooper pairs, for example. One point of view of the A-phase has three interpenetrating fluids coexisting in the liquid.

$^1$Besides the normal fluid component, $^3$He in the A-phase is sometimes thought of as having two superfluid components corresponding to different orientations of the orbital angular momentum vector of the Cooper pairs.
3) The Cooper pairs are in an $l=1$ orbital angular momentum state. Pairs are broken by interactions with boundaries unless the orbital angular momentum vectors are perpendicular to the boundaries. Pairs farther from the walls are also influenced because bending of the direction of the angular momentum vectors requires energy, called gradient energy. Because it lacks Cooper pairs, there are no comparable effects in $^4$He.

In spite of these hazards, experiences with $^4$He are likely to be a good guide to what to expect in $^3$He. For example, there is no obvious reason why two-fluid hydrodynamics should depend strongly on the detailed nature of the fluids if the fluids are reasonably independent of each other.

Textures

The orientations of the spin and orbital angular momenta of Cooper pairs are governed by many influences. To minimize the free energy, the orientations might be different in different parts of the sample of $^3$He. The liquid is said to have textures if the orientations of the pairs vary slowly compared to the pair radius (a few tens of nanometers).

The $l$-vector of Cooper pairs adjacent to a wall are aligned perpendicular to the wall. Away from the wall, the orientation of the pair changes to minimize bulk energies. The transition between orientations in different regions of the liquid is not abrupt. Instead, there is a gradual bending at a rate governed by the gradient energy. In the present of flow in the A-phase, it has been estimated (Leggett, 1975) that the distance over which pair orientation changes from that near a wall to that in the bulk fluid is about 0.01mm to 0.1mm.
It has been proposed that the effects we have observed could have been related to textures. For example, the region of liquid in which \( \frac{\pi}{2} \) is changing from being perpendicular to the wall to being parallel to the direction of flow is a quite large fraction of the volume of the channel. For the 1.5mm diameter channel, 3% to 30% of the liquid contained in it is in the transition region. The size of the satellite signals relative to the main liquid peak falls in this range and one might conclude there is a connection between textures and satellites. However, it would seem that textures should be stable entities and it is difficult to see how the transient satellites could be caused by them.

Explaining the attenuation of peak heights at sharply defined critical velocities as an effect of textures is even harder. Textures should change smoothly, with the transition zone near a wall becoming thinner as the velocity increases. There does not seem to be a way for decreasing thickness of the transition zone to produce an increasing loss of signal amplitude as the velocity increases nor does it seem feasible to attribute a sharp onset of amplitude decrease to a smooth variation of the thickness of the transition zone. Therefore, it is the opinion of this author that a different explanation must be sought.

Vortices

Vortices are a common type of excitation in fluids. There can be two different types, vortex lines, which must terminate at boundaries of the liquid, and vortex rings, which close upon themselves. Both types exist in superfluid \( ^4\text{He} \), but with a special constraint which does not apply in ordinary classical fluids; in superfluids they must be
Quantized, that is

\[ v_s = n \frac{h}{2\pi mr}, \quad n = 1, 2, 3 \]

where \( m \) is the mass of the atoms and \( r \) is the radius at which \( v_s \) is being measured. In experiments on \(^4\)He, the only value of \( n \) which is found is \( n = 1 \).

The energy per unit length of a vortex line is

\[ E_x = \rho_s (h/m) \left( \ln \left[ \frac{R}{a} \right] - \frac{a}{R} \right) / 4\pi. \]

\( R \) is radius of the outer limit of the vortex line (the radius of a cylindrical container with the vortex core at the axis, for example). For a ring, the energy is

\[ E_r = \frac{h^2}{2\rho_s} R \left( \ln \left( \frac{8R}{a} \right) - \frac{7}{4} \right) / m^2 \]

where \( R \) has a slightly different meaning here. It is the radius of the ring.

On the basis of an experiment by Rayfield and Reif (1964), it is believed that the core radius in \(^4\)He is roughly 100pm. There is no experiment suitable for estimating the core radius for \(^3\)He. Hence, the core radius will be assumed to be comparable to the radius of the Cooper pairs, about 30nm.

In \(^4\)He, superfluid flows without dissipation until a critical velocity is reached. At still higher velocities vortices are generated which, of course, requires energy. Vortices can persist for long periods, even after the liquid has ceased to flow. In fact, once formed, they are difficult to destroy. It is probable that vortices can be created in \(^3\)He as well (Packard (1976)). They offer hope as an explanation for our observations.
The possibility lies in the description of the resonant frequency of the moving liquid by means of Takagi's theory. For a single vortex line, the superfluid at the largest possible radius in the channel is 0.03mm/sec. However, this is a lower limit to the velocity of the fluid in the vortex; most of it is moving faster and at a wide range of velocities. More than one vortex can be present, so there may be a considerable amount of fast moving liquid in the channel at any time. In completing a single circuit around the core, liquid making up the vortex moves at every angle relative to a fixed vector in the plane of the circuit. The range of angles, $\psi$, between the direction of flow of the liquid and the orientation of $\hat{H}_o$ can be more limited depending upon the relative orientations of $\hat{H}_o$ and the vortex line. If Takagi's theory is correct, the NMR frequency of a particular portion of the liquid comprising the vortex would depend strongly on its location in the vortex. The signal for all of the liquid in the vortex would correspondingly be spread over a wide range of frequencies.

According to this model, the sudden decrease in the amplitude at the main peak at the critical velocity would be interpreted as evidence that the production of many vortices had begun. This is consistent as an explanation of the observation of Johnson, Kleinberg, Webb and Wheatley (1975). In their experiment, the onset of vortex production would have led to increased resistance to hydrodynamic flow and, therefore, to heat flow. Thus, it is probably that the similarity of the critical velocities for heat flow and the critical velocities for decreases in the NMR signal amplitudes is not an accident.

If one or more vortices persisted after the cessation of flow, the peak amplitude would remain depressed relative to its value if no
vortices remained. The peak amplitude would increase if a vortex decayed. The metastability of the signal amplitude seems to fit the model. Since the vortices are quantized, the discrete sizes of the peaks after amplitude changes also would be expected.

The disappearance of the absorption signal at lower temperatures and the skewing of the signal at temperatures near $T_C$ are both in qualitative agreement with the model. Takagi's theory predicts that the flow induced shifts will be toward lower frequencies, the direction of the observed skewing. Furthermore, he predicts that the amount of the shift increases as $v_\perp$ increases. Thus, for temperatures near $T_C$, the signal for the liquid in a vortex will be spread over a narrow range of frequencies compared to the range at lower temperatures where $v_\perp$ is larger. If the integrated absorption is to remain constant, spreading an absorption peak over a wider range of frequencies requires the amplitude of the peak to decrease. If this amplitude became small enough, it would explain our inability to find the signal which was missing from the main absorption peak.

Even the sensitivity of the behavior of the signal to the maintenance of high flow rates can be explained. Rapidly flowing liquid should be able to smooth localized protuberances on the solid $^3$He which almost certainly coats the walls of the channel. Vortex lines tend to become pinned to such protuberances so smoothing the channel probably reduces the number of pinned vortices.

The satellite signals are the most difficult feature to explain. The integrated size of the signals is in reasonable agreement with the size of the signal expected for the amount of liquid in a vortex. However, the shape and width of a satellite are difficult to reconcile
with that which would be anticipated for a mass of liquid moving at many velocities. The failure of satellites to reproduce on successive frequency sweeps is also troublesome. If satellites are simply observations of small, stable entities, the satellites themselves should be stable. Yet, pinned vortices are stable and the satellites are not.

It is suspected by this author that a satellite should be viewed as a record of a transition. The transition might be a change between two non-zero values of \( n \), the strength of the vortex, but it is more likely that the transition is the creation of a vortex and that the NMR rf-field is actively involved in providing part of the energy of the vortex. Since each vortex would be created only once, the appearance of the signal on only one frequency sweep is expected. The uniformity of satellite size is also expected, provided most of the energy for creating the satellite comes from the rf-field. Because the creation occurs in a short period of time, the satellites are narrow features. In fact, according to this interpretation, the apparent width on the oscilloscope screen results from the long time constants of the low-pass filters required for observing the ordinary NMR absorption peaks.

There is one other bit of circumstantial evidence. The energy absorbed by the liquid to produce an electrical signal the size of a satellite signal was approximately measured. This measurement was of the same order of magnitude as the energy calculated for a vortex line which just spans the channel.

There is a need for additional work, both theoretical and experimental, to verify whether the observed effects were really caused by vortices. However, the possibility of making magnetic observations
in $^3$He should make experiments on it easier than they have been in $^4$He. It may also be possible to actually manipulate the vortices magnetically so that new kinds of experiments will become available for the study of quantized vortices in superfluids.
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BIOGRAPHICAL SKETCH

Robert Martin Mueller was born March 19, 1939 in Chicago, Illinois. He received a Bachelor of Science degree in mathematics in February 1963 and a Master of Science degree in physics in 1964, both from DePaul University in Chicago. He was employed for several years at Nuclear-Chicago Corporation, where he was engaged in programs to study the interactions of low-energy charged particles with amorphous and crystalline matter and to develop medical instrumentation. Since leaving Nuclear-Chicago Corporation, he has been working toward the Doctor of Philosophy Degree at the University of Florida. He is married to the former Elizabeth Bush.
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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