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The Discovery of Superfluid Helium-3

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This article describes the experiments half a century ago performed by the author, D.M. Lee, and co-workers Robert Richardson and Douglas Osheroff. The figures illustrate the apparatus used by them in the discovery of two new superfluid phases in liquid helium-3.

KEYWORDS: Superfluid, ^{3}He

1. Introduction

It is my pleasure to provide a brief account of the discovery of the superfluid phases of liquid helium 3 in 1972, a half century ago made by Doug Osheroff, Bob Richardson, and David Lee. It provided an exciting prelude to the many important discoveries discussed in the following lectures. Figure 1 provides a photo of Bob Richardson, David Lee and Doug Osheroff, also showing the innards of the low termperature crysotat at Helsinki University of Technology (now Aalto University). We were joined in the later stages of the project by W.J. Gully, a young graduate student who became a member of our group.

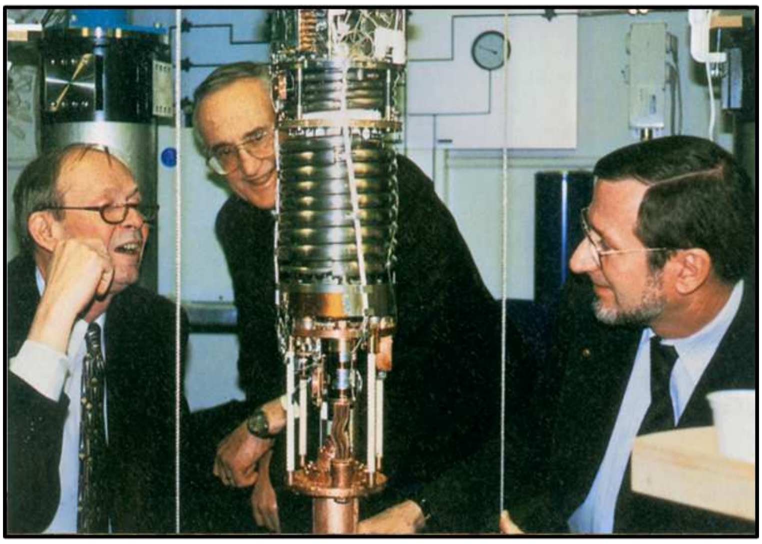

Fig. 1. Happy photo of Bob Richardson, Dave Lee and Doug Osheroff taken during a visit to the laboratory at Helsinki University of Technology.

Figure 2 summarizes some of the important features of the situation preceding the discovery. The BCS theory of superconductivity described how the Cooper pairing of the opposite spin electrons in certain metals exhibit quantum overlap at temperatures well below the Fermi level. Pitaevskii noted that the hard-repulsive cores of ^{3}He atoms prevented the formation of S-wave ($l = 0$) Cooper pairs. [1] Emery and Sessler [2] suggested the formation of $l = 2$, $S = 0$ pairs, but Layzer and Fay [3], on the basis of the large nuclear susceptibility of liquid ^{3}He proposed that ^{3}He atoms would form pairs with parallel spins. Anderson and Morel [4] postulated a p-wave phase corresponding to $S = 1$, $l = 1$, ↑↑ and ↓↓ pairs with an anisotropic energy gap along with gap nodes. Vdovin [5] and also Balian and Werthamer [6] considered a state containing p-wave ($l = 1$, $S = 1$) pairs containing substates ↑↑, ↓↓ and $\frac{1}{\sqrt{2}}$ (↑↓ +↓↑) with an isotropic energy gap.

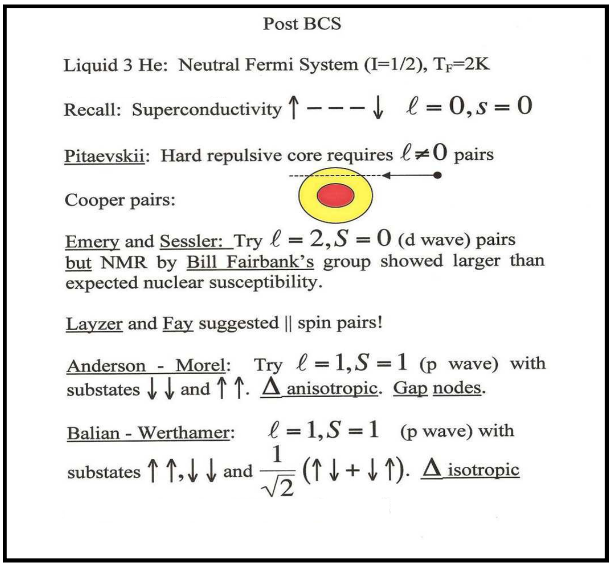

Fig. 2. Historical figure showing the early theories of potential configurations for the superfluid phase of liquid ^{3}He. The work by W. Fairbank et al [7] represents an important advance in studies of liquid ^{3}He. (The Balian-Werthamer State was also proposed by Vdovin)

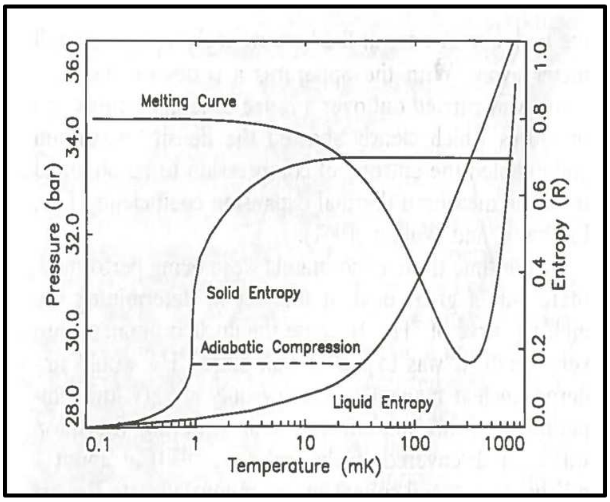

Fig. 3. Approximate entropy diagram for liquid and solid ^{3}He along Melting Curve as a function of temperature. The horizontal line joining two curves corresponds to the adiabatic compressional cooling.

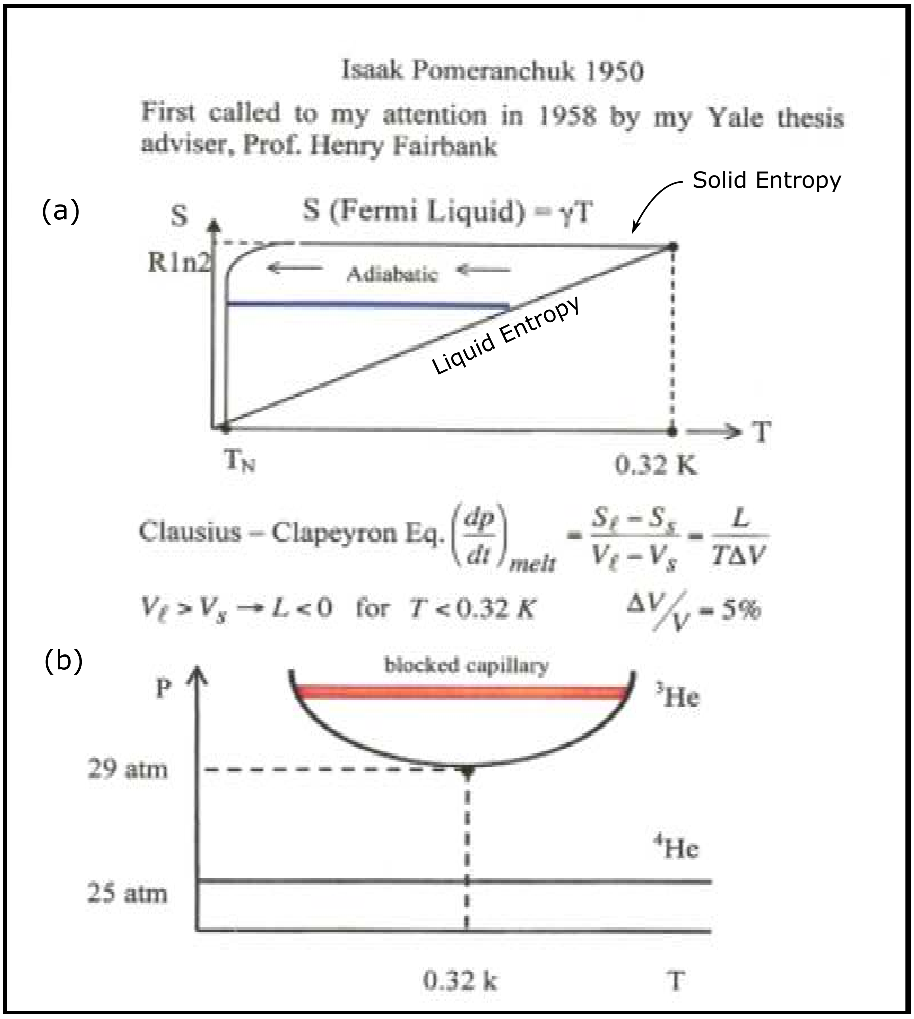

Fig. 4. (a) The P.T. plot showing approximate behavior of the melting curve. (b) The minimum blocks pressure communication between the high temperature and low temperature side of the diagram.

Figure 3 is a plot of the melting pressure vs. temperature showing a pronounced minimum at about 0.32K and approximately 29 atmospheres. Figure 4 shows at the top, rough plots of the entropy vs. temperature for liquid ^{3}He and solid ^{3}He for 0 < T < 0.32K, (where the two plots cross). It was suggested by a Russian theorist, I. Pomeranchuk [8] that a mixture of liquid and solid ^{3}He can be cooled to ultra-low temperature by adiabatic compression of liquid ^{3}He into solid ^{3}He as shown by the horizontal blue line. Temperatures of ~ 1 mK can be achieved by this method. The sample is typically connected to the outside ^{3}He source by a capillary which was thin to prevent heat leaks, but this capillary will be blocked below the melting curve minimum at 29 atm, as shown in the lower portion of Figure 4 which also shows the almost constant melting pressure at 25 atm of helium-4. Therefore, pressure cannot be applied to the sample below about 0.32K. In our experiment a flexible bellows was used to apply pressure to the ^{3}He below 0.32K when the sample cell capillary was blocked. The overall Pomeranchuk Cell is shown in Figure 5. The upper chamber contained He4 whose solidification/melting pressure is only 25 atm and thus required a large diameter bellows to provide sufficient force to compress the ^{3}He. The melting curve minimum (P ≈ 29 atm) was achieved by using the smaller diameter bellows projected into the lower ^{3}He chamber, (corresponding to a hydraulic press.)

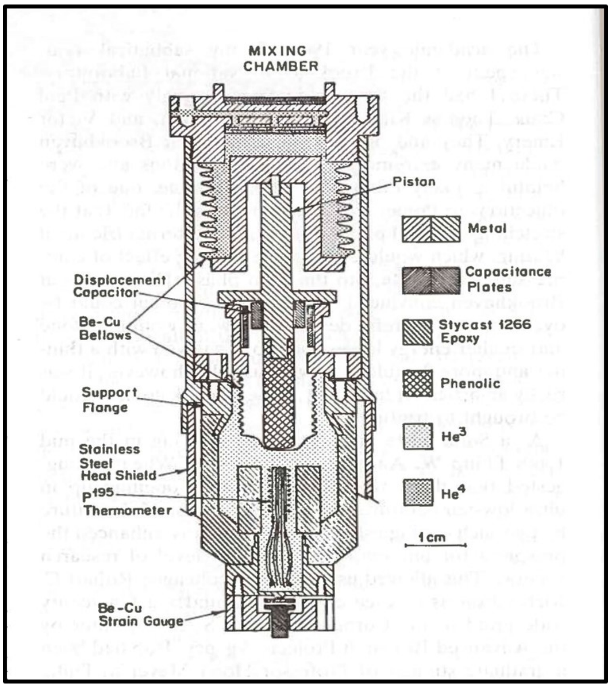

Fig. 5. Pressure applied to liquid He4 in upper large diameter bellows causes a piston to drive the lower bellows into the ^{3}He, thereby increasing its pressure leading to cooling as solid ^{3}He is formed. A strain gauge at the bottom monitors pressure. [9]

2. Results

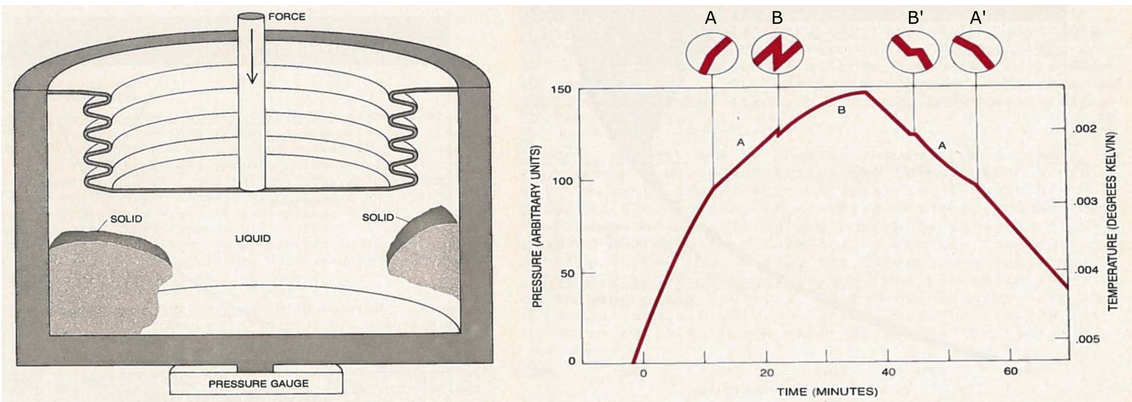

Fig. 6. (Left) Shows lower part of the Pomeranchuk cell containing the liquid-solid mixture of ^{3}He and (Right) the pressure increase causing cooling followed by a pressure decrease causing warming. The features corresponding to the phase transitions are clearly evident in the trace shown in the figure denoted A, A′, B, B′.

Figure 6 is a schematic of the lower chamber which contains a mixture of liquid and solid ^{3}He and is equipped with a sensitive pressure gauge at the bottom of the cell. In the right hand half of the figure is shown a plot of cell pressure vs. time in minutes as the liquid-solid mixture was compressed to a minimum temperature followed by warming the cell during decompression. Unique features [8] were observed during this process indicating possible phase transitions taking place. The lower pressure slope change of the trace labeled A on the left and A′ on the right, corresponds to the onset of a new phase labeled the A phase. As the pressure is increased, at a higher pressure a second anomalous change of the slope was observed. As the pressure increased, a sudden small drop labeled B was observed corresponding to the onset of a second phase. This behavior was reminiscent of a supercooling phenomenon. As the pressure was decreased again after reaching a peak, a small flat region was found at B′ indicating a latent heat. The features B and B′ were then associated with a second phase (the B phase). The question was, were these transitions in the liquid ^{3}He or the solid?

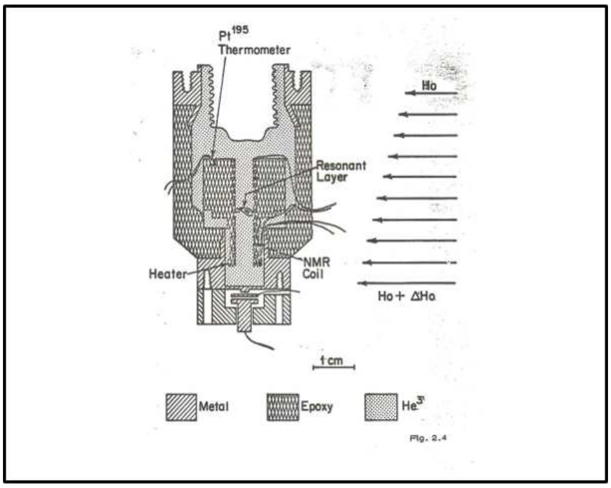

Fig. 7. Lower portion of the Pomeranchuk cell showing the NMR coil, and the applied field gradient. [10]

We discussed this question extensively among ourselves. At the time many people were very discouraged about observing a superfluid transition in liquid ^{3}He at any attainable temperature, so we finally decided to publish the results as corresponding to magnetic phase transitions in the solid. Many people questioned our interpretation. Fortunately, we were preparing an experiment to perform nuclear magnetic resonance studies of our samples. We decided to first perform these experiments in a magnetic field gradient [10] as shown in Figure 7.

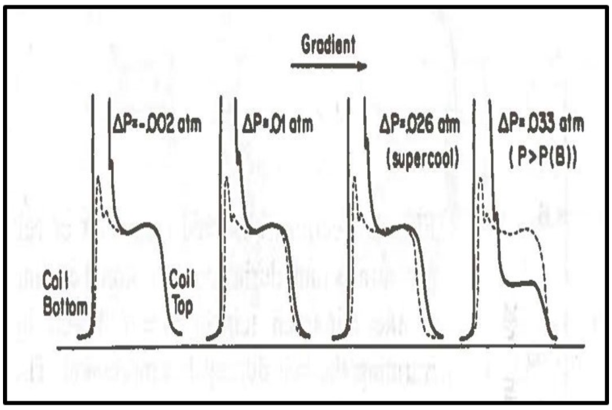

Fig. 8. NMR studies of cooling in a field gradient as the pressure was raised led to a sudden reduction by more than a factor of 2 at the B transition. [10] ΔP corresponds to the pressure change with temperature along the melting curve. The heavy line corresponds to the presence of liquid and solid ^{3}He. For the dotted line data, only liquid ^{3}He was present. Hence the pressure was too low to give Pomeranchuck cooling which requires the presence of both liquid and solid ^{3}He

Figure 8 shows a large signal mainly associated with the solid formed at the coil bottom and small broad signals formed near the coil top. The sample signal did not change appreciably until suddenly as the sample was cooled by the Pomeranchuk effect, the liquid signal suddenly dropped at the higher pressure (lower temperature) in Figure 6 at the B transition. Doug Osheroff was taking the data at the time and called me in the wee hours of the morning. I was totally elated.

In order to check on any frequency dependencies, the field gradient was removed and the experiment was repeated. Sure enough, during the pressure increase (shown in Figure 4b) a sharp liquid signal emerged during cooling through the first change in slope at A on the left-hand side of Figure 4. The liquid signal frequency (shown in Figure 9) shifted away from the solid signal as the pressure increased, corresponding to a lowering of temperature. This shifted signal vanished at the second slope change at B in Figure 4 during pressure measurements. At these lower temperatures (higher pressure) the unshifted reduced liquid signal was observed. We thus had found two separate superfluid phases of ^{3}He which behaved rather differently, with the higher temperature frequency shifting phase labeled A and the lower temperature phase B, unshifted but quite reduced in magnitude. [9]

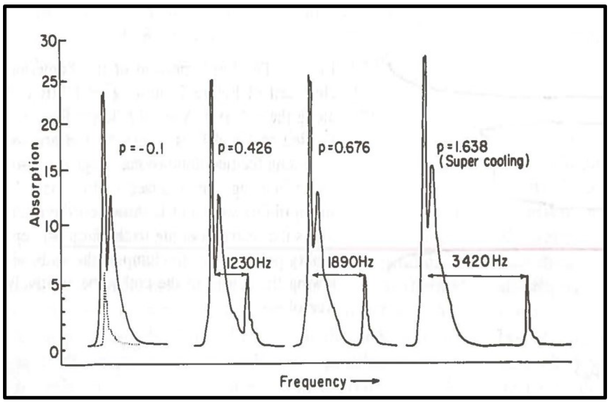

Fig. 9. When the field gradient was removed, a frequency shift in the liquid signal was observed upon cooling the sample through the A transition. The liquid signal frequency shift grew larger as the sample cooled. Upon entry into the B phase, the frequency shift disappeared. Thus, there are two new phases, the A and B phases as shown in Figure 6. These correspond to the newly discovered Superfluid ^{3}He phases. At the high pressure (~ 34 atm) the A transition was first revealed at about 2.7mK, and the B transition was first observed at 2.1mK and at a somewhat higher pressure. [10]

The A phase experimental data sets were taken at a variety of different steady magnetic fields. The results were plotted according to the relationships.

$$\nu_{liq}^2 - \nu_{sol}^2 = \nu_{internal}^2 \tag{1}$$

as a function of the pressure change ΔP corresponding to the temperature change as shown in Figure 10. (A Pythagorean Relationship when solving for ν_{liq}).

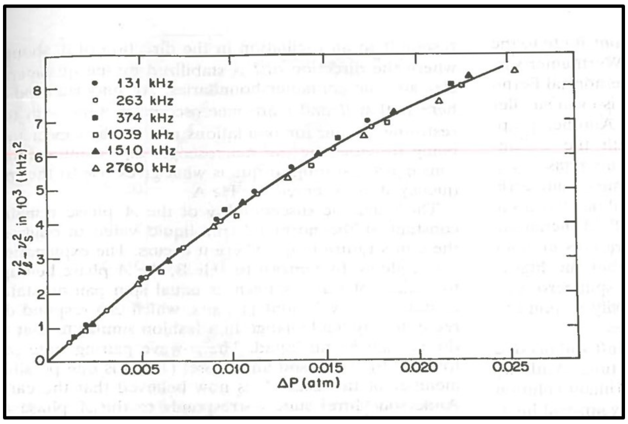

Fig. 10. The frequency differences for the A Phase studied at different magnetic fields between the liquid and solid phase (Larmor Frequency) are plotted vs ΔP as the sample cooled, showing excellent agreement with the Pythagorean relation: $\nu_{liq}^2 - \nu_{sol}^2 = \nu_{internal}^2$ [10]

P wave l=1 states corresponding to the A phase by Anderson and Morel [4] and the B phase by Vdovin [5], and Balian and Werthamer [6] were proposed well before the discovery. Anderson and Morel state: substates with spins down ↓↓ and up ↑↑ and a non-isotropic gap with two gap nodes. The Vdovin and Balian-Werthamer state: substates ↑↑, ↓↓ and $\frac{1}{\sqrt{2}}$ (↑↓ + ↓↑). The third term corresponded to Zero net spin, so it did not contribute to the magnetization, in qualitative agreement with the lower magnetization signal from the B phase. Furthermore, the B phase transition was shifted to lower temperatures at higher magnetic fields corresponding to suppression of the spinless substate.

The A phase frequency shifts were still a mystery until Anthony Leggett came upon the scene. The nuclear dipole moments by themselves seemed to be too small to provide such large frequency shifts. The Pythagorean relationship provided a clue, however. As the superfluid ^{3}He cooled, an effective field orthogonal to the applied field could occur. This could be the result of quantum overlap between the ^{3}He atoms. Anthony Leggett [11] called this spontaneously broken spin orbit symmetry (SBSOS) which in spite of possible thermal fluctuations was able to dominate via the quantum overlap. The correlations between the Cooper pairs locked together a macroscopic portion of the ^{3}He nuclei to provide an effective magnetic field orthogonal to the applied field, leading to the Pythagorean relation responsible for magnetic properties of the A phase.

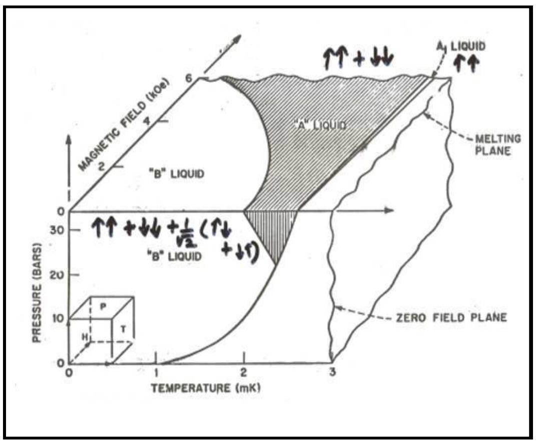

Fig. 11. Overall Phase Diagram. The upper right hand corner depicts a third superfluid phase A_1 corresponding to only the ↑↑ pairs.

The results of our early discoveries were presented at the 13th International Conference on Low Temperature Physics in 1972 at Boulder, Colorado, USA [12] and in Physical Review Letters. [10] The field expanded rapidly as world-wide many low temperature groups joined the effort to discover new phenomena in this expanding field. For example, John Wheatley [13] and co-workers extended studies to lower pressures using adiabatic demagnetization techniques to cool the sample which led to a complete phase diagram (see Figure 11). The actual magnetic phase transition in solid ^{3}He was first observed by Halperin, Richardson and co-workers at Cornell two years later. [14] The A_1 phase, contained only one spin component $\uparrow\uparrow$, so the normal fluid was always present. This allowed second sound to be detected by Osheroff and Corruccini. [15]

Acknowledgements

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