Direct Measurement of the Energy Gap of Superfluid ^{3}He-B in the Low-Temperature Limit

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The zero-temperature limit of the energy gap, $\Delta(P, T \to 0)$, of superfluid ^{3}He-B has been measured at $T/T_c \lesssim 0.25$, near 0.1 and 4.8 bars, and in zero magnetic field. The energy gap was determined from the 2Δ pair-breaking edge of an acoustic signal obtained by novel, pulsed Fourier-Transform ultrasonic spectroscopy. Our results are independent of the temperature scale and the theoretical model of the gap. The values for $\Delta(P, T \to 0)$ are lower than predicted by the weak-coupling-plus theory, and the $\Delta(P \approx 0.1$ bars, $T \to 0)$ values are lower than predicted by BCS theory. The data indicate that $\Delta(P, T \to 0)$ of superfluid ^{3}He-B is not well modeled at the lowest pressures.

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The pairing energy $2\Delta(T)$ of the Cooper pairs in superconductors and superfluids is a fundamental characteristic of these systems as all of their properties are linked to this energy scale. In fact, since most of the experimentally accessible physical quantities are expressed in terms of the value of the energy gap at zero temperature $\Delta(0)$, accurate measurements of this energy scale are desirable. In the limit of weak coupling, BCS theory provided the first theoretical estimate of this important energy, namely $\Delta_{\mathrm{BCS}}(0)/k_B T_c = 1.76$ [1], and this result is also valid for superfluid ^{3}He in this limit [2]. Furthermore, $\Delta(T)$ is expected to approach its fully-developed, low temperature value when $T/T_c \lesssim 0.25$, where T_c is the temperature of the transition from the normal to super state. However, in real systems, the idealized weak-coupling limit is rarely realized, and this situation clearly arises in the case of superfluid ^{3}He whose phase diagram in zero magnetic field suggests the presence of strong-coupling corrections to the pairing mechanisms [2]. Nevertheless, in zero magnetic field, superfluid ^{3}He-B is expected to possess an isotropic energy gap whose gross characteristics are described by BCS theory. Deviations from the weak-coupling limit have been modeled by Serene and Rainer, who used quasiclassical techniques to incorporate strong-coupling corrections in the weak-coupling-plus (WCP) model [3]. The resulting energy gap, $\Delta_+(P, T)$, may be calculated by using $T_c(P)$ and $\delta C/C_N(P)$, the jump in the specific heat at T_c, as input parameters [3,4].

The measurement of the energy gap in superconductors can be made in several ways, including tunneling and far-infrared spectroscopy, and the low temperature limit, i.e., $T/T_c \lesssim 0.25$, is easily accessible. For the case of superfluid ^{3}He, tunneling is impractical; however, ultrasonic techniques are well suited to study $2\Delta(P, T)$ as a well-defined zero sound mode propagates [4]. Since the superfluid transition temperature $T_c(P)$ varies from approximately 1 to 3 mK, depending on the pressure, the pairing energy is accessible by radio frequency (50–225 MHz) spectroscopy. In fact, when the ultrasonic frequency exceeds $2\Delta(P, T)/h$, a sudden increase of attenuation is observable as pair breaking occurs.

Although several studies were made close to T_c [4], one of the first experiments to measure $2\Delta(P, T < T_c)$ was reported by Adenwalla *et al.* [5], who worked at $T/T_c > 0.6$ and between 2 and 28 bars. These authors concluded that their measurements were consistent with the predictions of the WCP model. At about the same time, Movshovich, Kim, and Lee (MKL) [6], working in finite magnetic fields (0.9 kG $\leq H \leq$ 4.6 kG) and over a range of pressures (6.0 bars $\leq P \leq$ 29.6 bars) and temperatures ($0.3 \leq T/T_c \leq 0.5$), interpolated their data to the zero temperature and zero magnetic field limit to extract values for $\Delta(P, T \to 0)$ at 4.8, 9.8, and 18.1 bars. These authors concluded that their values above 9.8 bars were comparable with the WCP predictions, whereas the energy gap at 4.8 bars was approximately equal to the BCS value. Since work of MKL, no systematic and direct attempt has been made to measure the gap in the low temperature and low pressure limit. In fact, the results of MKL have been largely ignored, as most researchers studying superfluid ^{3}He-B at low pressure use $\Delta_+(P, T)$. For example, an ultralow temperature scale, which uses $\Delta_+(P, T)$ for calibration purposes, has been proposed [7].

In this Letter, through the use of novel, pulsed Fourier-transform (FT) ultrasonic spectroscopy, we report direct, precision measurements of the pair-breaking energy in superfluid ^{3}He-B. Our studies were performed at sufficiently low temperature so they are independent of issues arising about the details of our thermometry or choice of temperature scale. Since no external magnetic field was applied to the sample, the order parameter was not distorted as it was in the MKL work. Our data cover small windows of pressures in the vicinity of 0.1 and 4.8 bars and require no additional extrapolation to obtain the values of $\Delta(P, T \to 0)$.

The conventional method of using ultrasound involves sweeping the temperature while operating at an odd harmonic of a high-Q transducer. This method is suitable above $T/T_c \gtrsim 0.5$, where $\Delta(P, T)$ increases significantly as the temperature is decreased. However, below $T/T_c \lesssim 0.3$, $\Delta(P,T)$ starts to become temperature independent, so alternative methods must be employed. One possibility is to vary isothermally the pressure or magnetic field in order to tune $2\Delta(P,T)$ to the operating frequency of the transducer. This approach was employed by MKL, who varied the pressure in different magnetic fields in order to identify a kink in the response of their acoustic signal [6]. This kink was interpreted as the 2Δ pair-breaking edge, and these data were then interpolated to the zero temperature and zero magnetic field limit to extract a value of $\Delta(P, T \rightarrow 0)$. A broadband frequency approach to the experiments at low temperature would be more favorable, and several attempts to perform these studies have been reported [8,9]. Unfortunately, the plastic transducers have not been operated above $\approx$60 MHz, so the 2Δ pair-breaking boundary was not observed. For our experiment, we have used commercially available $LiNbO_3$ transducers whose bandwidth spans $\approx$4 MHz around the odd harmonics of the 21 MHz fundamental frequency. Although the bandwidth sensitivity is structured as a function of the operating/response frequency, this limitation is not relevant for the present experiment which simply seeks to identify the crossover from low to high attenuation.

The experimental cell consists of a pair of $LbNbO_3$ transducers, separated by a Macor spacer defining the path length of 3.22 ± 0.02 mm. This cell was contained in a silver tower that was coupled to a pressed silver powder heat exchanger ($\sim$30 m^2) which was bolted to Cryostat No. 2 in the Microkelvin Research Laboratory [10]. The stray magnetic field in the vicinity of the acoustic cell was <0.7 mT during the measurements. The cell pressure was monitored continuously by a strain gauge [11] which was located adjacent to the sound tower. The pressure was calibrated against a gauge located at room temperature while the cell was maintained at $\approx$100 mK. The temperature of the cell was monitored by a pulsed, Pt NMR thermometer and a ^{3}He melting curve thermometer, and both devices were bolted to the same cold platform. The Pt NMR thermometer was calibrated by using the T_A and T_N transitions as defined by the Florida temperature scale [12] and as detected by the melting curve thermometer. During this process, the temperature drift was <50 μK/h, slow enough to ensure the nuclear stage and the liquid sample were in equilibrium. Additional tests of equilibrium conditions were made by comparing, during both slow warming and cooling conditions, the response of the thermometers and $T_c(P)$ [4] as detected by the ultrasonic signal.

Although quite popular in NMR and optical experiments, FT spectroscopy is rarely applied in acoustic experiments [13]. Our 10.7 MHz heterodyne technique employs a commercial NMR spectrometer [14] to excite the transmitter and to detect the received signal coming from the receiver. Only the signal from the first pulse through the liquid was analyzed, as the FT analysis did not include the response from residual feed-thru effects or additional echoes [15]. Typical experiments involved using 0.4 μs excitation pulses (which delivered $\lesssim$1 nJ of maximum power to the transducers), averaging 128 times, and waiting 4 s between pulses. A pause of at least 8 min was used between signal acquisition periods. Care was taken to insure that the signals remained in a linear response regime [16,17]. At low T/T_c, we have estimated the temperature of the superfluid by analyzing the attenuation of the received signals while assuming the presence of a constant heat leak and a Kapitza boundary resistance ($\propto T^{-2\pm1}$). The most pessimistic estimates suggest that the lowest superfluid temperatures were $\lesssim$250 μK at 0.15 bars (i.e., $T/T_c \lesssim 0.26$) and $\lesssim$300 μK at 4.8 bars (i.e., $T/T_c \lesssim 0.21$).

A set of typical data is shown in Fig. 1, where the amplitudes of the FT power spectra are shown as a function of T/T_c at 4.7 bars when the excitation frequency $\nu_{ex} = 106$ MHz. For $T/T_c \lesssim 0.3$, the detected spectra are clearly cut off at high frequencies, which defines the transition from a low to a high attenuation regime. We interpret this feature as arising from the $2\Delta(P,T)$ pair-breaking phenomenon. At higher temperatures in the superfluid, the cut-off edge moves to lower frequencies and is less sharp. Furthermore, the entire FT response is attenuated when compared to the results at low T/T_c. Although not completely obvious from the presentation in Fig. 1, the softening of the cut-off feature and the increased amount of response that is detected above $2\Delta(P,T)$ arises from an increase in the population of thermally activated quasiparticles, whose density would vary as $\approx \exp(-\Delta/T)$.

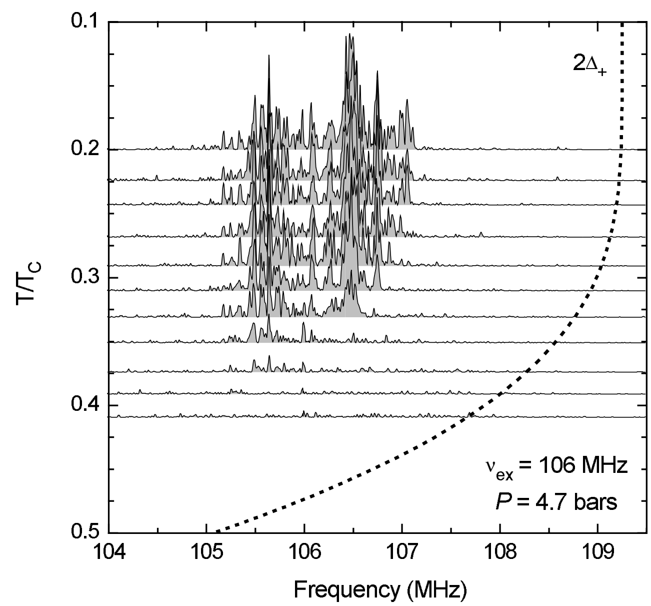

FIG. 1. The FT power spectra of the received signals are shown as a function of T/T_c when $\nu_{ex} = 106$ MHz and $P = 4.7$ bars. The structure of the spectra is an artifact of our technique [15], but the 2Δ cut-off edge is clearly visible. The $2\Delta_+(P = 4.7 \text{ bars}, T)$ values [4] are given by the broken line.

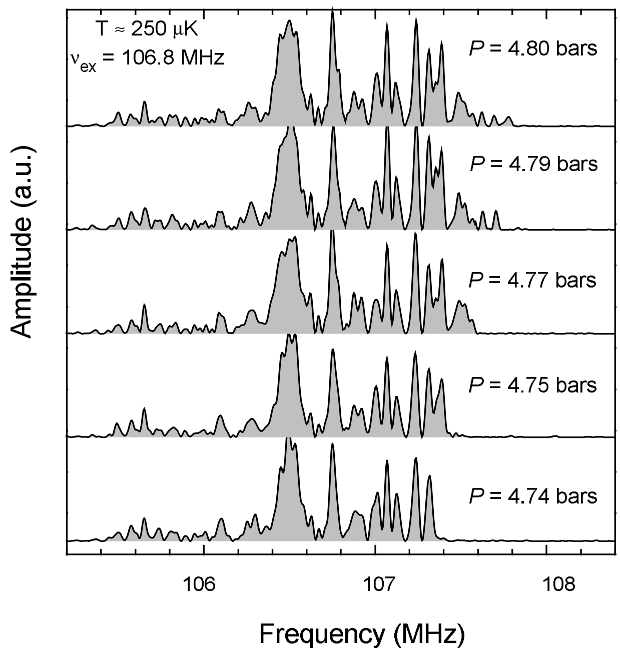

FIG. 2. Amplitudes of the FT power spectra of the received signals are shown as a function of pressure when $T \approx 250\ \mu$K and $\nu_{\rm ex} = 106.8$ MHz.

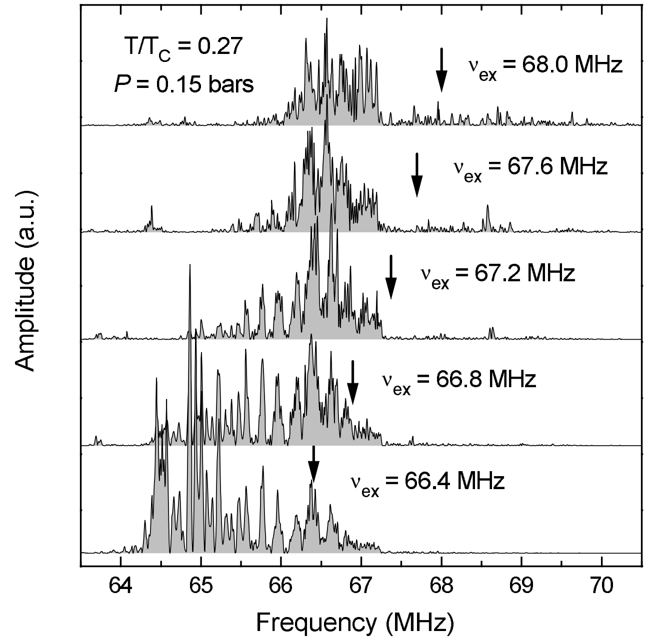

FIG. 3. Amplitudes of the FT power spectra of the received signals are shown as a function of $\nu_{\rm ex}$ when $T/T_c = 0.27$ and $P = 0.15$ bars. The 2Δ signature is well defined at 67.25 MHz. When $\nu_{\rm ex} > 2\Delta$, the signal above the pair-breaking edge appears to increase, as discussed in the text.

To insure that the observed cut-off features represent the $2\Delta(P,T)$ pair-breaking phenomenon, data were also acquired under isothermal conditions while varying the pressure with fixed $\nu_{\rm ex}$ (Fig. 2) or sweeping $\nu_{\rm ex}$ at fixed pressure (Fig. 3). For example, in Fig. 2, the cut-off frequency increases as the pressure is raised, while the fine structures of the FT spectra remain unchanged. Consequently, the fine structures in the response are not associated with any collective modes which should vary with pressure [4,18], but they are consequences of the properties of the transducers and our technique [15].

If a significant quantity of quasiparticles are excited by the pair-breaking process, then the energy gap may be expected to decrease. This possible distortion of the observed 2Δ edge may be tested by sweeping $\nu_{\rm ex}$, Fig. 3. When $\nu_{\rm ex}$ increases, additional pair breaking occurs because of the increase of additional Fourier components with frequencies $>2\Delta(P,T)/h$. In Fig. 3, the sharp cut-off edge at 67.25 MHz is independent of $\nu_{\rm ex}$, and consequently, we conclude that our determination of 2Δ is not influenced by any excitation dependent effects. It is noteworthy that some finite transmission is present above the cut-off edge when $\nu_{\rm ex} > 2\Delta(P,T)/h$. Although we have not yet identified the origin of this effect, we have considered the small dispersion distortion of the pair-breaking edge [19].

All of our data in the low temperature limit, i.e., $T/T_c \lesssim 0.25$, may be combined in one plot which compares our results with the predictions of the WCP and BCS models, Fig. 4. It is important to stress that the experimental data plotted in Fig. 4 do not depend on our thermometry or choice of the temperature scale. On the other hand, the theoretical predictions require inputting $T_c(P)$ and, in the case of the WCP model, $\delta C/C_N(P)$. Finally, our values for the energy gap in the low temperature liquid may be normalized by $k_B T_c(P)$ and may be compared to the results of MKL and the theoretical predictions, Fig. 5,

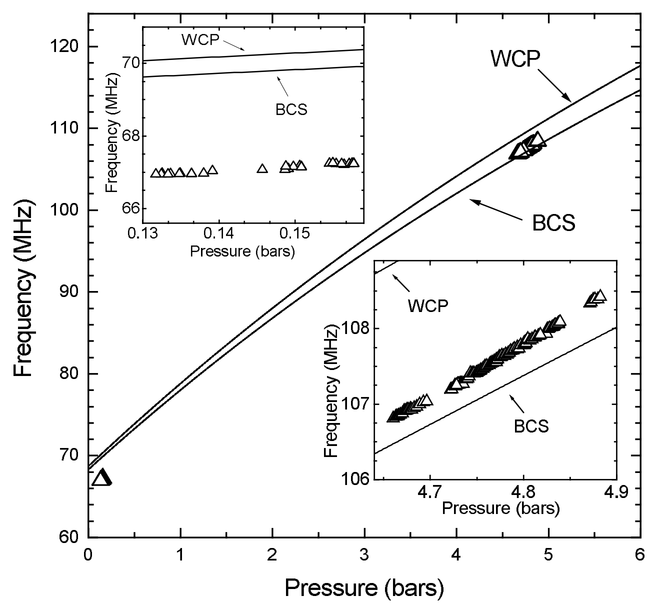

FIG. 4. Our $\Delta(P, T \to 0)$ values are shown as a function of pressure. The insets show expanded views of our data near 0.15 and 4.8 bars. The predictions of the WCP and BCS models are given by the lines [4].

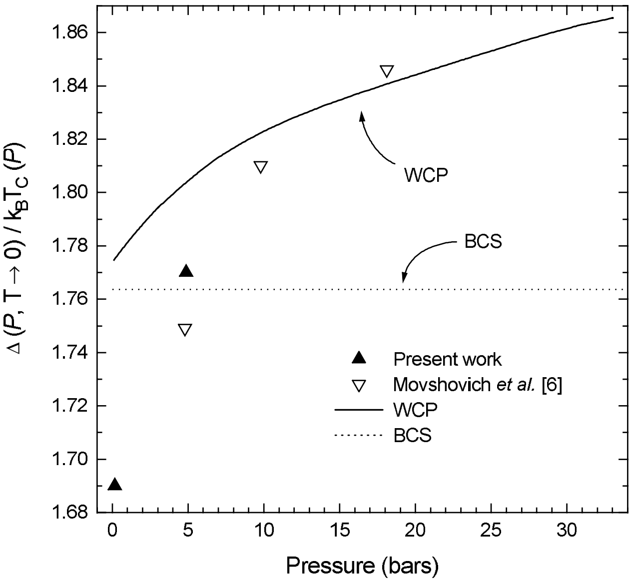

FIG. 5. $\Delta(P, T \to 0)/k_B T_c(P)$ values are shown as a function of pressure. The experimental data obtained by MKL [6] are displayed along with the predictions of the WCP and BCS models [4].

where choices of $T_c(P)$ and $\delta C/C_N(P)$ have to be made. For the purpose of consistent comparison in Figs. 4 and 5, the parameters compiled by Halperin and Varoquaux [4] have been used. The experimental results indicate that $\Delta(P, T \to 0)$ is smaller than theoretically expected, even if one allows for an uncertainty of $T_c(P)$ of $\lesssim 3\%$. Furthermore, the pressure dependence of the energy gap is significantly stronger at low pressure than predicted by the WCP model. Naturally, this discrepancy may suggest the need to include additional terms in the quasiclassical expansion and/or to revisit the experimental values of $\delta C/C_N(P)$ and $T_c(P)$.

In summary, $\Delta(P, T \to 0)$ of superfluid ^{3}He-B is not well modeled below $\approx$10 bars, and our results are significantly below the theoretically predicted values. Experimentally underestimating $\Delta(P, T \to 0)$ is not possible in our measurements. More specifically, magnetic field distortion [6], dispersion effects [19], corrections to our estimates of the minimum T/T_c values, and uncertainties in the pressure of the sample are too small to rectify the discrepancy. Consequently, the consistency of our results with the data of MKL [6] cannot be considered as a coincidence.

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