Measurements of the Pair-Breaking Edge in Superfluid ^{3}He-*B*

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We have made the first systematic study of the pair-breaking edge in superfluid ^{3}He-*B* over a wide range of pressures and frequencies. This direct measurement of the gap enables us to experimentally verify the predictions made for strong-coupling corrections to the gap. In addition, it indirectly lends support to the temperature scale of Greywall.

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In this paper we present the first systematic (and direct) measurements of the superfluid gap in the *B* phase of ^{3}He; this is surely one of the more fundamental properties of paired-fermion superfluids. We compare our measurements to the predictions of the weak-coupling-plus model.[1,2] The comparison depends on the temperature scale used;[3,4] however, weak-coupling theory does not provide an accurate description for either temperature scale. We find that the best agreement occurs if we use a combination of the Greywall temperature scale[3] and the weak-coupling-plus model[1,2] for the gap.

Earlier sound-attenuation measurements in the superfluid showed a minimum in the attenuation at a temperature between T_c and the squashing mode.[5,6] However, these experiments were done either at high T/T_c or in a long-path-length cell, precluding a systematic study of the precise location of the zero-field pair-breaking edge as a function of temperature and pressure.

Certain properties of superfluid ^{3}He show marked deviations from the predictions of the weak-coupling theory. According to the weak-coupling theory, the specific-heat jump at the transition should be $\Delta C/C_N = 1.43$; the measured specific-heat jump in ^{3}He varies from nearly the BCS value at the vapor pressure to 1.9 at the melting pressure.[3] Moreover, the *B* phase is the only stable phase predicted by weak-coupling theory, but in ^{3}He at pressures above 21 bars the *A* phase is also stable. These deviations from the weak-coupling theory are the result of strong-coupling corrections. Theoretical models for incorporating the effect of strong coupling on the size of the gap, Δ, include the renormalized gap,[7] $\Delta = (\Delta C/C_N)^{1/2}\Delta_{\mathrm{BCS}}$, and the weak-coupling-plus model of Rainer and Serene.[1,2] In the weak-coupling-plus model,[1] the contributions to the free-energy difference between the superfluid and normal states are arranged in powers of T_c/T_F. The BCS free energy is the leading term in this expansion and is of order $(T_c/T_F)^2$. The weak-coupling-plus model retains terms to order $(T_c/T_F)^3$ and these corrections depend upon the quasiparticle scattering amplitudes for the normal Fermi liquid. For most superconductors, in which $T_c/T_F \sim 10^{-4}$–10^{-5}, the superfluid state is well described by the weak-coupling BCS theory. In ^{3}He, however, $T_c/T_F \sim 10^{-3}$ and there is a strong residual interaction between quasiparticles, which is an order of magnitude stronger than in most superconducting metals. These two effects combine to make the $(T_c/T_F)^3$ term important in ^{3}He.

Measurements of the acoustic pair-breaking edge (the frequency above which pairs are broken by the absorbtion of a zero-sound quanta) in ^{3}He-*B* provide fundamental information in a number of ways: (i) A direct measurement of $\Delta(P,T)$ determines the pressure range over which the weak-coupling theory is applicable and tests the predictions of the weak-coupling-plus model. (ii) The order parameter in ^{3}He is a 3×3 matrix and the structure of the order parameter leads to many collective modes.[8,9] In a simple model, the eigenfrequencies, ν, of the modes are given by $h\nu = a_\nu\Delta$, where a_ν is a coefficient depending on the mode; a direct measurement of the gap allows a determination of the pressure and temperature dependences of these coefficients. At present it is not clear whether the observed pressure and temperature dependences[10,11] are due to the non-BCS-type behavior of $\Delta(P,T)$ or model-dependent corrections to the coefficients.[12] (iii) There is still disagreement about the correct temperature scale[3,4,13] and a measurement of the gap would provide information about the temperature scale in two ways: (a) A measurement of the gap at very low pressures (where the weak-coupling theory is still applicable) and at low T/T_c (where we measure essentially the zero-temperature gap) would unambiguously determine the transition temperature at that (low) pressure through the BCS relation $1.764k_BT_c = \Delta_{\mathrm{BCS}}(0)$. $T_c(P)$ is then compared with that predicted by the different temperature scales (two of which[3,4] currently are related to each other by a multiplicative constant). (b) The coefficient of the various collective modes and of the pair-breaking edge are dependent on the temperature scale used. Since (on model-independent kinematic grounds) the coefficient of the pair-breaking edge must be 2, we can adjust the temperature scale used so that our data points cluster around 2. However, this adjustment *assumes* a particular model for the gap.

We have measured the pair-breaking edge, 2Δ, using a cw, single-ended acoustic impedance technique described earlier.[14] Our acoustic cell contains two quartz transducers separated by two lengths of thin, gold-plated tungsten wire bent into semicircles. The distance between the two transducers is 190.5 μm and thus the round-trip-path length is 381 μm. Experiments were performed up to the thirteenth harmonic of our 12.79-MHz fundamental transducer. Our unloaded transducers result in a very good electrical-to-mechanical efficiency at the expense of a narrow bandwidth. This leads to nonoverlapping transducer resonances at higher frequencies favoring a single-ended technique. We used an La-diluted cerium magnetisum nitrate (LCMN) thermometer[14,15] mounted above the acoustic cell, out of the field of the demagnetization magnet, which was calibrated against the superfluid transition signature at various pressures. To analyze our data, we used the temperature scale and the values for $\Delta C/C_N$ as a function of pressure reported by Greywall.[3]

A typical temperature (pressure) trace is shown in Fig. 1. As we cool into the superfluid, there is a step in the impedance at T_c. Below T_c, the attenuation is high (due to damping by the pair-breaking process) and continues to increase as we cool. At a temperature $T_{\rm PB}$, where $h\nu = 2\Delta(T_{\rm PB})$, the sound attention decreases abruptly and we observe the onset of oscillations due to the presence of standing waves in the cell. [The oscillations are caused by the changes in the sound velocity with temperature or pressure and can only appear when the attenuation is low enough that the returning (reflected) wave causes a measurable shift in the transducer response.] The decrease in the period of the oscillations is due to the approach of the squashing mode (the velocity changes very rapidly near this strongly coupled collective mode). Note that the squashing mode peak (SQ) is split; this phenomena will be the subject of a future report. The point at which the oscillations appear (implying the presence of a standing-wave pattern in the cell and hence a sudden decrease in attenuation) is taken as the pair-breaking edge, 2Δ.

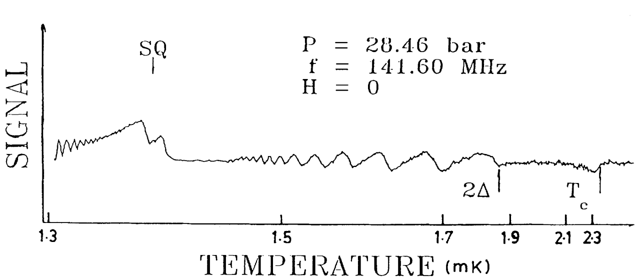

FIG. 1. Typical temperature (pressure) sweep. For details, see text.

The pair-breaking edge was measured by varying both the pressure and the temperature. We have described the technique, involving alternating between temperature and pressure sweeps, elsewhere.[14] The technique was also used recently to study the Zeeman splitting of the squashing mode.[16] The pressure sweeps give a clearer signature of the edge (especially at low T/T_c), since the velocity changes more rapidly with pressure than with temperature, causing the oscillations to have a shorter period. The measurements were made for pressures ranging from 2 to 28 bars and over a temperature range from 1 to 2.1 mK, corresponding to T/T_c ranging from 0.62 to 0.95.

In Fig. 2, we have plotted our data for the pair-breaking edge in the pressure-temperature plane. The curves correspond to the calculated values for 2Δ obtained using both $\Delta_{\rm BCS}$ and Δ^+ (the weak-coupling-plus model of Rainer and Serene[1,2]) for the frequencies 64.33, 90.05, 141.6, and 167.4 MHz. From this figure, it can be seen that our data are fitted by the weak-coupling-plus model much better than by BCS theory. The scatter in our data is chiefly due to our thermometry.

As mentioned earlier the LCMN thermometer is located in the low-field region, resulting in some temperature uncertainty. To compensate for any temperature gradient between the region of the transducers and the thermometer, all data reported are those taken under similar conditions, that is while demagnetizing or depressurizing. Also since the data were taken over a long period of 9 to 12 months covering a wide range of frequency, pressure, and temperature, it was necessary to warm the cryostat to room temperature on several occasions. This recycling introduces an uncertainty in the thermometry between different cooldowns.

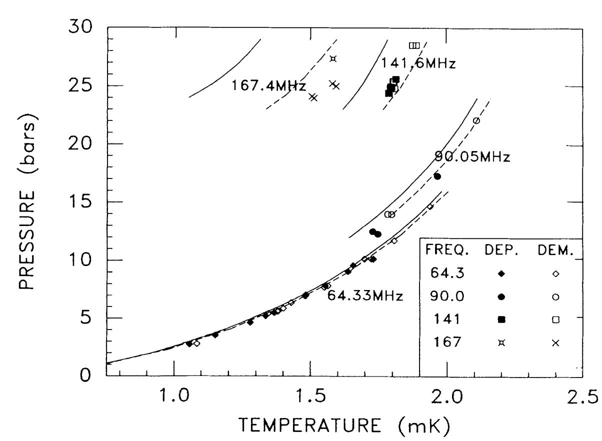

FIG. 2. Pair-breaking edge in the pressure-temperature plane. The solid curves correspond to $2\Delta_{\rm BCS}$ and the dashed curves to $2\Delta^+$ for each frequency. The data were taken during depressurizations (DEP) and demagnetizations (DEM).

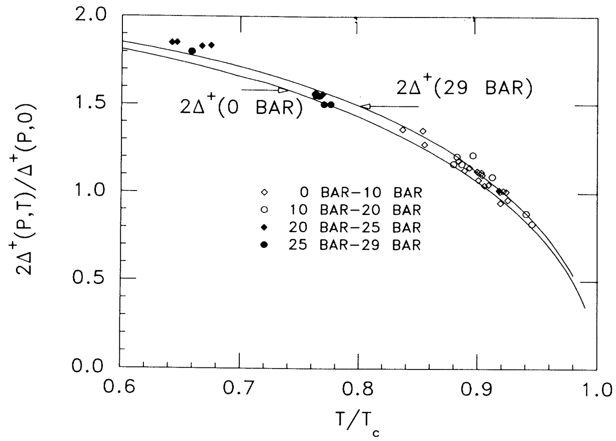

FIG. 3. Frequency of the edge [normalized to $\Delta^+(0)$] vs T/T_c. The two solid curves are $2\Delta^+$(at 0 bar) and $2\Delta^+$(at 29 bars).

The frequency of the edge [normalized to the calculated value of $\Delta^+(0)$] as a function of the reduced temperature is shown in Fig. 3. The two solid curves are $2\Delta^+$(at 0 bar) and $2\Delta^+$(at 29 bars) (the latter is the highest pressure at which data were taken) and join together at $T/T_c=0$ and $T/T_c=1$. The scatter in our data precludes our seeing any tendency for the higher-pressure data to cluster near the upper curve. However, most data points lie between the two curves.

As stressed earlier, the coefficient of the gap, a_ν (in the expression $h\nu=a_\nu\Delta$), for the pair-breaking edge must be 2. We have calculated the coefficient for all our data points using both the Helsinki temperature scale[4] and the Greywall temperature scale[3] as shown in Figs. 4(a) and 4(b). Note that the points near T_c inevitably have a greater scatter. If our data points are to cluster around 2, it is necessary to use both the Greywall temperature scale[3] and the weak-coupling-plus gap.[1,2] If we use the Helsinki temperature scale[4] the majority of the data lie below the $a_\nu=2$ line—if we use the weak-coupling-plus model, the coefficient is reduced still further. These results provide an indirect confirmation of the Greywall temperature scale. Independent measurements of the pair-breaking edge by Movshovich, Kim, and Lee at low temperatures also reach the same conclusion.[17]

We have not taken into account the effect of quasiparticle broadening. The effect of broadening would be to shift our signature of the pair-breaking edge to temperatures lower than 2Δ; however, the nearly vertical character of the edge,[18] combined with our very short path length tends to minimize this effect.[19] There is a suggestion in the data that the coefficient at $T/T_c=0$ will be greater than 2. This would imply that the weak-coupling-plus model tends to *underestimate* the strong-coupling corrections. Heat-capacity measurements (by Alvesalo, Haavasoja, and Manninen[20] and Greywall[3]) at high pressures (> 25 bars) also indicate that other

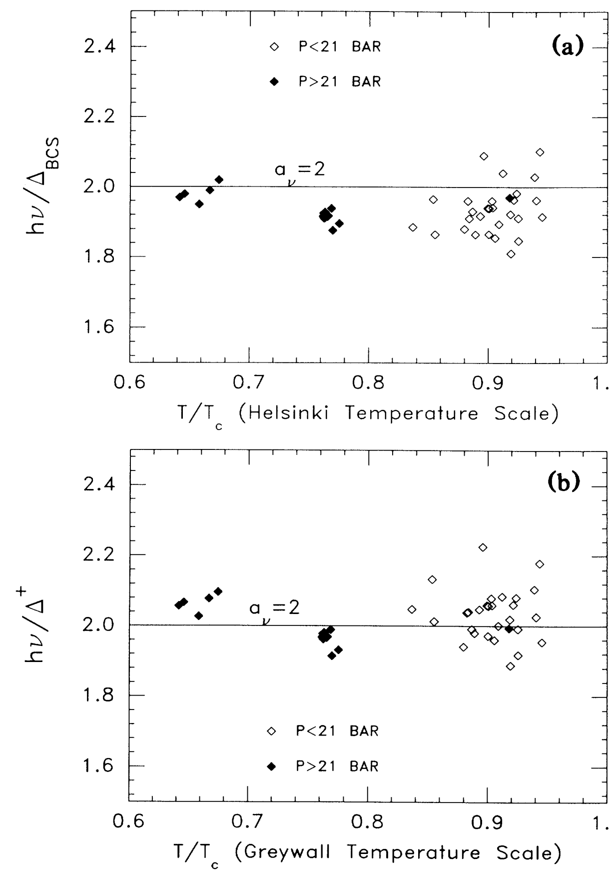

FIG. 4. The coefficient of the edge calculated using (a) the Helsinki temperature scale with the BCS gap and (b) the Greywall temperature scale with the weak-coupling-plus gap.

strong-coupling effects may be important.

In conclusion, we have made the first systematic measurements of $\Delta(P,T)$ in the B phase of ^3He. Our results support the weak-coupling-plus model and, indirectly, the temperature scale of Greywall.

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