1990

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Resolution of a Doublet Splitting of the Squashing Mode in Superfluid ^{3}He-B

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(Received 11 May 1990)

The single-ended, cw impedance technique has been employed to study the squashing mode of superfluid ^{3}He-B in a sound cell with a path length of 381 μm with ultrasound frequencies of 115.8 and 141.6 MHz. A doublet splitting of the squashing mode has been observed and the width of the splitting is dependent on the thermal gradient within the acoustic cell, which strongly suggests that the observed phenomena is induced by superflow.

PACS numbers: 67.50.Fi

The squashing (SQ) collective mode in ^{3}He-B [1,2] is a dramatic manifestation of its unconventional $L=1$, $S=1$ superfluidity. This $J=2$ ($J=L+S$) mode can undergo a fivefold Zeeman splitting in the presence of a magnetic field or a threefold splitting due to finite wave vector, electric fields, or superflow. The Zeeman splitting was recently observed by the Cornell group.[3] The study of the SQ mode is complicated by the enormously high attenuation that occurs near the mode. Two ways to approach this experimental problem are to use a short-path-length cell (for propagation experiments) or the acoustic impedance technique, which is especially sensitive to the high-attenuation region.

In this Letter we report a study of the SQ mode with the cw acoustic impedance technique in a sound cell containing a pair of X-cut quartz transducers with a fundamental frequency of 12.8 MHz. The data to be reported here were taken at frequencies of 115.8 and 141.6 MHz, corresponding to the ninth and tenth harmonics. The transducers were separated by a pair of gold-plated tungsten wires; the resulting separation was 190.5 μm but the single-ended technique employed resulted in a round-trip path length of 381 μm. Other experimental details have been published elsewhere.[4]

A typical temperature trace is shown in Fig. 1. The steplike feature in the trace corresponds to the normal-to-superfluid transition. As the temperature is further decreased, a clear onset of oscillations is observed, corresponding to the disappearance of acoustic pair breaking. The oscillations themselves arise from a continuous change in the standing-wave pattern in the cell caused by a shift in the phase velocity of zero sound associated with the approach of the collective mode (to be discussed next); as we approach the SQ mode, the oscillations gradually die away because of the increased attenuation, and become closer together due to a more rapid change of the phase velocity.

The new phenomenon which we are reporting here is the doublet splitting observed at the SQ-mode peak. The behavior of this splitting has been studied for pressures in the range from 19.2 to 27.7 bars in zero magnetic field. Measurements with the magnetic field perpendicular to $\mathbf{q}$ (the sound propagation direction) were performed up to 1.36 kG at a single pressure of 27.3 bars. The doublet splitting of the SQ mode was observed in both zero and finite magnetic field; thus, there was no threshold value of the field required to produce the splitting and, furthermore, no substantial magnetic-field dependence of the splitting (at the fixed pressure of 27.7 bars) was observed below 1.36 kG.

A Lorentzian fit of the form

$$y=\frac{\beta\cos\phi}{(T-T_0)^2+(w)^2}+\frac{(\beta/w)(T-T_0)\sin\phi}{(T-T_0)^2+(w)^2} \qquad (1)$$

yields a good representation of the data; here T_0, w, and ϕ are, respectively, the peak position, the half width at half maximum (HWHM), and the phase of the detected signal. The area under a Lorentzian is given by $\pi\beta/w$. Figure 2 shows an example of a conventional nonlinear least-squares fit to a temperature sweep performed at a pressure of 19.2 bars with a sound frequency of 115.8 MHz in zero field. In order to best represent the splitting feature, the fit was performed in the range 1.51 to 1.55 mK, although the resulting curve is plotted over a

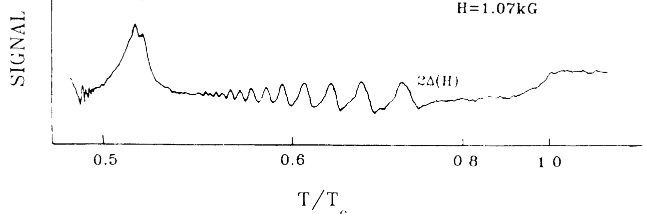

FIG. 1. Typical demagnetization traces of the acoustic impedance signal: $P=27.7$ bars, $f=141.6$ MHz, $H=1.07$ kG. The traces are taken as a function of time with the approximate temperatures as shown.

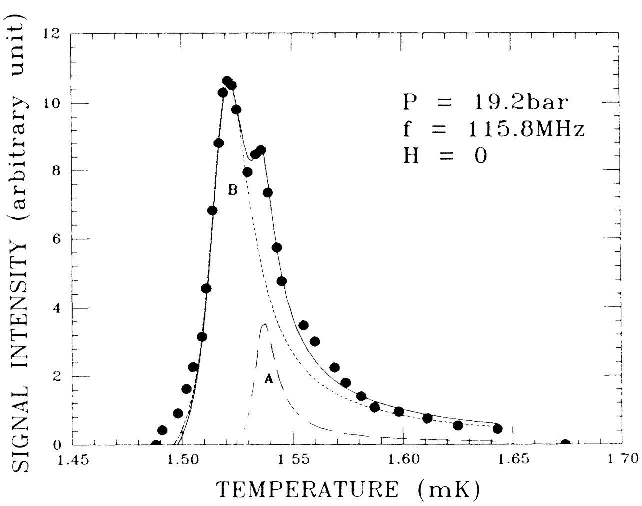

FIG. 2. A Lorentzian fit to the doublet splitting of the SQ mode. The fits to the two components of the collective mode, referred to as A and B, are shown as the dot-dashed and dashed lines, respectively. The solid line is the resultant curve. The experimental data are shown as solid circles.

wider temperature range. Two Lorentzian lines were assumed which are depicted by the dot-dashed line (A) and the dashed line (B). The resultant trace, shown as the solid line, is in reasonably good agreement with the experimental data, which are depicted by the solid circles. The fitting yields the following parameters: $\phi = 25.5°$,

$$\beta_A = 1.3\times10^{-4}, \quad T_{0A} = 1.533\ \text{mK},$$

$$w_A^{-1} = 1.73\times10^{2}\ \text{K}^{-1};$$

$$\beta_B = 13.7\times10^{-4}, \quad T_{0B} = 1.517\ \text{mK},$$

$$w_B^{-1} = 0.91\times10^{2}\ \text{K}^{-1}.$$

The coupling strength λ of the collective-mode components will be assumed to be proportional to the area under the corresponding Lorentzian; by this criteria the ratio of the coupling strength of these two components is $\lambda_A/\lambda_B \sim 0.18$. We emphasize that $T_{0A} > T_{0B}$, so that $\omega_{A(T)} > \omega_{B(T)}$ (for a given temperature), where ω_A and ω_B are respective frequencies of peaks A and B. Also, since peak A couples much more weakly than peak B with sound, peak A *cannot* be the $J_z = 0$ component of the SQ mode. Avenel *et al.*[5] have generated a model to interpret the acoustic impedance signal when only one of the SQ-mode components couples to zero sound; this model could be generalized. We adopted a Lorentzian form here for simplicity.

A pressure dependence of the zero-field splitting (using a sound frequency of 141.6 MHz) was observed and the results are plotted in Fig. 3(a). Clearly, the splitting increases as the pressure is increased. The T/T_c dependence of the splitting (at the frequency studied) is plotted in Fig. 3(b). Furthermore, the splitting near 27 bars

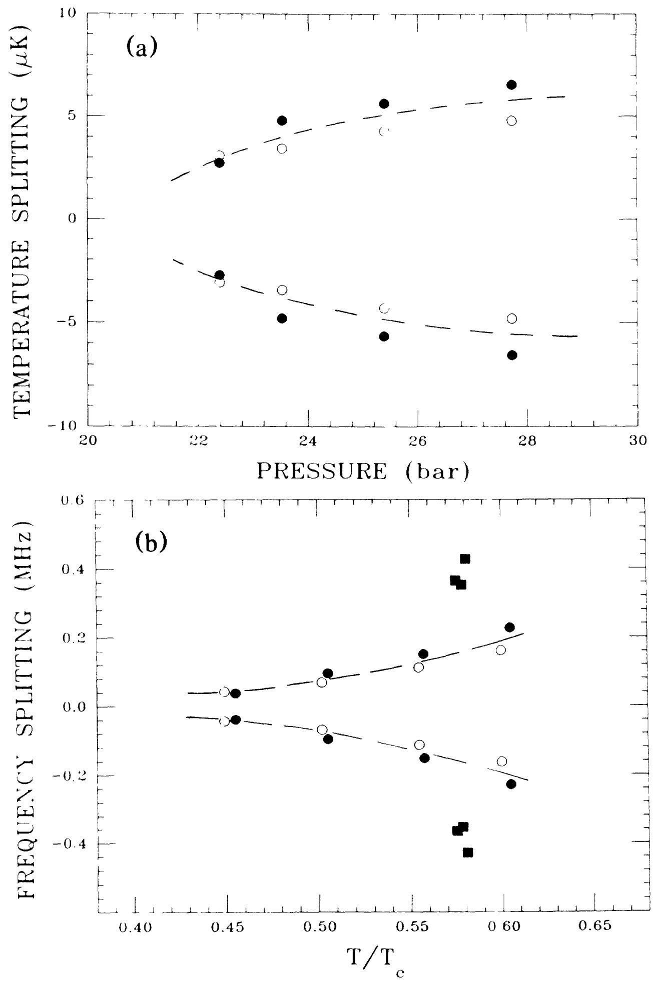

FIG. 3. (a) Pressure dependence of the width (in temperature) of the doublet splitting of the SQ mode, where $f = 141.6$ MHz and $H = 0$. The open (solid) circles are data taken during demagnetization (magnetization). The dashed lines are guides to the eye. (b) The measured temperature splitting [shown in (a)] is converted to a frequency splitting and plotted here against T/T_c (circles). The squares represent data taken from a different demagnetization of faster rate. The dashed lines are guides to the eye.

at $f = 141.6$ MHz was studied with two different demagnetization rates when the data were taken: 14 G/min (open circles) and 20 G/min (squares). The corresponding cooling rates are respectively ~ 6 and ~ 11 μK/min. Evidently, cooling with different rates causes different thermal gradients, and hence different heat flows inside the cell, which is basically a 7-in.-long cylindrical silver tube placed on the nuclear stage along the field direction. Therefore, Fig. 3(b) unambiguously tells us that the observed splitting increases with increasing thermal gradient inside the acoustic cell. This new feature of the SQ mode has not been resolved for sound frequencies of 90.1 and 64.3. MHz.

In short, the observed doublet splitting of the SQ mode is strongly pressure and thermal gradient dependent but independent of magnetic field (in the range studied).

It was unexpected that a doublet splitting rather than a threefold splitting was observed (as was the case for the dispersion-induced splitting for the real SQ mode[6]); for a total angular momentum of $J=2$ a threefold splitting would be induced by dispersion, superflow, or an electric field (which is not the case here).

There arise two possibilities: Either a twofold splitting has been observed or only two components of a threefold splitting have been resolved. Two arguments that would support the existence of a twofold splitting are (a) a texture effect induced by the restricted geometry, or (b) the possible existence of some other phase near the transducer interface. Fujita *et al.*[7] have shown that the B phase may evolve into a 2D phase, with an order parameter $A_{ij} \sim \Delta(T)(\delta_{i1}\delta_{j1}+\delta_{i2}\delta_{j2})$, close to a boundary. Calculations on the spectrum of the collective modes in such a 2D phase[8] show that part of the spectrum in the 2D phase is the same as in the A phase (e.g., the clapping mode, pair breaking, or the superflapping mode). It was estimated that the difference between the SQ mode in ^{3}He-B and the superflapping mode of the 2D phase is of the order of a few tens of μK at $T/T_c=0.7$. This is quite close to our experimental results.

A threefold splitting could arise from either dispersion-induced splitting (DIS) or superflow-induced splitting (SIS).[9,10] However, note the following two features of the DIS: The splitting decreases with increasing T/T_c and the mode spectrum has the ordering $\omega_0 > \omega_1 > \omega_2$, where the subscript is equal to $|J_z|$. Apparently these two features are contradictory to our observed results.

In the case of SIS, the superflow has a twofold effect on the order parameter: It aligns the direction of the vector $\mathbf{n}$ along the superflow velocity $\mathbf{V}_s$; it also leads to a gap distortion transverse, $\Delta_\perp^2=\Delta^2+\Omega^2$, and parallel, $\Delta_\parallel^2=\Delta^2+\alpha\Omega^2$, to the direction of superflow $\mathbf{V}_s$, where α and Ω^2 are functions of the superflow velocity and reduced temperature (T/T_c). The calculations performed by Brusov[10] and Nasten'ka and Brusov[11] give the following frequencies for the superflow-induced splitting of the SQ mode:

$$\omega_0^2=\frac{12}{5}\Delta^2+\frac{2\alpha+3}{2}\Omega^2, \quad J_z=0, \tag{2a}$$

$$\omega_1^2=\frac{12}{5}\Delta^2+\frac{6\alpha+11}{10}\Omega^2, \quad J_z=\pm 1, \tag{2b}$$

$$\omega_2^2=\frac{12}{5}\Delta^2+\frac{3(\alpha+3)}{5}\Omega^2, \quad J_z=\pm 2, \tag{2c}$$

where the branches of the SQ mode with $|J_z|=1,2$ couple to the zero sound via the texture which in this case is created by the simultaneous effect of superflow and restricted geometry.

In order to show the semiquantitative relation between the SIS values of the SQ mode and the reduced temperature T/T_c an estimate was made to span the temperature range $0.3 \le T/T_c \le 0.6$. Estimates have been made for two different V_s values for each fixed value of T/T_c. The results are listed in Table I and display the following features: (a) The frequency spectrum has the ordering $\omega_2 > \omega_1 > \omega_0$; (b) the splitting increases with increasing T/T_c for the same V_s; and (c) at fixed T/T_c the splitting increases with V_s, which, from the theory, should increase with increasing thermal gradient. Features (a) and (b) are probably unique to superflow. The agreement of all three features with the experimental results strongly suggests the superflow interpretation. In the case of SIS, there are two possible reasons for the observation of a doublet (rather than a threefold) splitting of the SQ mode: (a) The coupling between the sound and the $J_z=\pm 2$ component is too weak to observe; or (b) the $J_z=0$ and $J_z=\pm 1$ components are too close to resolve (which is not inconsistent with the very strong coupling observed for the B peak). Since we know the absolute values of neither the coupling strength nor the superflow velocity, we are unable to distinguish between these options.

TABLE I. The calculated values of the superflow-induced splitting of the SQ mode [$\Delta_{BCS}(0)=1.764k_BT_c$].

T/T_c	V_s (mm/s)	α	$\Omega^2/\Delta_{BCS}^2(0)$	$(\omega_2-\omega_0)/\Delta_{BCS}(0)$	$(\omega_1-\omega_0)/\Delta_{BCS}(0)$
0.3	14.8	−4.19	0.010(5)	0.0067	0.0043(5)
0.3	21.0	−2.00	0.059(5)	0.0220	0.0078
0.4	13.7	−2.25	0.024	0.0096	0.0039(9)
0.4	19.4	−1.86	0.087	0.0310	0.0101
0.5	12.6	−2.00	0.040	0.0150	0.0055
0.5	17.7	−1.94	0.110	0.0420	0.0146
0.6	11.2	−1.63	0.054	0.0188	0.0050
0.6	15.9	−1.84	0.114	0.0460	0.0144

In conclusion, we have observed a doublet splitting of the SQ mode which, most probably, should be ascribed to superflow. From the measured values of the splitting, it is possible to estimate the superflow velocity V_s. Since the superfluid velocity is a difficult quantity to measure directly, one might use the doublet splitting as a *probe* of the superfluid velocity in future experiments designed to study superflow-induced phenomena.[12] Our results strongly suggest that such experiments are now possible.

We would like to thank B. H. Lin and M. C. Shih for their help in the data fitting. This work was supported by NSF Grant No. DMR-89-07396.

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