The method of superfluid velocity measurement in He^3-B

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A doublet splitting of the squashing mode in $He^3 - B$, which has been observed recently, is connected with the existence of superflow. We estimate the value of this effect on the basis of the Brusov-Nasten'ka-Kleinert theory. The possibility of using the collective mode splitting as a measure of superfluid velocity is discussed.

In a recent letter[1] we discussed the structure of the ultrasound absorption spectrum of the squashing-mode (SQ) and suggested that this phenomenon is induced by superflow. In this paper we propose a method of determining the superfluid velocity using ultrasound: the order parameter collective mode splitting may be a measure of the superfluid velocity. The accuracy of the theoretical estimate in Ref. 1 is also increased.

The squashing-mode, which is one of the ^3He order-parameter collective modes, was discovered in 1974. This is a fivefold degenerate mode with an imaginary amplitude and a total angular momentum $J = 2$, which undergoes a fivefold Zeeman splitting,[2] and a threefold splitting with dispersion,[3–5] electric field,[6,7] or superflow.[8] Experimentally, only a Zeeman[2] and doublet[1] splitting have been observed. Note that the sound absorption in this mode is very high, which makes it difficult to observe the fine structure. For this reason, the dispersion-induced SQ-mode splitting, which has been predicted independently by Vdovin,[3] Maki,[9] Brusov,[4] and Popov,[4] has not been observed.

We have previously reported a study of the squashing-mode using the cw acoustic impedance techniques. The data to be reported here were obtained at frequencies of 115.8 MHz and 141.6 MHz.

A typical temperature trace is shown in Fig. 1. The step-like feature in the trace corresponds to the normal to the superfluid transition. A further decrease in the temperature gives rise to oscillations which correspond to the disappearance of acoustic pair breaking. The oscillations themselves arise from a continuous change in the standing wave pattern in the cell, which is 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 decay because of the increased attenuation, and draw closer together due to a more rapid change of the phase velocity.

The new phenomenon was the doublet splitting observed at the SQ-mode peak.

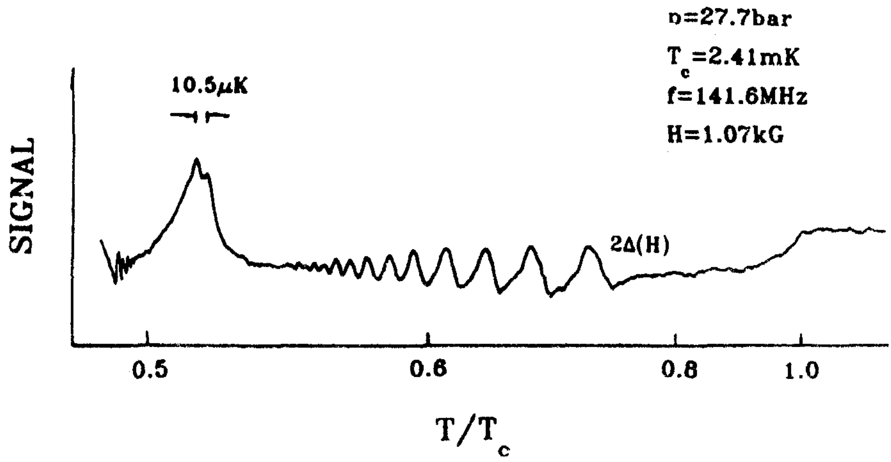

FIG. 1.

The behavior of this splitting was studied at pressures in the range from 19.2 bar to 27.7 bar in a zero magnetic field. Measurements in a magnetic field perpendicular to $\vec{q}$ (the sound propagation direction) were performed up 1.36 kG at a pressure of 27.3 bar. The doublet splitting of the SQ was observed in a zero field and a finite magnetic field; thus there was no threshold value of the field required to produce the splitting and no substantial magnetic field dependence of the splitting (at a fixed pressure of 27.7 bar) was observed below 1.36 kG.

A pressure dependence of the zero field splitting (using a sound frequency of 141.6 MHz) which increased with increasing pressure, was observed. The T/T_c dependence of the splitting (at the frequency studied) is plotted in Fig. 2. The splitting near 27 bar at $f =$ 141.6 MHz was studied at two different demagnetization rates: 14 G/min (circles) and 20 G/min (squares). Evidently, cooling with different rates causes different thermal gradients, and hence different heat fluxes inside the cell, which is basically a 7-inch-long cylindrical silver tube placed in the nuclear stage along the field direction. Therefore, Fig. 2 unambiguously shows 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 MHz and 64.3 MHz.

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

It was surprising to see that a doublet splitting rather than a threefold splitting would be observed (as was the case for the dispersion-induced splitting for the RSQ mode); for a total angular momentum $J = 2$ a threefold splitting would be induced by dispersion, superflow, or an electric field.

There are two possibilities: either a twofold splitting is observed or only two components of a threefold splitting are resolved. Two arguments that would support the existence of a twofold splitting are: a) a texture effect induced by the restricted

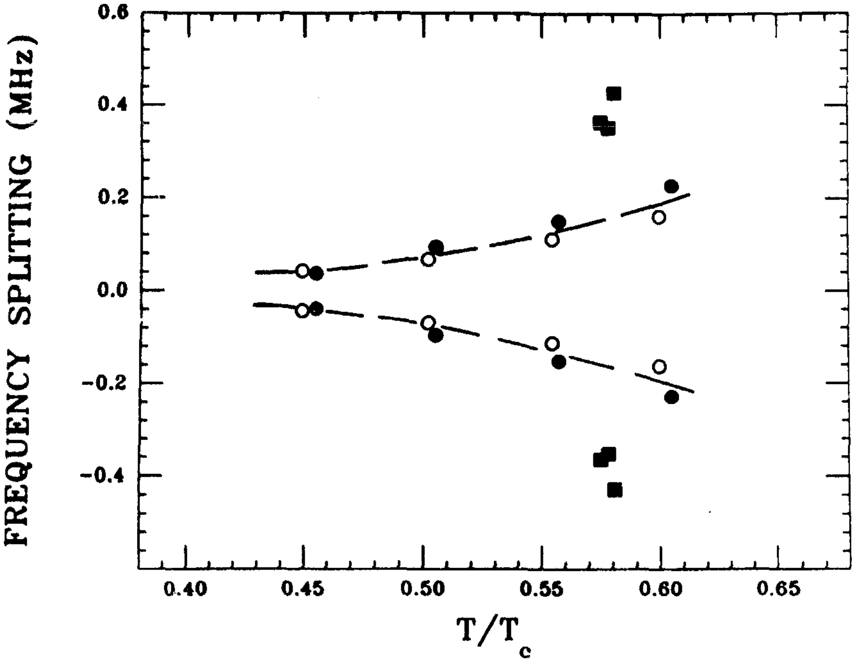

FIG. 2.

geometry or b) the possible existence of some other phase near the transducer interface. Fujita *et al.*[13] have shown that the *B* phase may evolve into a 2 *D* phase, with the order parameter $A_{ij} \sim \Delta(T)(\delta_{i1}\delta_{i1} + \delta_{i2}\delta_{j2})$ close to the boundary. Calculations on the spectrum of the collective modes in such a 2*D* phase[6] show that part of the spectrum in the 2*D* phase is the same as 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 2*D* phase is of the order of a few tens of μK at $T/T_c = 0.7$, in good agreement with our experimental results.

A threefold splitting could arise from either the dispersion-induced splitting (DIS)[3,4,9] or superflow-induced splitting (SIS).[8,11] 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 $|J_z|$. Clearly, these two features contradict 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 $\vec{n}$ along the superflow velocity, $\vec{V}_\perp^s$, and it leads to a gap distorion transverse, $\Delta^2 = \Delta^2 + \Omega^2$, and parallel, $\Delta_\parallel^2 = \Delta^2 + \alpha\Omega^2$, to the direction of superflow, $\vec{V}_s$, where α and Ω^2 are functions of the superflow velocity and reduced temperature (T/T_c). The calculations performed by Brusov[8] and Nasten'ka and Brusov[13] 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 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 semi-quantitative relation between the SIS values of the SQ mode and the critical temperature T/T_c, an estimate was made to span the temperature range $0.3 \leqslant T/T_c \leqslant 0.6$. Estimates have been performed for two different V_s values for each fixed value of T/T_c. The results listed in Table I reveal 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; both behaviors are probably unique to superflow; and c) at fixed T/T_c the splitting increases with V_s, which, from the theory, should increase with increasing thermal gradient. The agreement of these three features with the experimental results strongly suggests that the superflow interpretation is correct. In the case of *SIS*, there are two possible reasons for the observation of a double (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 be observed or (b) $J_z = 0$ and $J_z = \pm 1$ components are too close to resolve.

The coupling strength of the $|J_z| = 2$ modes with sound is not known, so we cannot address the first possibility. But from Table I we can conclude that the second possibility seems very likely, because ω_1 and ω_2 are quite close to each other. (We were unable to make this conclusion in our previous Letter[1] due to inaccuracy in the numerical estimates.)

TABLE I. Calculated values of the superflow-induced splitting of the SQ mode.

T/T_c	V_s (mm/s)	α	$\frac{\Omega^2}{\Delta^2_{BCS}(0)}$	$\frac{\omega_2\omega_0}{\Delta_{BCS}(0)}$	$\frac{\omega_1\omega_0}{\Delta_{BCS}(0)}$
0.3	14.8	-21	0.003	0.008(5)	0.007(8)
0.3	21.0	-6.7	0.024	0.023	0.017(7)
0.4	13.7	-12	0.006	0.010	0.008(7)
0.4	19.4	-6.5	0.036	0.034	0.026
0.5	12.6	-12.5	0.010	0.020	0.015(9)
0.5	17.7	-16.25	0.020	0.044	0.040(6)
0.6	11.2	-33.5	0.004	0.019	0.018(4)
0.6	15.9	-19.25	0.016	0.038	0.036

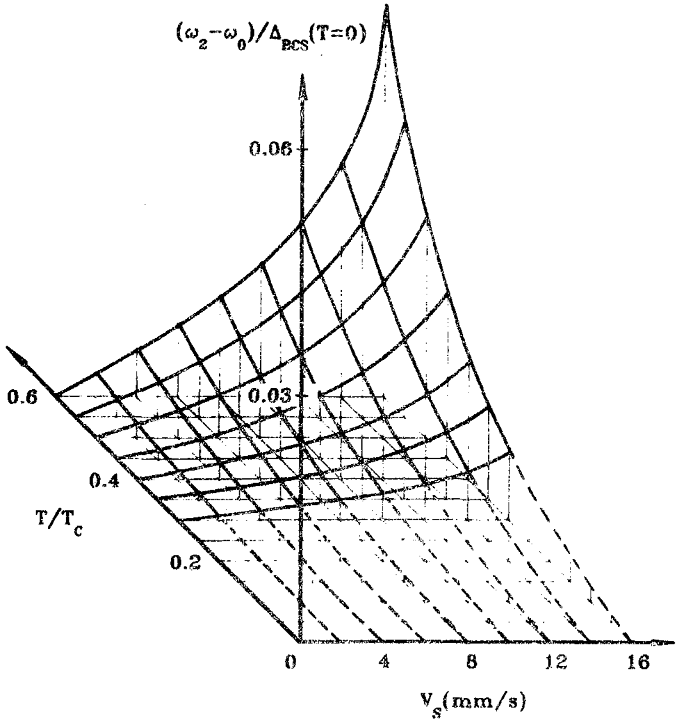

FIG. 3.

In conclusion, we note that the SQ mode splitting can be used as a measure of the superfluid velocity V_s, which is not easy to obtain. Using broad-band, piezoelectric, plastic-film transducers, one is not restricted to odd harmonics of the fundamental transducer resonance frequency; i.e., one may monitor the superflow velocity continuously as a function of thermal gradient, pressure, and temperature. The frequency would be swept through the (split) resonance and the response monitored via a nonresonant, acoustic-impedance technique. Figure 3 can be used to determine the dependence of the maximum splitting, $\Delta\omega_{2-0}$, on T/T_c and on the superfluid velocity, V_s, (obtained from the Brusov-Nasten'ka-Kleinert theory). Measuring the splitting and knowing the temperature, it is easy to find superfluid velocity. For example, for the splitting obtained in our experiment the value of superfluid velocity turns out to be of order 1.7 *mm/s*–3 *mm/*3 (at $T/T_c = 0.45$ and $T/T_c = 0.6$, respectively). Note that our experiments are performed at finite $\vec{q}$ (the sound propagates perpendicular to the thermal gradient), while the theory is presently limited to $q = 0$; the theory is presently being extended to finite q, which will allow a more accurate comparison with experiment.

Note that there is some uncertainty in the values of V_s obtained, because we do not know which branch of the SQ mode ($|J_z| = 1$ or $|J_z| = 2$) contributes the second attenuation peak. These modes are very close to each other (as can easily be seen from Table I), and thus the uncertainty is not high.

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