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 within 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 phenomena is induced by superflow. In this paper we propose a method to determine the superfluid velocity using ultrasound: the order parameter collective mode splitting may be as 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 ^{3}He order parameter collective modes, was discovered in 1974. This is a file fold degenerate mode with an imaginary amplitude and a total angular moment $J = 2$. It undergoes a 5-fold Zeeman splitting [2], and a three-fold 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 into this mode is enormously high which makes it difficult to observe the fine structure. For this reason the dispersion induced sq-mode splitting, which has been predicted by independently Vdovin [3], Maki [9] and Brusov and Popov [4] has not been observed.

We previosly reported a study of the SQ mode ising the c.w. acoustic impedance techniques. The data to be reported here were taken 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 superfiuid transition. As the tempereture 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 phenomena was the doublet splitting observed at the SQ mode peak. The behavior of this splitting has been studied for pressures in the range from

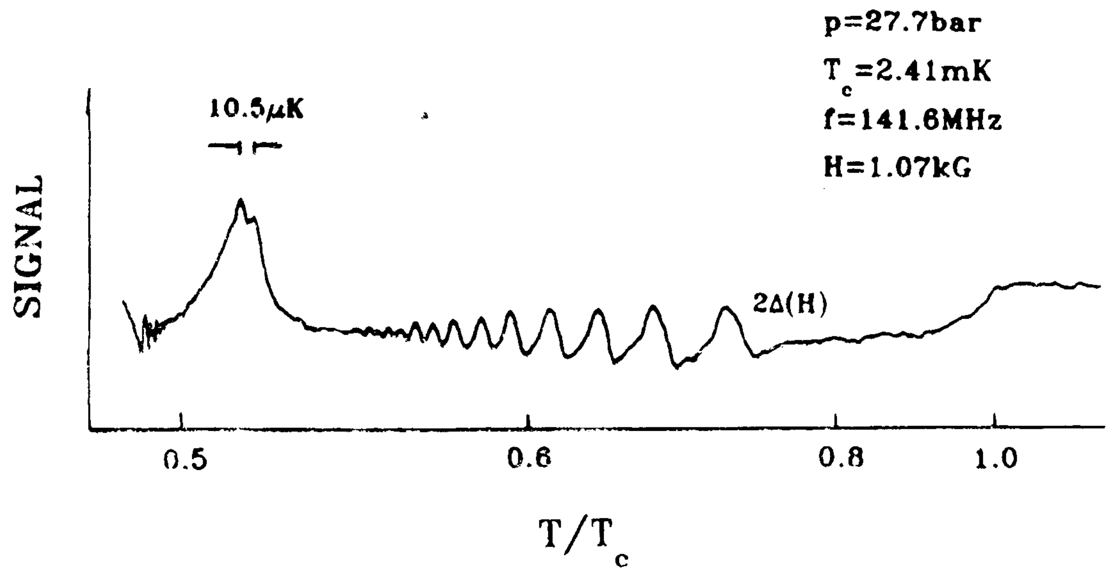

Fig.1

19.2 bar to 27.7 bar in zero magnetic field. Measurements with the magnetic field perpendicular to $\vec{q}$ (the sound propagation direction) were performed up 1.36 kG at a single pressure of 27.3 bar. The doublet splitting of the SQ 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 bar) was observed below 1.36 kG.

A pressure dependence of the zero field splitting (using a sound frequency of 141.6 MHz) was observed, the splitting increases as the pressure is increased. 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 with two different demagnetization rates: 14 Gauss per min (circles) and 20 Gauss per min (squares). Evidently, cooling with different rates causes different thermal gradients, and hence different heat flows inside the cell, which is basically a 7 inch long cylindrical silver tube placed on the nuclear stage along the field direction. Therefore, Fig.2 unambiguously tells us that the observed splitting increases with the increasing thermal gradient inside 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 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 three-fold splitting would be observed (as was the case for the dispersion induced splitting for the RSQ mode); for a total angular momentum of $J = 2$ a three-fold splitting would be induced by dispersion, superflow or an electric field.

There arise two possibilities: either a two-fold splitting has been observed or

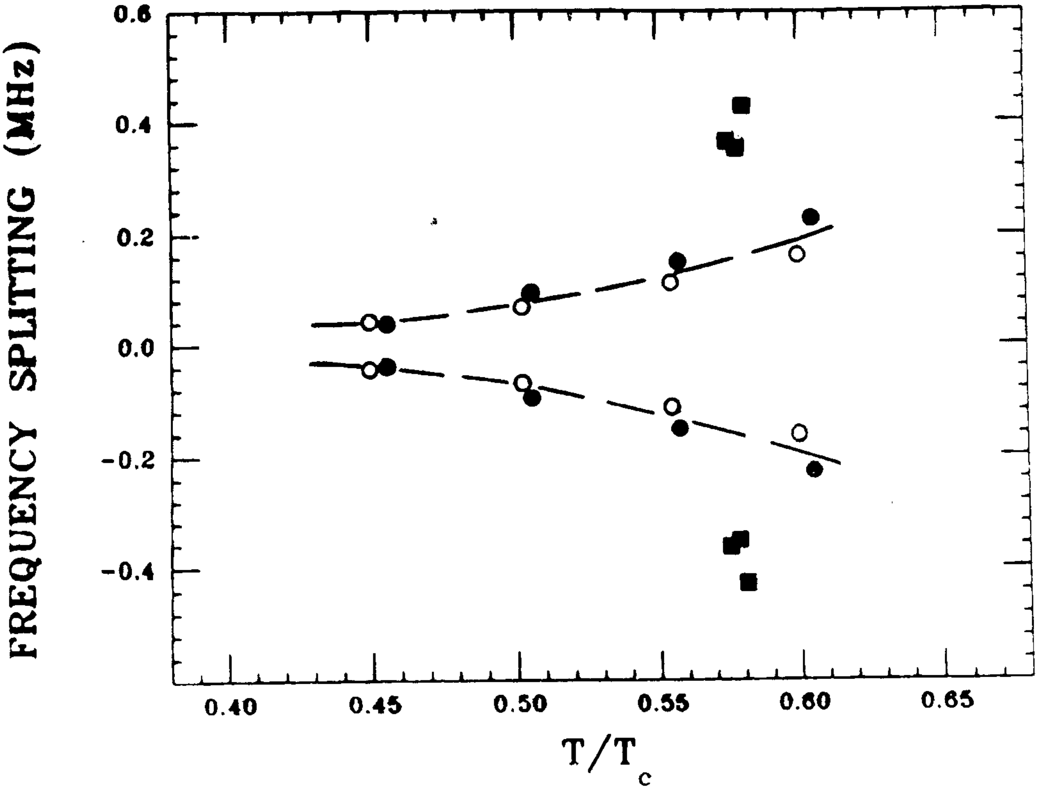

Fig.2

only two components of a three-fold splitting have been resolved. Two arguments that would support the existence of a two-fold 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. [13] 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 [6] show that part of the spectrum in the $2D$-phase is the same as the same as the A-phase (e.g. the clapping mode, pair-breaking or the super-flapping mode.) It was estimated that the difference between SQ mode in ^{3}He-B and the super-flapping-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 three-fold splitting could arise from either 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 $|J_z|$. Apparently these two features are contradictory to our observed results.

In the case of SIS, the superflow has a two-fold effect on the order parameter: it aligns the direction of the vector $\vec{n}$ along the superflow velocity, $\vec{V}_s$; it also leads to a gap distorion transverse, $\Delta_\perp^2 = \Delta^2+\Omega^2$, 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'rf and Brusov [13] give the following frequencies for the superflow induced splittinf of the SQ mode

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

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

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

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 $0.3 \leq T/T_c \leq 0.6$. Estimates have been performed for two different V_s values for each fixed value of T/T_c. The results are listed in Table and display the followinf 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 the superflow interpretation. In the case of SIS, there are two possible reasons for the observation of a doublet (rather than a three-fold) 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) $J_z = 0$ 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 the Table 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 numerical the estimates).

In conclusion we note that the sq-mode spliting can be used as a measure of the superfluid velcosity V_s, which is not readily obtainable. Using broad-band, piezoelectricplastic-film transducers, one is not restricted to odd harmonics of a 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 non-resonant, acoustic-impedance technique. Fig. 3 may be used to obtain the dependence of the maximum splitting, $\Delta\omega_{2-0}$, on T/T_c and the superfluid velocity, V_s, (obtained from 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 $1.7\frac{mm}{s} \div 3\frac{mm}{s}$ (at $\frac{T}{T_c} = .45$ and $\frac{T}{T_c} = .6$ respectively). Note that our experiments are performed at finite $\vec{q}$ (the sound propagates perpendicular to the thermal graident) while the theory is presently

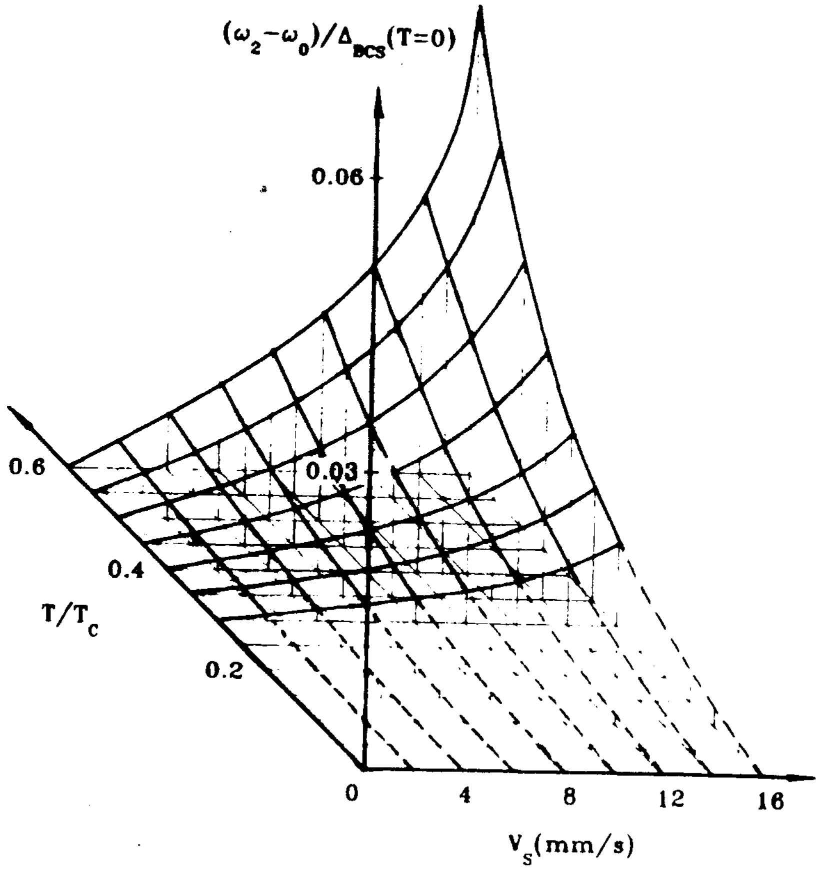

Fig.3

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 V_s values obtained, because we do not know which branch of the sq-mode ($|J_z| = 1$ or $|J_z| = 2$) contributs the second attenuation peak. These modes are very close to each other (as easily seen from Table) and thus the uncertainty is not high.

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The 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

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