Ultrasonic Spectroscopy of the $J=1^-$ Collective Mode in Superfluid ^{3}He-B

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Measurements of the attenuation of zero sound in superfluid ^{3}He-B show coupling to a collective mode in applied magnetic fields at frequencies $\nu \simeq 2\Delta(T)$, which is identified as the $J=1^-$ mode. The attenuation as a function of reduced temperature in zero magnetic field is subtracted from that measured in magnetic fields up to 80 mT to reveal both the $J_z=+1$ and $J_z=-1$ components. The measured g factor is in good agreement with theory. The $J_z=+1$ resonance occurs in the pair-excitation continuum and subtracts from the total attenuation, resulting in an antipeak.

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The structure of the order parameter of superfluid ^{3}He allows it to support a variety of order-parameter collective modes, some of which may be studied via their coupling to zero sound.[1] In the B phase in zero magnetic field, the superfluid energy gap $\Delta(T)$ is isotropic and Cooper pairs may only be excited if the zero-sound frequency ν exceeds $2\Delta(T)$. The existence of a sharp cutoff in this pair-breaking continuum at $\nu=2\Delta(T)$ implies that the collective modes, with $\nu=a_i\Delta(T)$ and $a_i<2$, are well defined, but broadened by collisions. In the B phase, these collective modes are classified[2] according to their total angular momentum $J=0,1,2$ and according to whether the oscillations occur in the real or imaginary part of the order parameter, denoted by a superscript (plus or minus, respectively). The squashing mode $J=2^-$ has predicted eigenvalue $a_{\mathrm{sq}}=\sqrt{\frac{12}{5}}$ in the absence of interaction effects and couples strongly to zero sound. The real squashing mode $J=2^+$ has predicted eigenvalue $a_{\mathrm{rsq}}=\sqrt{\frac{8}{5}}$ and couples weakly through particle-hole asymmetry.[3] These two modes have been extensively studied.[4] These eigenvalues have corrections which depend on the strength of Fermi-liquid interactions and $l=3$ pairing fluctuations, which result in a_{sq}, a_{rsq} being temperature dependent. The interpretation of measurements of the eigenvalues relies heavily on assumptions concerning the temperature scale. The application of external magnetic fields has provided an invaluable tool for the characterization of these modes. At low magnetic fields the $J=2^+$ mode splits linearly into $2J+1=5$ components.[5] This splitting becomes nonlinear at high fields as a result of the field-induced gap distortion.[4]

In contrast, the pair-breaking attenuation and the region $\nu \sim 2\Delta$ have been very little studied. These measurements require frequencies comparable to the gap frequency in order to achieve adequate temperature resolution between the pair-breaking feature and the squashing mode. The maximum pair-breaking acoustic attenuation is typically of order 100 cm^{-1} at low pressure and at frequencies 30–50 MHz, so that the most suitable technique is to measure the attenuation in transmission with a short path length. In this Letter we describe measurements at $\nu \sim 2\Delta(T)$ of the $J=1^-$ mode, and show that it couples to zero sound only in the presence of a magnetic field. We have measured the attenuation from both of the $J_z=\pm 1$ components of the mode, and so determined the Landé g factor. The $J_z=+1$ component has $\nu>2\Delta$, so that it lies in the continuum, and produces a decrease in the acoustic attenuation (an "antipeak") in this region, which we have now observed.

The experimental procedure is to measure the attenuation relative to its value at T_c as a function of the reduced temperature T/T_c in zero magnetic field, and in various applied magnetic fields up to 80 mT. The sound is generated by a 5-MHz fundamental quartz crystal separated by a 250-μm-thick quartz ring spacer, containing superfluid, from a Z-cut quartz delay rod. At the other end of this rod the sound is detected by a thin-film cadmium sulfide transducer. The magnetic field is applied perpendicular to the sound propagation direction by a solenoid located in the helium bath. The temperature is measured by a melting-curve thermometer placed in a field-compensated region. Thermal contact between the thermometer and the liquid ^{3}He in the cell is made through silver wires sintered to a heat exchanger of surface area 20 m^2. The temperature scale that we have adopted in this work to generate reduced temperatures is the melting-curve scale of Halperin, Rasmussen, Archie, and Richardson.[6] The T_c values of Greywall,[7] determined by melting-curve thermometry and adjusted[8] to $T_A=2.49$, have been used. There is currently some disagreement over the relationship between this scale, the platinum NMR scale, and absolute temperature,[8,9] but this is not important for most of the physics discussed in this Letter.

The acoustic attenuation was measured as a function of reduced temperature and magnetic field in the B phase at a pressure of 3.9 bars with use of frequencies of 34.2, 44.2, and 54.0 MHz. Data in a series of magnetic fields, with a measuring frequency of 44.2 MHz, are plotted in Fig. 1. These show an intense peak whose maximum is not observed, due to the squashing mode,

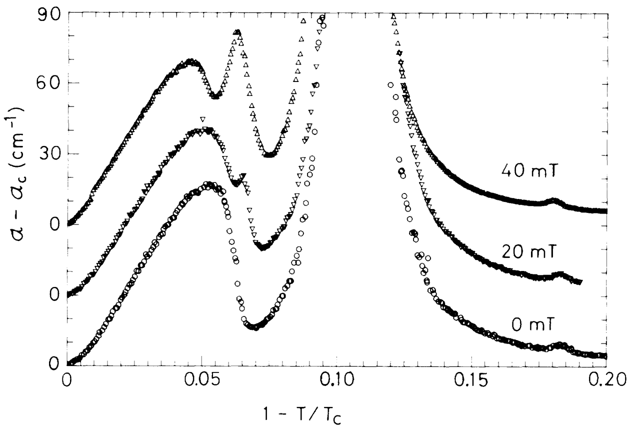

FIG. 1. Acoustic attenuation relative to its value at T_c as a function of reduced temperature at frequency 44.2 MHz and pressure 3.9 bars in applied magnetic field 0 mT (circles), 20 mT (inverted triangles), and 40 mT (triangles). Data are plotted with shifted zeros.

and a small peak at $T/T_c \simeq 0.82$ due to the real squashing mode. In addition, the field dependence of the attenuation close to T_c reveals a third peak, which increases in intensity and broadens when the magnetic field is increased, as we reported previously.[10] With thermometry of improved sensitivity and reproducibility, we can now subtract the attenuation data measured in zero field from that in a magnetic field at the same pressure and frequency. An example of data which have been treated in this way is given in Fig. 2, where measurements made at 44.2 and 54.0 MHz are shown. The peak-antipeak structure is interpreted as resulting from the field splitting of the $J=1^-$ collective mode. This is clearly shown: The $J_z=-1$ component appears as a positive contribution to the attenuation, whereas at $\nu > 2\Delta(T)$ there is a negative contribution to the total attenuation due to the $J_z=+1$ component. As well as the field splitting, the data show a superimposed shift of the peaks to higher temperatures. With our experimental procedure, we are not sure whether this is a real effect or a systematic dependence of apparent reduced temperature on magnetic field.

We assume that the only field-dependent contribution to the attenuation comes from the $J=1^-$ mode. By clearly identifying both of the $J_z=\pm 1$ components, we can determine the g factor of the mode. If the observed reduced temperatures of the peak and antipeak are denoted by t_- and t_+, respectively, then the reduced frequency splitting of the $J_z=\pm 1$ components is $\delta(\Delta/\Delta_0)=[\Delta(t_-)-\Delta(t_+)]/\Delta_0$, where Δ_0 is the BCS gap at $T=0$. This is related to the g factor through $g=(\Delta_0/\Omega)\delta(\Delta/\Delta_0)$. We assume that the reduced energy gap $\Delta(t)/\Delta_0$ is of the BCS form as tabulated by Mühlschlegel.[11] The reduced frequency splitting $\delta(\Delta/\Delta_0)$ is shown as a function of magnetic field in Fig.

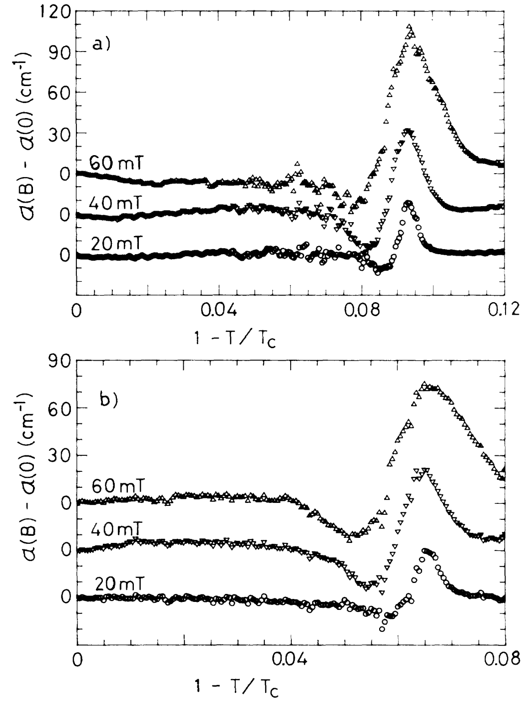

FIG. 2. Temperature dependence of the difference between acoustic attenuation measured in applied field, $\alpha(B)$, and that measured in zero field, $\alpha(0)$, for applied fields 20 mT (circles), 40 mT (inverted triangles), and 60 mT (triangles), and at sound frequency (a) 54.0 MHz and (b) 44.2 MHz. Data for the three fields are plotted with shifted zeros.

3. Nonlinear effects in the Zeeman splitting are not apparent within the scatter of the data.

Following our first observation[10] of field-dependent structure in the vicinity of $\nu \simeq 2\Delta(T)$, Schopohl and

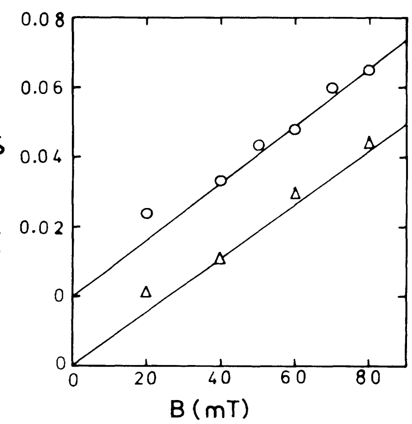

FIG. 3. Frequency splitting of the $J_z=\pm 1$ components, $\delta(\Delta/\Delta_0)$, as a function of applied magnetic field B, at frequencies 44.2 MHz (circles) and 54.0 MHz (triangles) (shifted zeros). The theoretical prediction is also shown at both frequencies (see text).

Tewordt[12] showed that the $J=1^-$ mode couples to zero sound in the presence of a magnetic field and calculated the Zeeman splitting. The coupling is driven by the field-induced gap anisotropy, the field dependence of the coupling strength being contained in a factor $(\Delta_1-\Delta_2)^2\Gamma^{-1}$, where Δ_1 and Δ_2 are the energy gaps perpendicular and parallel to the field direction, respectively, and Γ is the linewidth of the mode. This coupling factor is proportional to Ω^3 where Ω is the renormalized Larmor frequency given by $\Omega=\gamma B[1+\frac{1}{3}F_0^a(2+Y)]^{-1}$, γ is the gyromagnetic ratio, B is the magnetic field, Y the Yosida function, and F_0^a a Landau parameter. The prediction of this theory that the $J_z=0$ component of $J=1^-$ does not couple is confirmed by our data. Further, the $J_z=+1$ component is predicted to produce an antipeak, which we have now observed. The frequencies of the $J_z=\pm 1$ components of the mode are $\nu=2\Delta \pm g\Omega$, where the g factor takes the theoretical value of 0.392. The predicted linewidth is $\Gamma=0.178\ \Omega$. The experimental values of the g factor obtained from a linear fit to the 44.2- and 54.0-MHz data in Fig. 3 are 0.40 and 0.41, respectively. The straight lines shown in the figure are the theoretical Zeeman splittings, evaluated with F_0^a taken from Greywall.[8] For the 44.2-MHz data at $T/T_c\simeq 0.94$ the theoretical splitting of the components $(g\Omega/B)$ is 42.3 MHz T^{-1}, which may be compared with typical frequency splittings for the real squashing mode[4] of order 10 MHz T^{-1}. The measured linewidth of the $J_z=-1$ component is proportional to applied field as predicted, but is significantly larger. The physical origin of the linewidth is damping of the mode by the excitation of pairs. In a magnetic field, the pair-breaking threshold is shifted[13] from 2Δ to $2\Delta_2-\Omega$, or $2\Delta-\Omega$ to first order in Ω, and this frequency always lies below that of the $J_z=-1$ component.

However, a number of qualitative features of the data are in disagreement with the theoretical predictions: (i) The attenuation maximum of the $J_z=-1$ component increases in proportion to Ω over the field range studied, rather than the predicted Ω^3 dependence; (ii) although the absolute value of the peak attenuation of the $J_z=+1$ component "antipeak" increases initially with magnetic field, it appears to saturate at higher fields; (iii) the theory also predicts a positive contribution to the attenuation due to the $J_z=+1$ component at temperatures higher than the antipeak. Schopohl[14] has suggested that this is an analog to the Fano[15] resonances observed in atomic spectra. There is possibly some indication of a positive contribution in the data, but the procedure of subtracting attenuation data of two separate runs is not of sufficient accuracy for us to be certain of this observation. However, we do not find a positive contribution of the size predicted,[12] which would be observable. We note that Schopohl and Tewordt[12] assumed that the $\hat{\mathbf{n}}$ vector was oriented parallel to the magnetic field, which is not the case in our experiment. This and the nonuniformity of our sample texture may have influenced the observed field dependence of the coupling to the modes.

The validity of the subtraction procedure we have adopted to reveal the $J_z=\pm 1$ peak and antipeak clearly relies on assumptions concerning the other attenuation processes in the vicinity of 2Δ. The field dependence of the pair-breaking attenuation has yet to be calculated. This includes contributions from the $J=0^-,2^-$ modes which may be field dependent at $\nu>2\Delta$. There are also other collective modes coupling to zero sound that may contribute in the region $\nu\simeq 2\Delta$. The $J=0^+$ mode couples to sound via particle-hole asymmetry and has frequency $\nu=2\Delta$ in zero field at $q=0$, independent of Fermi-liquid corrections. Its frequency has been predicted to shift down with increasing magnetic field.[16] There is also the possibility of a $J=4^-$ mode at frequency close to 2Δ resulting from $l=3$ pairing fluctuations.[17] In our earlier observations of structure at the pair-breaking edge,[18] we had conjectured that the $J=4^-$ mode might be responsible. There is no evidence of coupling to these modes in our new data. The distinct peak-antipeak structure observed in this work leads us to conclude that the field-dependent attenuation near 2Δ is dominated by the $J=1^-$ mode. Observation of the possible $J=4^-$ mode would therefore appear to be difficult.

We now return to a discussion of the acoustic attenuation for $\nu>2\Delta$. This has recently been reformulated in a physically transparent way by Kopp and Wölfle.[19] In this treatment, transitions between the ground state and excited states of a Cooper pair are described in terms of Bloch equations. The time-varying field inducing such transitions consists of a sum of terms resulting from density fluctuations, current-density fluctuations, and order-parameter fluctuations, the latter tending to rotate the Bloch vector in an opposite sense. As a result of the $J=0^-$ excitations of the gap field, terms up to first order in v_F/c_1 cancel, where v_F is the Fermi velocity and c_1 the velocity of first sound. The $J=2^-$ squashing mode must then also be included, since this couples to order $(v_F/c_1)^2$ to density and this partially cancels out the other mean fields. The form of the attenuation due to the excitation of Cooper pairs thus results from a series of cancellations between the various mean fields with both the $J=0^-$ and $J=2^-$ modes tending to reduce the attenuation for $\nu>2\Delta$. Although the $J=1^-$ mode has not so far been included in this formulation, it would seem plausible that a negative contribution to the total attenuation is a general feature of all order-parameter fluctuations for $\nu>2\Delta$. The observation of the "antipeak" of controllable intensity in this experiment is a direct manifestation of this phenomenon. As has been indicated, the form of the attenuation due to excitation of Cooper pairs results in part from negative contributions to total attenuation from the $J=0^-$ and 2^- modes. It is therefore of interest to compare with theory the pair-breaking contribution to the attenuation measured in zero magnetic field, using the measured attenuation maximum at 34.2 MHz in the normal Field liquid to scale the attenuation data. At a pressure of 3.9 bars, where the corrections due to F_2^s (taking values measured by Engel and Ihas[20]) are a few percent, we find good agreement between the collisionless expressions given by Wölfle[21] and the measured values at 34.2, 44.2, and 54.0 MHz using the temperature scale adopted here. Details of these measurements and the use of the pair-breaking attenuation as a measure of $\Delta(T)$ to determine the eigenvalues of the squashing and real squashing modes in a way largely independent of temperature scale will be published elsewhere.[22]

The interaction of a discrete state with a continuum is a well-known phenomenon in atomic physics (Fano resonance). Mixing of the discrete state with the continuum states leads to interference effects which may result in a variety of line shapes, depending on the matrix element of the pure discrete line.[23] It may be that direct analogs occur in the superfluid system, corresponding to mixing between the excited pair states and the discrete $J=1^-$, $J_z=+1$ state and subject to lifetime restrictions. If so, this would constitute a form of macroscopic quantum interference. The superfluid states differ from atomic states in allowing negative absorption strength for gap fluctuations at $\nu > 2\Delta$, resulting in an antipeak, such as we have observed. On the other hand, direct observation of both positive and negative contributions to the total sound attenuation from the $J_z=+1$ component of the $J=1^-$ mode would be evidence of interference effects.

In conclusion, we have described the first direct experimental evidence of an order-parameter collective-mode resonance at $\nu > 2\Delta$ in the B phase, identified the $J=1^-$ mode through its field-dependent coupling to zero sound, and measured its g factor.

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