Nonlinear Zeeman Shifts in the Collective-Mode Spectrum of ^{3}He-B

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Zeeman shifts in one of the $J=2$ order-parameter collective-mode multiplets in ^{3}He-B have been measured in magnetic fields up to 0.16 T. The observed shifts are extremely nonlinear at higher fields. The extent of nonlinearity decreases as $T/T_c \to 0$ and for a given T/T_c is more predominant at lower pressures and/or frequencies. The observed effects can be attributed to the distortion of the B-phase energy gap in the presence of a magnetic field as suggested by Schopohl, Warnke, and Tewordt.

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The ground state in superfluid ^{3}He has Cooper pairs in an $l=1$, $s=1$ paired state.[1] The tensorial order parameter that results has eighteen independent components. An equal number of collective modes, associated with fluctuations in these components, have been predicted to occur in both the A and B phases.[2] Various features of the collective modes have been observed which are reminiscent of phenomena in atomic physics. The collective modes viewed as excited states of the Cooper pairs may be assigned total angular momentum quantum numbers, J.[2,3] In the B phase there are two $J=2$ modes which have been observed in zero-sound experiments, the squashing mode[4] and the real squashing mode (rsq mode).[5] The predicted[6] fivefold Zeeman splitting of the rsq mode, corresponding to the five values of J_z, was first observed in pulsed-transmission studies in magnetic fields less than 50 mT.[7] Recently we reported measurements using a high-resolution acoustic impedance technique which revealed a "doublet structure" in the $J_z=0$ component of the rsq mode.[8] This structure becomes apparent only in the low-temperature limit, $T \to 0$.

In this Letter we report new measurements, using the same acoustic impedance technique, on the magnetic field evolution of the rsq mode in the other temperature limit, $T \to T_c$. We have discovered a strong nonlinear evolution of the rsq-mode states in large fields. The extent of nonlinearity increases as $T \to T_c$. For a given T/T_c the nonlinear effects are stronger at lower pressures and/or frequencies.[9] It has been suggested by Schopohl, Warnke, and Tewordt that these results can be attributed to the distortion of the B-phase energy gap in the presence of a magnetic field and correspond to the onset of a Paschen-Back regime in the field evolution of the rsq mode.[10]

Our cryogenics and thermometry have been described previously.[5,11] Nuclear cooling of copper wires was used to obtain temperatures down to 0.4 mK. Temperatures in the ^{3}He were determined by measuring the magnetic susceptibility of lanthanum cerium magnesium nitrate calibrated against a Pt NMR thermometer. The acoustic cell, made of silver, has two X-cut 12.7-MHz transducers separated by a 4-mm quartz spacer. Measurements reported here were made at 38.24 MHz around 1 bar and 63.77 MHz around 7 bars. Magnetic fields up to 0.16 T perpendicular to the sound propagation direction could be ramped up and down without significant warming of the superfluid.[12] Our continuous-wave acoustic impedance technique, which has been described earlier,[8,11,13] consists of applying a frequency-modulated radio-frequency signal to a transducer in contact with the ^{3}He. The electrical signal reflected from the transducer is nulled in a bridge circuit. Changes in the acoustic impedance that occur in the vicinity of a collective mode cause readily detectable anomalies in this reflected signal. The mode positions are taken to be the centers of the anomalies.[8]

The Zeeman effect in ^{3}He-B, or the linear field evolution of the collective-mode states, was predicted to occur for $H < 0.1$ T.[6] Earlier measurements[7,8,14] confirming this prediction were done either in small applied magnetic fields ($H < 50$ mT) or at low T/T_c. On extending these measurements to higher temperatures and larger magnetic fields we find an extremely nonlinear evolution of the states, shown in Fig. 1(a).[15] The nonlinearity is clearly evident for $H > 0.1$ T. For the data shown in Fig. 1(a), there is a mode crossing between the $J_z=-1$ and $J_z=-2$ states in a field of 0.14 T. In addition the $J_z=0$ state shifts from its zero-field position in large magnetic fields. This can be determined less accurately than the splittings themselves and is shown

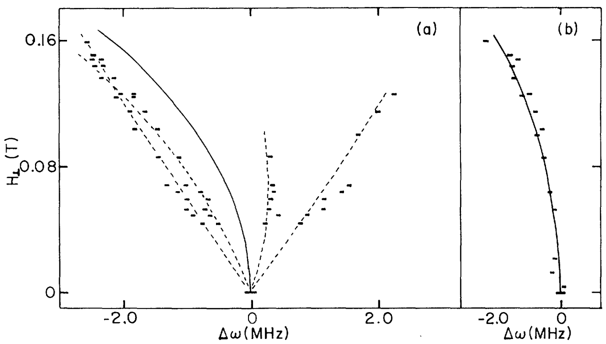

FIG. 1. (a) The magnetic field evolution of the rsq mode at 1.35 bars, 38.24 MHz, $T/T_c = 0.767$. The lines are a result of the fit by Eq. (1) to the observed frequency shifts. For the data shown $\alpha = 8.20$ MHz T^{-1}, $\beta = 21.0$ MHz T^{-2}, and $\Gamma = 83.0$ MHz T^{-2}. For fields greater than 0.1 T, the $J_z = +1$ state is not observed. (b) The raw data for the positions of the $J_z = 0$ state. The "doublet structure" reported earlier in Ref. 8 is not resolved at this temperature.

separately in Fig. 1(b). The extent of nonlinearity depends on T/T_c. In smaller magnetic fields ($H < 0.1$ T) the rsq-mode states are distributed asymmetrically about the $J_z = 0$ state. The distribution becomes more symmetric as the position of the $J_z = 0$ state is shifted to lower temperatures and at the same time there is an increase in the magnetic field at which mode crossing between the $J_z = -1$ and $J_z = -2$ states occurs. In order to understand our results quantitatively we have fitted the observed frequency shifts with an expression quadratic in the applied magnetic field. We find that all of our data are well fitted by

$$\Delta\omega = \alpha(T,P)J_z H + \beta(T,P)J_z{}^2 H^2 - \Gamma(T,P)H^2. \quad (1)$$

Figure 2 is a plot of the coefficients α, β, and Γ. The magnitude of the linear coefficient, α, is in good agreement with earlier work.[7,8] α is significantly pressure dependent, but appears to be relatively insensitive to T/T_c. On the other hand the quadratic term, β, is relatively insensitive to pressure and/or frequency but exhibits a stronger temperature dependence. Furthermore, β appears to go to zero as $T \to 0$.

Recent calculations by Schopohl, Warnke, and Tewordt[10] have shown that the nonlinearity arises from a distortion of the B-phase energy gap. In a magnetic field, the energy gap becomes ellipsoidal and two parameters Δ_1 and Δ_2 are needed to describe it. In addition to the magnetic field dependence Δ_1 and Δ_2 are strongly temperature dependent. For the range of magnetic fields and temperatures explored in this work $\Delta_2/\Delta_1 = 0.6$ to 0.8. Schopohl, Warnke, and Tewordt find that this corresponds to a region of crossover from the Zeeman to the Paschen-Back regimes. Generalizing the $T = 0$ expressions of Ref. 6 one may

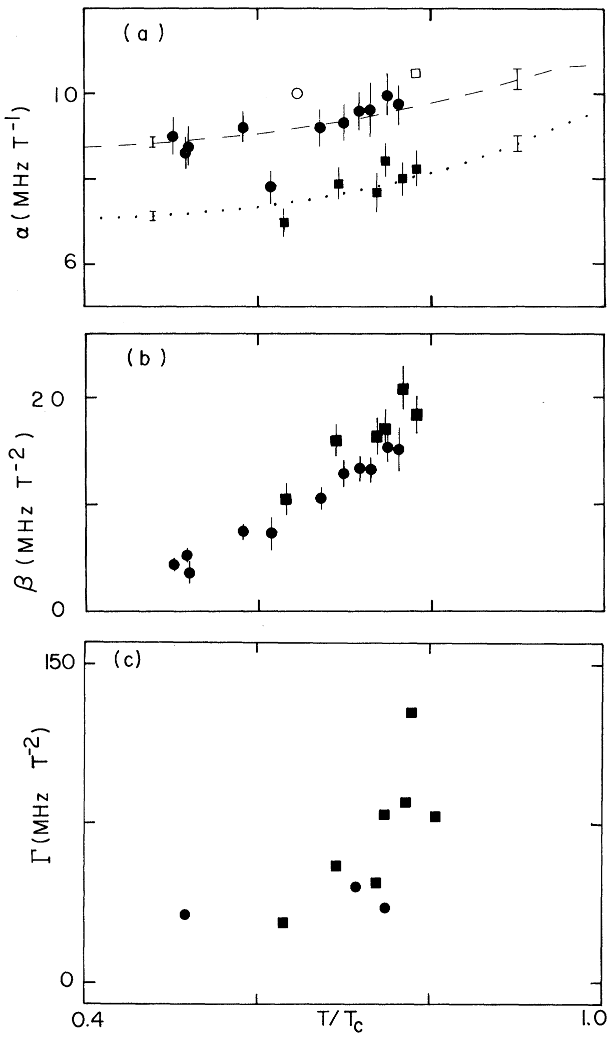

FIG. 2. The coefficients α, β, and Γ of Eq. (1) as functions of T/T_c. Closed circles (closed squares) represent data taken over a pressure range of 5.18 to 10.13 bars at 63.77 MHz (0.20 to 1.45 bars, 38.24 MHz). (a) The open circle (square) is the data from Ref. 7 at 11.0 bars, 74.5 MHz (3.5 bars, 44.7 MHz). The lines are the result of calculations using the expressions of Ref. 16 with $x_3{}^{-1} = 0$. m^*/m values of Ref. 17 have been used, and the dashed line (dotted line) corresponds to $P = 7.3$ bars, $F_0{}^a = -0.740$, $F_2{}^a = -1.13$ ($P = 0.80$ bar, $F_0{}^a = -0.709$, $F_2{}^a = -2.50$). The bars at $T/T_c = 0.9$ and 0.45 represent the shifts in the lines when $F_0{}^a$ is changed over the pressure range of the data.

write, to second order in magnetic field, $\Delta_1^2 - \Delta_0^2 = \frac{1}{4}\delta(T)H^2$ and $\Delta_2^2 - \Delta_0^2 = -\frac{1}{2}\delta(T)H^2$. With such an expansion of the gap parameters we find that the expressions of Ref. 10 reduce to the form of Eq. (1) with $\Gamma = 2\beta$. From Fig. 1 it is clear that Eq. (1) is an accurate representation of our data. However, there are some systematic deviations and in particular Γ is greater than 2β (Fig. 2). This in all likelihood points to the extreme nonlinear dependence of the gap parameters Δ_1 and Δ_2. Results of susceptibility experiments in strong magnetic fields in the B phase have also been interpreted as evidence for gap distortion.[18]

A detailed comparison of the measured frequency shifts, $\Delta\omega$, with theory can be made when Fermi-liquid corrections and the effect of the $l = 3$ pairing interaction are taken into account. Such a theory exists only for the linear term, α.[16,19] Using the results of recent specific-heat measurements[17] and neglecting the $l = 3$ interaction effects in the expressions of Sauls and Serene,[16] we find $F_2^a = -2.50$ at 0.8 bar and $F_2^a = -1.13$ at 7.3 bars. Incorporating the interaction effects to second order in the magnetic field may enable one self-consistently to calculate higher-order Fermi-liquid coefficients and the strength of the $l = 3$ pairing interaction.

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[15]The observed temperature positions of the rsq-mode states have been converted to frequency via the relation $\omega = a_{\mathrm{rsq}}(T)\,\Delta_{\mathrm{BCS}}(T)$. The function $a_{\mathrm{rsq}}(T)$ has been defined in Refs. 5 and 13. The frequency shifts $\Delta\omega$ are then given by $\Delta\omega = \omega_0 - \omega(J_z, H)$, where ω_0 is the rsq-mode frequency at $H = 0$.

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