Brief Reports

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Ultrasonic behavior of the heavy-fermion superconductor URu_2Si_2

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Experimental results of ultrasonic measurements on a single crystal of URu_2Si_2 exhibit an attenuation peak just below the superconducting transition and a broad maximum centered at 10 K. A relatively small magnetic field suppresses the attenuation peak below T_c. In addition, a 1.3×10^{-4} relative change of velocity across the superconducting transition is observed.

URu_2Si_2 is one in a class of uranium- or cesium-based heavy-fermion systems. The conduction electrons in these systems have heavy effective masses as determined from low-temperature electronic specific heat. Several of these compounds show magnetic ordering at low temperatures and a few, such as UBe_{13}, UPt_3, and $CeCu_2Si_2$ (Ref. 1) as well as URu_2Si_2, have superconducting transitions around 1 K. The interest in studying the superconductivity of these systems comes from the speculation that the pairing of the electrons in the superconducting state may not be the spin-zero pairing of the BCS theory. Spin-one pairing as well as anisotropic energy gaps with nodes or lines of zeros on the Fermi surface have been suggested. Measurements on UBe_{13} and UPt_3 have revealed unusual ultrasonic behavior.[2-4] An enhanced sound energy dissipation below the superconducting transition has been observed in the temperature-dependent attenuation curves of both kinds of samples. An anisotropic superconducting energy gap could explain these results. However, due to the facts (i) that the attenuation peaks of these two systems behaved differently when a dc magnetic field was applied, (ii) that properties such as longitudinal sound velocity do not quite satisfy the conditions for an excitation of collective modes as observed in ^3He, and (iii) that other mechanisms can possibly interpret the excess sound energy loss below T_c, the pairing mechanism for the heavy-fermion superconductors remains uncertain. It is quite interesting that an attenuation anomaly below T_c also occurs in URu_2Si_2, while it exhibits a relatively large sound-velocity variation across the superconducting transition and comparatively simple magnetic behavior.

A 29-MHz $LiNbO_3$ longitudinal transducer was epoxy bonded to one end of a URu_2Si_2 single crystal, 0.37 cm in thickness. The sound propagated perpendicularly to the c axis of the sample with a velocity of 5.2×10^3 m/sec at room temperature. Pulsed-echo techniques were used for providing the attenuation and velocity data. The magnetic state of the sample was monitored by ac (17 Hz) magnetic susceptibility coils placed around it. A magnetic field could also be applied by means of a superconducting magnet. The details of the experimental setup were the same as those described by Sun.[5]

Figure 1 shows the low-temperature sound data at 85 MHz, which is the second overtone of the transducer, taken in a ^3He cryostat. The susceptibility shows an onset of superconductivity at 1.4 K. The transition is relatively broad and the sample is not completely superconducting until $\sim$1.25 K. We shall designate the temperature corresponding to the midpoint of the susceptibility transition curve as the superconducting temperature, which is approximately at the shoulder in the susceptibility curve, that is, $T_c=1.35$ K. The attenuation first shows an increase below the superconducting transition, reaching a peak at 1.2 K, and then decreases below its normal-state value at a temperature of $\sim$1.15 K. Similar anomalous behavior in attenuation below the superconducting transition has also been observed in UBe_{13} (Ref. 2) and UPt_3.[3,4]

Peaks in attenuation below T_c are not usually seen in conventional superconductors but appear to be inherent in these heavy-fermion compounds. Some attempts have been made to interpret the peak as evidence of a collective mode associated with nonzero spin pairing, similar to that seen in superfluid ^3He.[6] However, no conclusive arguments to that effect have yet been given. Recently report-

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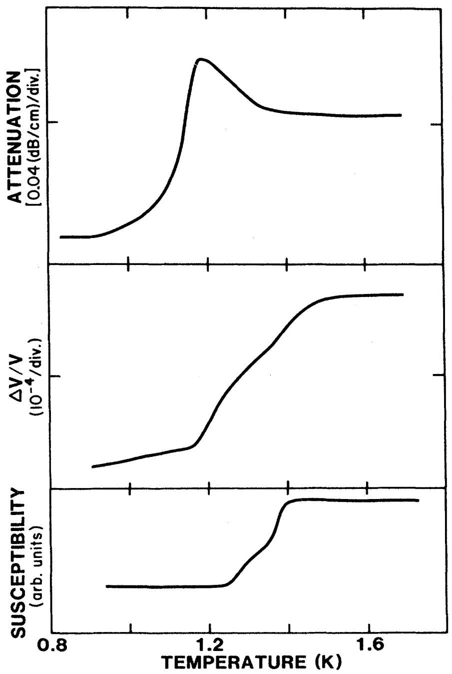

FIG. 1. Ultrasonic attenuation, relative velocity change, and ac magnetic susceptibility of URu_2Si_2 as a function of temperature across the superconducting transition.

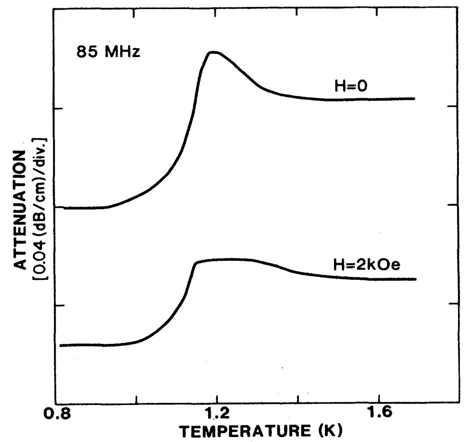

FIG. 2. Sound attenuation vs temperature of URu_2Si_2 in 0- and 2-kOe magnetic field.

ed longitudinal ultrasonic measurements on one sample of URu_2Si_2 failed to see a peak but showed that the attenuation did not start to drop until temperatures around $0.8T_c$.[7]

An alternative mechanism to explain this attenuation peak may be Landau-Khalatnikov damping of the superconducting order parameter. The superconducting order parameter has to relax to its local equilibrium, as determined by the dilatation of the lattice, when longitudinal sound waves are propagating through the sample. No attenuation peak would then be expected for transverse waves except as a second-order effect. For longitudinal waves, the theory of Landau-Khalatnikov damping predicts[8] the temperature as well as the frequency-dependent magnitude of the attenuation peak close to the transition. The calculated peak height fits the temperature-dependent attenuation data of UBe_{13} and UPt_{13} relatively well.[8] For URu_2Si_2, the velocity change ($\Delta v/v$) across the transition $\sim 1.3\times 10^{-4}$ would give an attenuation peak height of 0.29 dB/cm at 85 MHz, which is much larger than the $\sim$00.2 dB/cm observed. In addition, the observed peak position (1.2 K) is at $0.9T_c$, which is too far away from T_c (1.35 K) when compared with the predicted value ($>0.99T_c$). However, these discrepancies could be attributed to the very broad superconducting transition of this sample ($\Delta T_c \sim 0.15$ K$\sim 0.1T_c$). Figure 2 displays the effect of a magnetic field on this enhanced attenuation around T_c. As can be seen, a small field suppresses the attenuation anomaly substantially but does not shift the decrease (below 1.15 K) in the attenuation curve to lower temperatures, which differs from what is observed for UB_{13} (Ref. 2) and UPt_3.[3,4] Since the observed[9] $(-dH_{c2}/dT)_{T_c}$ is 92 kOe/K and the calculated[9] one is 62 kOe/K, the 2-kOe applied field in our measurements should not change T_c by a detectable amount. Therefore, the disappearance of the attenuation peak produced by this relatively small magnetic field may provide some insight for discriminating between different theoretical models.

Figure 3 shows the attenuation data for the same URu_2Si_2 sample, at temperatures up to 18 K. The effect of antiferromagnetic ordering in URu_2Si_2 can be seen in the displayed susceptibility curve at 17.5 K. This transition has also been observed in measurements of resistance and heat capacity[9] and in neutron scattering.[10] The small hump in the attenuation curve at around 16 K could be the result of this magnetic phase transition. We do not have an exact interpretation for the broad attenuation peak centered around 10 K yet. Since the peak position is not frequency dependent (measurements at 29 MHz also show the peak at $T=10$ K), it could not be caused by a relaxation process unless it is associated with a phase transition. Inelastic neutron-scattering measurements on

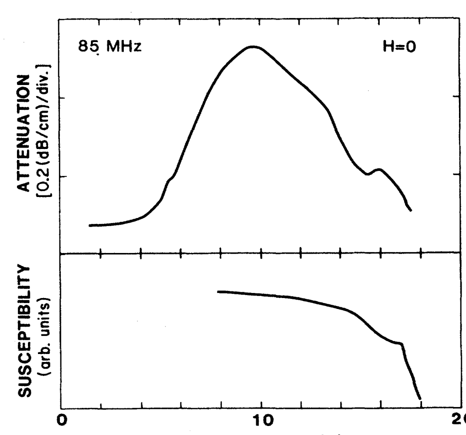

FIG. 3. Sound attenuation and susceptibility vs temperature of URu_2Si_2. An antiferromagnetic transition occurs at 17.5 K.

URu_2Si_2 have revealed that a sharp gaplike magnetic excitation of 5.3 meV occurred at 10 K.[11] Transport, thermal, and magnetic measurements on URu_2Si_2 indicated[9] that an energy gap opened up over a portion of the Fermi surface below the antiferromagnetic ordering temperature. It might be plausible to say that the increase of sound energy loss, below 20 K, is caused by the viscosity of electrons at low temperatures, and that the opening of the energy gap stops this increasing, thus, producing a maximum at 10 K which is then followed by a monotonic decrease in attenuation with decreasing temperature. However, the change in attenuation is too large to be explained by such a mechanism. Therefore, it is likely that the peak is due to fluctuations. Ultrasonic measurements of transverse waves in constant external fields, which may provide information about the shape of Fermi surfaces, may also provide information which could explain why the appearance of the partially gapped Fermi surface produces a maximum in attenuation around 10 K.

In summary, ultrasonic measurements of longitudinal waves on a single crystal of URu_2Si_2 showed a peak below T_c as well as a broad maximum in attenuation centered at 10 K, and a relatively large variation ($\Delta v/v - 1.3\times 10^{-4}$) in velocity across the superconducting transitions. Whether the peak in attenuation below T_c is associated with a collective-mode mechanism or is the result of Landau-Khalatnikov damping close to T_c remains undetermined due to the relatively broad phase transition of our sample. A higher-quality sample may be needed in order to discriminate between these different theoretical interpretations. The attenuation maximum at 10 K might be the result of a magnetic gaplike excitation at this temperature, whose occurrence correlates with the onset of the antiferromagnetic ordering at 17.5 K. If an anisotropic energy-gap model is appropriate for explaining the magnetic and superconducting behavior of heavy-fermion superconductors, ultrasonic measurements of transverse waves with magnetic fields applied in various orientations with respect to the crystal axes may become important.

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