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Unrenormalized ultrasound attenuation in the heavy-fermion state

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Quantitative studies of ultrasound absorption in the heavy-fermion state of UPt_3 and UBe_{13} are reported. The magnitude of the absorption due to electrons in the normal state is not enhanced compared to that of ordinary metals, indicating a cancellation of the mass enhancement by a reduction of the electron-phonon coupling parameter. This implies that the mass enhancement is described by a different Landau Fermi-liquid parameter than in ^{3}He. The T^2 variation of the normal-state sound velocity at lowest temperatures is consistent with the large electronic specific heat.

The formation of the heavy-fermion state out of what appears at high temperatures to be local magnetic moments embedded regularly in a metallic matrix is the subject of intensive current research. The unconventional properties of the superconducting ground state, into which some of the heavy-fermion systems condense,[1-3] indicates a novel type of superconductivity characterized by large anisotropies of the order parameter[4-10] and, as suggested by Varma[11] and by Anderson,[12] nonsinglet pairing of the electrons. On the other hand, much less is known about the normal state of the heavy fermions. The enhancement of the effective mass by two orders of magnitude over ordinary metals is accompanied by a corresponding enhancement of the magnetic susceptibility, keeping their ratio of order unity.[13] The question then arises whether other properties of the heavy fermions are similarly enhanced. One of these is the attenuation of sound, a particular type of transport property, which is determined by the electron-phonon coupling strength and the effective mass of the quasiparticles.

Here we present a quantitative study of the ultrasound propagation in UPt_3 and UBe_{13} at low temperatures. The main result is that the magnitude of the ultrasound attenuation is the same as in ordinary metals, and not enhanced by 10^4–10^5 as might be expected from the large effective mass. This implies, as discussed by Varma,[14] a compensation of the mass enhancement by a reduction of the electron-phonon coupling strength and places severe constraints on any theories for the heavy-fermion state. In particular, it is the Landau parameter F_0^S which characterizes the mass enhancement, and not F_1^S as in the case of the well-studied Fermi-liquid ^{3}He.

The experiments on UPt_3 were performed on a single crystal grown in an ultrahigh-vacuum float-zone apparatus from a previously synthesized ingot. A crystal of 0.7 cm length was cut from a cylindrical sample of 5 cm length and 0.6 cm diameter. The ultrasound transducers ($LiNbO_3$) were attached to optically flat opposite surfaces and longitudinal sound was propagated in directions parallel to either the hexagonal c axis or the basal plane. The frequency range extended from ~ 50 to 500 MHz. The experiments on UBe_{13} were done on single crystals, grown from Al flux, and evaporated zinc oxide transducers allowed studies at ultrasound frequencies up to 2 GHz. The attenuation due to electron-phonon scattering is so weak in UBe_{13} that it can be measured only at these high frequencies.

Before discussing the experimental results, we recall the physical principles involved in the attenuation of ultrasound by electrons.[15] Both classical and quantum-mechanical methods have been applied and give identical results for free electrons, but the quantum-mechanical treatment starts from a conceptually more appealing description. The electron's energy in a crystal deformed by a longitudinal elastic wave is described as

$$E(k,\delta)=E_0+\hbar^2k^2/2m^*+E_1\nabla\delta \ , \tag{1}$$

where m^* is the effective mass from the $E(k)$ dispersion, δ the deformation, and E_1 the deformation potential, a measure of the electron-phonon coupling strength. The result for the amplitude attenuation coefficient α is then readily obtained for the limit of where the sound wavelength λ is smaller than the mean free path l_e, i.e., $ql_e >> 1$ ($q = 2\pi/\lambda$). The corrections for finite mean free path ($ql < 1$) are done within the classical framework and are found to describe the behavior of real metals very well. We obtain for α in the limit $ql << 1$,

$$\alpha = \frac{4}{5\pi}\frac{(m^*E_1)^2\nu}{\rho_0 u^2\hbar^3} ql_e \; . \tag{2}$$

Here u is the sound velocity, ρ_0 the mass density, and ν the sound frequency.

In the following we show that (2) indeed describes the results in the normal state of UPt_3 and UBe_{13}. In Fig. 1(a) the attenuation in UPt_3 is shown as function of the square of the temperature. This is a very useful representation of the data for two reasons. First, it illustrates that $\alpha(T)$ in the normal state (α_n) has the same T dependence as the electron mean free path $l_e(T)$ as deduced from the resistance, shown in Fig. 1(b). Second, the attenuation in the superconducting state (α_s) also varies as T^2 for $T << T_c$. The normalized quantity α_s/α_n, where α_n is extrapolated into the superconducting range, also varies almost as T^2 over a wide temperature range. By contrast to ordinary superconductors where α_s/α_s varies exponentially at $T << T_c$, the superconducting order parameter in UPt_3 was concluded to be very anisotropic, vanishing along lines on the Fermi surface.[4] Recent measurements of the thermal conductivity and specific heat support this conclusion.[16,17] Figure 1 also shows how we separate the electronic contribution to the sound attenuation from other contributions, which cause a background attenuation. Because both α_n and α_s vary as T^2, extrapolation of α_s to $T = 0$ gives the zero for the ordinate, and the total electronic part of $\alpha(T = 0)$ is obtained by extrapolating α_n to $T = 0$. The uncertainty in $\alpha_n(0)$ is very small and irrelevant in the context of this paper. In UBe_{13}, the magnitude of α_n is determined as the difference of α_n just above T_c and α_s for $T \rightarrow 0$. No special correction for the temperature dependence of l_e (and therefore α_n) is necessary, because the variation of the resistivity with temperature is much less pronounced in UBe_{13} than in UPt_3. Here we note that the temperature dependence of α in UBe_{13} at $T << T_c$ is consistent with a T^2 law, as in UPt_3, and shows a peak just at T_c. This latter feature has been observed for the first time in a superconductor and is the subject of a separate publication.[18] In Fig. 2 the frequency dependence of $\alpha_n(0)$ is plotted on a double logarithmic scale. The observed f^2 law again supports the $ql << 1$ description given by (2).

A comparison with other metals can be done in two different ways. Either the microscopic parameters m^*E_1 are calculated for a given ql or the attenuation is extrapolated (or directly measured) in the $ql >> 1$ regime where it is independent of l_e. In either case the mean free path has to be estimated from the resistivity, a step which introduces some uncertainty. We like to point out, however, that our main conclusion does *not* rely on the exact value of l_e. Given the residual resistivity of the UPt_3 sample of ~ 0.5 $\mu\Omega$ cm and following an earlier analysis based on Friedel's maximum scattering argument, we infer ~ 2200 Å for l_e.[19,20] At 100 MHz this gives $ql \simeq 3.5 \times 10^{-2}$. The experimental quantity to be compared with other metals is the $ql >> 1$ limiting at-

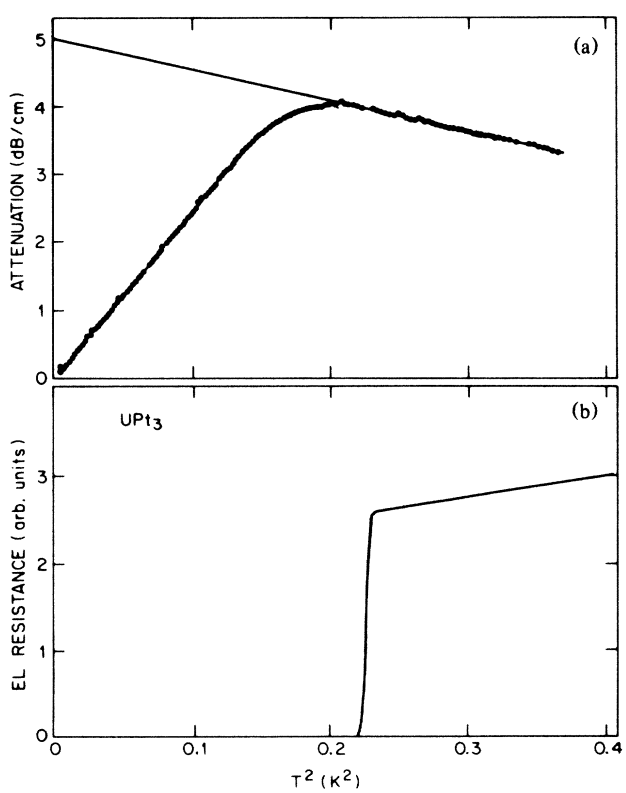

FIG. 1. (a) The attenuation of longitudinally polarized ultrasound propagating along the hexagonal axis in UPt_3, plotted as a function of the square of the temperature. (b) Temperature dependence of the electrical resistivity. The $T = 0$ resistivity is ~ 0.5 $\mu\Omega$ cm (after Ref. 25).

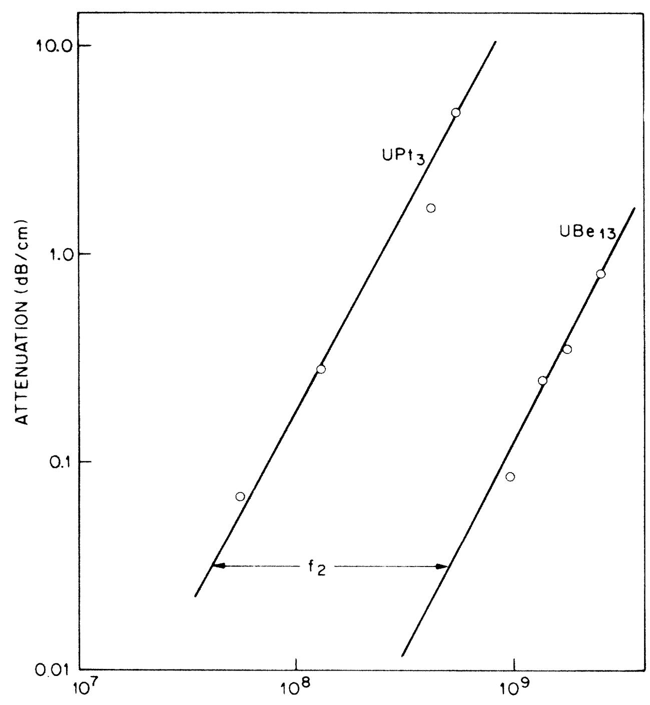

FIG. 2. Frequency dependence of the normal-state electronic contribution to the ultrasound attenuation in UPt_3 and UBe_{13}.

tenuation per frequency, which for UPt_3 we calculate to be ~ 0.1 dB cm^{-1} MHz^{-1}. When measured directly in the $ql >> 1$ limit, this quantity is direction dependent, and our results, therefore, represent an average over the Fermi surface. A similar analysis for UBe_{13} with a mean free path of 13 Å (Ref. 20) and $ql = 10^{-3}$ at 1 GHz (Ref. 18) results in a limiting attenuation of 0.08 dB cm^{-1} MHz^{-1}, very close to the UPt_3 value. It is worth noting that the difference between the measured attenuation in UPt_3 and UBe_{13} is mainly due to the different mean free path of the electrons. It also illustrates the necessity to study the attenuation UBe_{13} in the GHz regime.

The values of ~ 0.1 dB cm^{-1} MHz^{-1} for the heavy-fermion metals are well within the range measured in various crystallographic directions for about a dozen non-heavy-fermion metals[21] (e.g., Cu: 0.05–0.18, In: 0.23–0.42, Pb: 0.18). The main point of this paper is the observation that *this particular transport property in the heavy-fermion state is not renormalized.*

According to the physical picture leading to Eq. (2), this nonrenormalization of the ultrasound attenuation implies that the product of the microscopic parameters m^* and E_1 is of the same magnitude as in ordinary metals, namely, $E_1 m^*/m_e \sim 5$–10 eV (m_e is the free electron mass).[22] Given a mass enhancement of order 10^2, the attenuation would be expected to be enhanced by $\sim 10^4$ over ordinary metals if the coupling constant E_1 were not reduced. The experimental observations in UPt_3 and UBe_{13} therefore point to a cancellation of the mass enhancement by a proportional decrease of the electron-phonon coupling strength probed by longitudinal sound. The results of the ultrasound studies are used by Varma[14] to formulate a phenomenological theory of the heavy-fermion state. The main point is that *the effective mass is given by the Landau Fermi-liquid parameter* F_0^s, *and not by* F_1^s *as in* ^{3}*He*. This is also borne out by recent model calculations based on the Gutzwiller approach to the Anderson lattice.[23,24]

In addition to the attenuation we have also studied the velocity of sound propagating along the hexagonal axis and in the basal plane for UPt_3. In Fig. 3 the variation of the sound velocity u is plotted as a function of the square of the temperature, emphasizing the T^2 behavior at lowest temperatures. In the higher-temperature range the velocity parallel to c decreases further by ~ 1300 ppm before going through a minimum at ~ 18 K. For the sound velocity in the basal plane no minimum up to 20 K is observed, but the change is larger and amounts to ~ 3800 ppm at 22 K.[25]

The sound velocity changes at lowest temperatures are consistent with the very large electronic specific heat typical for the heavy-fermion state. The argument is based on the definition of the bulk modulus as the second derivative of the free energy with respect to volume, and can proceed in either a very general way[26] or within a particular model for the electron-lattice coupling.[27] Straightforward thermodynamic derivations give a contribution to the bulk modulus change ΔB, due to the electronic contribution to the entropy part of the free energy. Whereas this ΔB is not dominant in ordinary metals, it can be clearly measurable in heavy-fermion systems, and ΔB will be proportional to the integral over the specific heat $c(T)$. Given the huge electronic $c(T)$, ΔB will vary to first order as T^2. This is indeed observed in UPt_3, and we ascribe the difference in the prefactor for the two directions to contributions involving the thermal expansion coefficient, which is of different signs in the two directions.[28] A quantitative analysis, however, can only be done when all necessary thermodynamical derivatives are measured with respect to the strains corresponding to the elastic deformations associated with the sound propagation in the various directions.

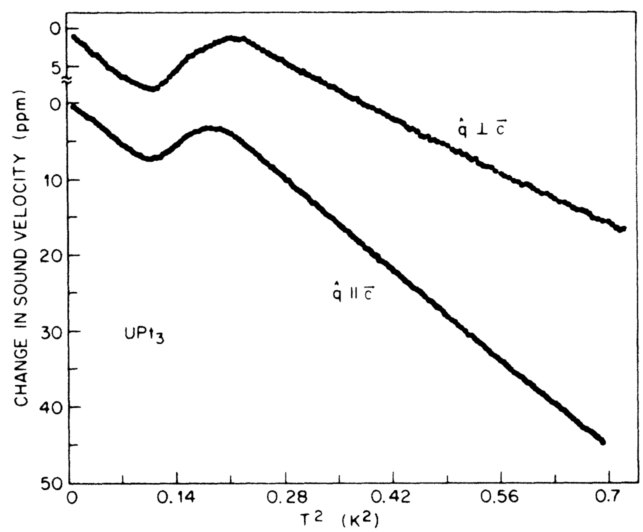

FIG. 3. Temperature dependence of the sound velocity change in UPt_3 for propagation parallel and perpendicular to the hexagonal axis.

A very similar type of analysis has been successfully applied to $CeAl_3$, another heavy-fermion metal, where the bulk modulus decreases as T^2 up to ~ 0.4 K.[27,29]

In conclusion, we note that the attenuation of ultrasound in the heavy-fermion state in UPt_3 and UBe_{13} is of the same order of magnitude as in ordinary metals. The mass enhancement of the quasiparticles by two orders of magnitude is therefore compensated by a reduction of the coupling strength. These observations demonstrate that the parametrization of the mass enhancement in the heavy-fermion state has to involve a different Landau Fermi-liquid parameter than in ^{3}He. The variation of sound velocity is consistent with the dominance of the electronic contribution to the entropy in the heavy-fermion state.

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