Nonlinear acoustic properties of the $CeAl_3$ Kondo system at low temperatures

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A sharp change in the nonlinear acoustic properties has been observed at low temperatures in the Kondo compound $CeAl_3$. This change is associated with the formation of an Abrikosov-Suhl giant resonance near the Fermi level.

Heavy-fermion systems have recently become the subject of extremely active research.[1] Most such systems are nonmagnetic Kondo lattices in which there is an Abrikosov-Suhl giant resonance in the electron state density at the Fermi level. The width of the resonance is determined by the Kondo temperature T_K, which lies in the interval 1–10 K for typical nonmagnetic Kondo lattices.

Corresponding to a narrow resonance of this sort are "heavy fermions," i.e., quasiparticles with an effective mass $m^*_{\rm HF}$ some 10^2–10^3 times the typical effective carrier masses in normal metals.[1] At low temperatures, $T \lesssim T_K$, where the width of the thermal spreading of the Fermi distribution is smaller than the width of the Abrikosov-Suhl resonance in the state density, all the Fermi electrons become "heavy," so the low-temperature properties of a nonmagnetic Kondo lattice are strikingly different from those of ordinary metals.

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For example, the Fermi velocity of the heavy fermions, v_F^{HF}, is only $\sim 10^5$ cm/s. This figure agrees in order of magnitude with the sound velocity in metals: $v_F^{HF} \sim v_s$. In normal (i.e., non-Kondo) metals, on the other hand, we have $v_F/v_s \sim 10^3$. In a situation with $v_F \sim v_s$, we would expect to see several distinctive features in the acoustic properties of a nonmagnetic Kondo lattice: a significant increase in the electronic absorption of longitudinal acoustic waves, anomalies in other properties at $T \sim T_K$, etc. The distinctive features of the electron-phonon interaction near $T \sim T_K$ should also have a strong effect on the nonlinear acoustic properties of a nonmagnetic Kondo lattice: the generation of higher harmonics of the sound wave, an interaction of waves, etc. To the best of our knowledge, however, there has been no previous study of the nonlinear acoustic properties of heavy-fermion compounds.

Our purpose in the present study was to determine how the restructuring of the energy spectrum of electrons, which occurs near T_K, influences the nonlinear elastic properties of the-Kondo compound $CeAl_3$.

The test sample was a polycrystalline $CeAl_3$ sample (the dimensions of the crystallites were 10–30 μm) which had the values $m^*_{HF}/m_0 \sim 60$ (m_0 is the mass of a free electron) and $v_F \sim 10^5$ cm/s at $T_K \approx 4$ K. From the temperature dependence of the

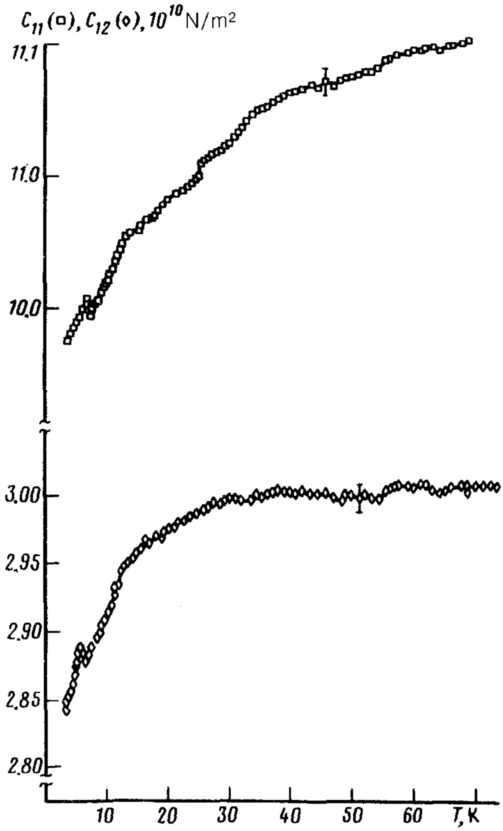

FIG. 1. Temperature dependence of the linear elastic moduli of the Kondo compound $CeAl_3$.

velocities of longitudinal and shear acoustic waves we calculated the behavior of the linear elastic moduli of the sample, C_{11} and C_{12}, the changes in which amounted to 2% and 4%, respectively, over the temperature range studied, $T = 80$–4.2 K (Fig. 1). The anomalies seen on the curves of $C_{11}(T)$ and $C_{12}(T)$ at $T \approx 6$ K correspond to a transition of a Ce_3Al_{11} impurity in the sample, to a magnetically ordered state. Similar anomalies have been seen previously[1] in the temperature dependence of the heat capacity of the compound $CeAl_3$.

We studied the nonlinear acoustic properties by two methods: on the basis of the temperature dependence of the third-order elastic moduli and by a spectral method based on the efficiency of the generation of the second harmonic of longitudinal acoustic waves over the range $T = 80$–4.2 K.

The values of the third-order elastic moduli were determined by the standard technique[2] of studying the relative changes in the phase velocities of acoustic waves in the sample upon the application of uniaxial static stresses to the sample.

Measurements were carried out at the frequency 30 MHz at temperatures $T = 80$, 35, 10, and 4.2 K. These measurements yielded all the independent components of the third-order elastic-modulus tensor of isotropic $CeAl_3$: C_{111}, C_{112}, and C_{123}. The error in these measurements was no worse than 20%. Figure 2 shows the temperature dependence of the third-order elastic moduli for the Kondo system $CeAl_3$. The experimental points in Fig. 2 have been connected by cubic splines.

Working from our study of the temperature dependence of the amplitude of the

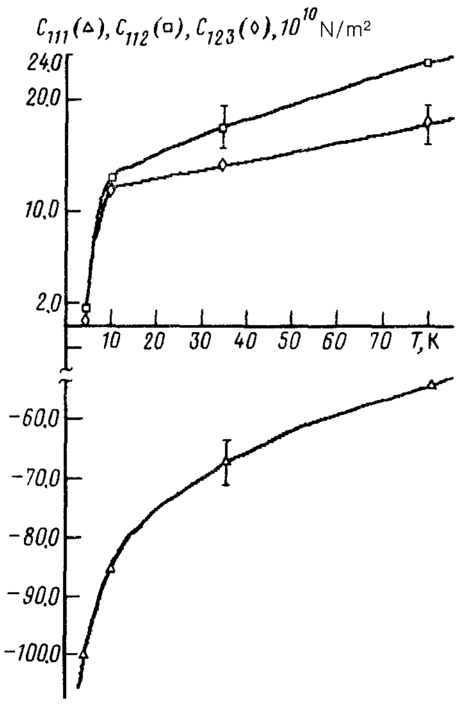

FIG. 2. Temperature dependence of the third-order elastic moduli of the Kondo compound $CeAl_3$.

second harmonic of the longitudinal acoustic waves in the sample, we calculated a nonlinear parameter of the medium, allowing for the attenuation of the sound at the fundamental frequency (30 MHz) and at twice this frequency[3]:

$$N = \frac{U_{2\omega}}{(kU_\omega)^2} \frac{\alpha_{2\omega} - \alpha_\omega}{1 - \exp[-(\alpha_{2\omega} - \alpha_\omega)l]} . \tag{1}$$

(U_ω, $U_{2\omega}$, α_ω, and $\alpha_{2\omega}$ are the amplitudes of the signals corresponding to the wave at the fundamental frequency and to the second harmonic and the absorption coefficients of these waves, respectively; k is the wave number of the wave at the fundamental frequency, and l is the length of the sample.)

The nonlinear parameter of the medium can also be expressed in terms of the third-order elastic moduli[3]:

$$N = 3 + (C_{111}/C_{11}). \tag{2}$$

The curves of the nonlinear parameter $N_n(T)$, normalized to the value of this parameter at $T = 80$ K, for the nonlinear Kondo lattice of $CeAl_3$ which we have calculated from Eqs. (1) and (2) agree well (Fig. 3).

The nearly threefold increase in the relative nonlinear parameter of the medium near T_K is evidence of a significant increase in the elastic nonlinearity of $CeAl_3$ at the transition to the Kondo state. It is natural to suggest that the intensification of the nonlinear properties of the Kondo systems at low temperatures is due primarily to heavy fermions.

An interesting aspect of the nonlinear elastic properties of $CeAl_3$ is seen at $T \leqslant 10$K, where the width of the thermal spreading of the Fermi distribution of carriers becomes comparable to the width of the Abrikosov-Suhl resonance. At this point there is a sharp change (by essentially an order of magnitude) in the nondiagnonal compo-

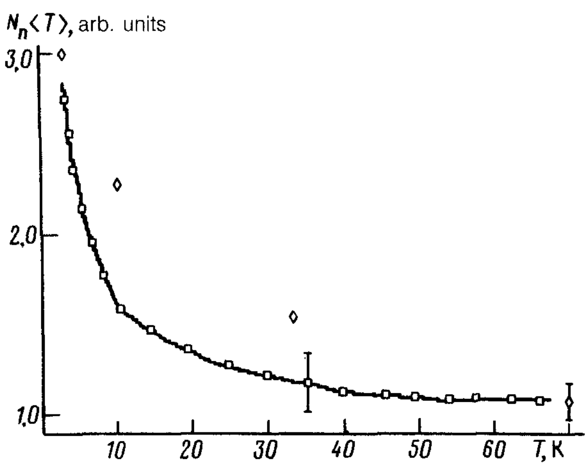

FIG. 3. Temperature dependence of the relative nonlinear parameter of $CeAl_3$. ■—calculated from Eq. (1); ◆—calculated from Eq. (2).

nents of the third-order elastic-modulus tensor of the sample, while the temperature-induced change in the value of the modulus C_{111} is fairly smooth (Fig. 2).

Interestingly, the sharp increase in the elastic nonlinearity of the nonmagnetic Kondo lattice observed in these experiments at the transition to the Kondo state agrees qualitatively with the intensification of the nonlinear acoustic properties which has been seen in the alloy BiSb near an electron topological transition.[4] This result may be evidence that the influence of the particular features of the restructuring of the energy spectrum of the carriers, without a change in their density, on the acoustic nonlinearity of metals is of a common nature.

We conclude by noting that a study of the elastic properties (particularly, the nonlinear elastic properties) of nonmagnetic Kondo lattices near $T \sim T_K$ constitutes a sensitive method for studying the electronic properties of these materials. It can also yield additional information about the process by which heavy fermions form in metals.

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