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Physica B 367 (2005) 101–113
PHYSICA B
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Electron–phonon coupling and longitudinal sound velocity in heavy fermion systems

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Received 9 March 2005; received in revised form 24 May 2005; accepted 1 June 2005

Abstract

Heavy fermion systems show pronounced elastic anomalies at low temperatures below a characteristic temperature T^* where quasi-particle bands are formed. To explain these anomalies a microscopic theory of electron–phonon interaction in heavy fermion systems is considered for the Periodic Anderson Model. The volume dependence of the hybridization between the f-electrons and the conduction electrons and of the bare f-electrons gives rise to the electron–phonon interaction. The phonon propagator, the phonon self-energy and the velocity of sound in the normal state are calculated at finite temperature and long wavelength limit of phonons. The effects of the phonon coupling strengths, f-level position and the hybridization on the anomalous temperature dependence of the velocity of sound are investigated. The results are discussed on the basis of the experimental results.

PACS: 74.70.Tx; 71.28.+d; 63.20.Kr

Keywords: Heavy fermion systems; Narrow band systems; Electron–phonon interactions

1. Introduction

It is well documented that ultrasonic methods are extremely valuable in elucidating the electron–phonon coupling mechanism, especially in compounds with rare earth (like Ce) or actinides (like U) ions [1]. For systems exhibiting mixed-valence properties or heavy fermion (HF) effects, high-frequency sound waves can couple very strongly via volume strain. The electron–phonon coupling enables the measurement of the elastic constant, velocity of sound and ultrasonic attenuation of the systems [2]. Only the longitudinal mode of elastic constants exhibits an anomalous

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doi:10.1016/j.physb.2005.06.003

temperature dependence on the heavy fermions in the normal state. Examples are UPt_3 [3], URu_2Si_2 [4], $CeRu_2Si_2$ [5] and others. The Ce-based systems exhibit two types of temperature dependence of the longitudinal elastic constants. The first group of compounds shows low fluctuation temperatures T^* and high specific heat coefficients (γ in $mJ/mole\,K^2$). They are $CeCu_6$ ($T^* = 4\,K, \gamma = 1450$) [1], $CeRu_2Si_2$ ($T^* = 15\,K, \gamma = 385$) [5], and $CeCu_2Si_2$ ($T^* = 10\,K, \gamma = 1100$). They lie in a localized regime and exhibit heavy fermion behaviour with the f-level lying far below the Fermi level. The compounds exhibit an elastic constant increase with increase in temperature. The second group of compounds are distinguished from the former ones by having lower specific heat coefficients and much higher fluctuation temperatures $T^* = 260\,K$ for $CeSn_3$ [6] and $T^* = 340\,K$ for $CeBe_{13}$ [7]. They therefore, lie close to the mixed valence regime with the f-level lying nearer to the Fermi level. These compounds exhibit an elastic constant minimum for the temperatures T_m that are somewhat smaller than the fluctuation temperatures i.e. $T_m \sim 125\,K$ for $CeSn_3$ and $T_m \sim 150\,K$ for $CeBe_{13}$ [7]. This points to different types of elastic constants for the Ce-based compounds. The elastic modes in the case of the U-based systems are completely different. Both UPt_3 [3] and URu_2Si_2 [4] exhibit intermediate fluctuation temperature T^*, i.e. 20 and 70 K with intermediate specific heat coefficients 400 and 65 mJ/mole K^2, respectively. URu_2Si_2 exhibits an elastic constant minimum for temperature 30 K which is somewhat smaller than the fluctuation temperature. But UPt_3 shows a very flat minimum in its longitudinal elastic constant. Moreover, a pronounced ultrasonic absorption peak has been observed by Müller et al. [16] in the heavy fermion system UPt_3 in its normal state at a temperature of about 12 K which is the temperature below the fluctuation temperature $T^* \sim 20\,K$. The authors could explain this experimental result due to the presence of a narrow $\sim k_B T^*$ Kondo-type resonance in the density of state near the Fermi level. In the superconducting state UPt_3 shows a step-like function in its elastic constant at a superconducting transition temperature [2]. Similarly, the longitudinal elastic constant of superconducting URu_2Si_2 exhibits a step-like anomaly of the order of $\Delta C/C_0 \sim 10^{-4}$ at T_c. The step-like anomaly in the superconducting phase is due to the coupling of the lattice to the condensate (order parameter). Indeed, this mechanism has been proposed to be the driving force to explain superconductivity in some of the HF materials, notably $CeCu_2Si_2$ [8]. The normal state experimental results also indicate that the coupling of the elastic strains and long wavelength phonons to the quasi-particle bands is important in heavy fermion compounds. As a first step, this coupling was described in a phenomenological way by introducing a deformation potential coupling to the heavy-quasi-particle bands. Such an approach has been used by Lüthi and coworkers to explain the elastic constant and ultrasonic absorption anomalies [9,10].

The deformation potential is characterized by an electronic *Grüneisen* parameter (GP) which is a measure of the strain dependence of the quasi-particle energy. In order to explain the longitudinal elastic constant anomaly near the fluctuation temperature T^*, Thalmeier [11] has considered the GP coupling of sound waves to the conduction bands to explain the elastic constant anomalies of some heavy fermion compounds in the quasi-particle regime and in the normal state. Wojciechowski et al. [12] have derived the electron–phonon coupling Hamiltonian resulting from a volume dependence of the bare hybridization strength. They have calculated all the electronic quantities from the Anderson Model within the mean-field-approximation for slave bosons and finally calculated the velocity of sound using the random-phase-approximation (RPA)-like procedure for the phonon self-energy. A similar Hamiltonian has been derived and examined by Keller et al. [13] at $T = 0\,K$ to describe the self-energy effects in heavy fermion systems. In the present communication, we consider the Periodic Anderson Model where the onsite f-electron Coulomb interaction is linearized in Hartree–Fock approximation to determine the electronic quantities of the subatomic system of the HF compounds. The coupling of the long wavelength phonons to the bare hybridization between f-electrons and conduction electrons as well as to the bare f-electrons are assumed to arise