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Comment

Effective mass decrease due to electron-phonon interaction in heavy fermion systems

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Abstract. It is argued that in heavy fermion systems the electron-phonon interaction results in a decrease of the quasiparticle mass. This is in contrast to ordinary metals where this interaction is known to increase the effective mass. A simple expression is derived which relates the effective mass change to the electronic Grüneisen parameter, the Kondo temperature and the bulk modulus. For $CeRu_2Si_2$ the effective-mass decrease is estimated to be 25%.

In ordinary metals the quasiparticle mass m^* increases when the electron-phonon interaction is turned on. The electron with its phonon cloud is heavier than without it and the change is known to be $m^*_{ph}=m^*_0(1+\lambda)$ where the subscripts *ph* and 0 refer to the presence and absence of electron-phonon interactions. The quantity λ is a measure of the ionic contribution to screening and is approximately given by an integral over the Fermi surface of the inverse electronic velocity $|\underline{v}(\underline{k})|^{-1}$, multiplied by $e^2/(2\pi^2 k_0^2)$ where k_0 is the Thomas-Fermi wave vector [1].

In heavy fermion systems the effect of the electron-phonon interaction is quite different. First one must recall the origin of the heavy quasiparticle mass. Considering the system as a Kondo lattice, a singlet is formed at low temperatures at each rare earth or actinide site between the f electrons and the conduction electrons. The energy gain due to the singlet formation is denoted by $E_0=-k_B T^*$ where T^* is the equivalent of the Kondo temperature for the lattice. It defines the low energy scale of the system. In particular, the quasiparticle mass m^*_0 is proportional to $(T^*)^{-1}$ [2].

When the electron-phonon interaction is turned on the energy gain due to singlet formation increases. The hybridization of the f electrons with the conduction electrons on which T^* crucially depends, increases when the neighbors move closer to an f site. A measure of this change is provided by the electronic Grüneisen parameter [3].

$$\eta=-\frac{\Omega}{T^*}\frac{dT^*}{d\Omega} \tag{1}$$

which specifies the change in T^* which changing volume Ω. In heavy fermion systems η is of order 100 [4]. Because the energy gain due to singlet formation is increased by the electron-phonon interaction the effective mass must decrease, because the excitations which break the singlets are spread over a larger energy interval.

In order to quantify the above mentioned effect we assume the zero temperature limit and express the change in the energy of N f-sites (e.g. Ce ions) in a volume Ω as function of a volume change $\delta\Omega$ as

$$N\delta E_0=-N k_B\,\delta T^*+\frac{\Omega}{2}c_B^0\,\varepsilon_\Omega^2 \tag{2}$$

where $\varepsilon_\Omega=\delta\Omega/\Omega$ and c_B^0 is the bulk modulus at $T=0$. By making use of (1) we write

$$N\delta E_0=N k_B\,T^*\eta\,\varepsilon_\Omega+\frac{\Omega}{2}c_B^0\,\varepsilon_\Omega^2. \tag{3}$$

The energy is minimized by

$$\varepsilon_\Omega=-\frac{n\eta k_B T^*}{c_B^0} \tag{4}$$

where $n=N/\Omega$ is the density of f sites. The energy per site in the presence of the electron-phonon interaction is therefore

$$E_0+\delta E_0=-k_B T^*\left(1+\eta^2\frac{n k_B T^*}{2c_B^0}\right). \tag{5}$$

Note the similarity of these findings with the "Kondo volume collaps" [5, 6]. The change in the effective mass is thus given by

$$m_{ph}^{*}=\frac{m_0^*}{1+\eta^2 \dfrac{n k_B T^*}{2 c_B^0}}. \tag{6}$$

In order to estimate the size of the reduction of m_{ph}^*/m_0^* we consider $CeRu_2Si_2$ as an example. The following values are used [7, 8]:

$T^*=21$ K, $\eta=150$, $c_B^0=11.2 \cdot 10^{11}$ erg/cm^3. The volume of the unit cell is vol$=171$ Å^3 and contains two Ce ions. When these numbers are inserted into (6) one obtains $m_{ph}^*/m_0^*=0.74$. The effect calculated here is due to a reduction of the strong electron correlations (through an increase of the hybridization of the f electrons) when one allows for lattice compressions. There will be additional contributions to m_{ph}^* from phonons with $q \neq 0$, which counteract the mass reduction derived here. They are difficult to calculate quantitatively, but we expect them to be relatively small in the systems of interest.

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