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The de Haas-van Alpen effect in Kondo systems with crystalline electric field

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Abstract

The effective mass probed by the de Haas-van Alphen oscillations is studied for a model Ce system under magnetic field higher than the Kondo energy. In the mean-field theory, the mass enhancement per Ce ion in the periodic system is identical with that in the dilute system. With decreasing magnetic field, the effective mass tends to diverge corresponding to a formation of the Kondo ground state. The effective mass can be very different between up and down spins depending on the nature of the 4f wave functions.

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The de Haas-van Alpen (dHvA) effect is a powerful measure to observe the quasi-particle behavior of each spin component separately. In dilute Kondo systems, earlier work concerned about the spin splitting and the Dingle temperature. In more recent dHvA experiments on CeB$_6$, which shows a typical Kondo effect, it has been found that one of spin components does not contribute to oscillatory magnetization [5,6]. Furthermore, the cyclotron effective mass of the observed spin component tends to diverge as applied magnetic field decreases [7,8]. Since enhancement of the effective mass in Ce$_2$La$_{1-x}$B$_6$ is proportional to Ce concentration $x$ [7,8,9], the origin of the anomalous mass enhancement as well as its spin dependence are ascribed to the single-site effect. The purpose of this paper is to clarify the influence of the Kondo effect on the cyclotron effective mass starting with the dilute limit. The results are compared with those obtained for periodic systems with SU(N) symmetry [10].

The oscillatory part $M_{osc}$ of magnetization per unit volume is given in terms of the cross-sectional area $S$ of the Fermi surface, the cyclotron frequency $\omega_c = eH/mc$ without many-body effect, and the self-energy $\Sigma_\sigma(\omega_n)$ of conduction electrons with $\omega_n = (2n + 1)\pi T$ the fermion Matsubara frequency as follows ($h = k_B = 1$) [3,11]:

$$M_{osc} = \frac{e^{1/2}T}{2\pi^3 cH} \left( \sum_{\sigma = \pm} S \frac{\sum_{\omega_n}^{\infty} \partial^2 S}{\partial k^2} \right)^{-1/2}$$

where the momentum dependence is neglected. The transformation coefficient $w_{\sigma,\alpha}$ depends strongly on the CEF states. The component $n = 0$ gives a dominant contribution near of the Fermi level in eq. (1), provided $2\pi^2 T/\hbar\omega_c \gg 1$. We expand $\Sigma_\sigma(\omega_0)$ as follows:

$$\Sigma_\sigma(\omega_0) \simeq \Sigma_\sigma(0) + i\omega_0 \partial \Sigma_\sigma(\omega) / \partial \omega |_{\omega=0}.$$  (3)

Consequently, $\text{Re}\Sigma_\sigma(0)$ gives a shift of the dHvA frequency, and $\text{Im}\Sigma_\sigma(0)$ yields the relaxation rate or the Dingle temperature. The cyclotron mass $m$ is replaced by a spin-dependent effective mass $m_{c,\sigma}$ defined in terms of $t_\sigma(\omega)$ by

$$m_{c,\sigma} / m - 1 = -x \partial \text{Re} t_\sigma(\omega) / \partial \omega |_{\omega=0} = x \mu_\sigma.$$  (4)

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In this paper we restrict our consideration to the effective mass, relegating the spin splitting to another publication.

It is well-known that the ground state of the Kondo impurity system is a local Fermi liquid, provided the number of internal degrees of freedom matches the number of screening channels. However the lifetime of conduction electrons, which appears in the dHvA oscillation, can remain finite since it always refers to the Bloch basis. If the lifetime is short, the effective mass as defined by eq. (4) can take even a negative value, and is not related to an observable. In such a case, the impurity specific heat is not determined by the concentration factor. We remark that eq. (7) applies even in the weak field for the periodic system [10].

Figure 1 shows the enhancement factor \( \mu_\alpha \) with \( g_\alpha > 0 \) for \( N = 4 \) in the SBMFA. Since \( D/T_K \) is of order 10\(^4\) for \( \text{Ce}_2\text{La}_{1-x}\text{B}_6 \), \( \mu_\alpha \) is of order 10\(^3\). In dilute systems, \( \mu_\alpha \) becomes negative around \( h_\alpha \sim T_K \). For periodic systems, on the other hand, \( \mu_\alpha \) diverges at \( h_\alpha = T_K \) corresponding to the Kondo resonance.

The negative value of \( \mu_\alpha \) in the dilute systems at \( h_\alpha \sim T_K \) is an outcome of a short lifetime of conduction electrons. In addition to the large relaxation, low magnetic field with small energy interval of the Landau levels should make the dHvA signals almost invisible. Therefore extrapolation of the mass enhancement from high field region leads to a divergence around \( h_\alpha \sim T_K \). The inset of Fig. 1 shows the inverse effective mass which tends to zero. On the other hand, in periodic systems at \( h_\alpha \sim T_K \), the Fermi surface includes 4f electrons. Thus the topology should change drastically as the field decreases.

We now apply the above results to \( \text{Ce}_2\text{La}_{1-x}\text{B}_6 \). Spin-dependent enhancement factor \( \mu_\sigma \) is evaluated by \( \mu_\sigma = \sum_\sigma \omega_{\sigma,\alpha} \mu_\alpha \). Hence the character of each signal is dominated by the orbital having the largest value of \( \mu_\alpha \), i.e., the most stable one in the magnetic field. According to a simple calculation with the \( \Gamma_8 \) CEF wave function, the lowest orbital under \( H//[001] \) includes up and down spins in the proportion of 16/21 to 5/21. Consequently, the conduction band with up spin is more difficult to observe due to the heavier mass and the large relaxation. On the other hand, the down spin is easier to observe, and \( \mu_\sigma \) should behave like Fig. 1 against magnetic field.

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References