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Emergent phenomena in actinides / Phénomènes émergents dans les actinides

Fermi surface, magnetic, and superconducting properties in actinide compounds

Surface de Fermi, magnétisme et supraconductivité dans les composés d'actinides

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ABSTRACT

The de Haas–van Alphen effect, which is a powerful method to explore Fermi surface properties, has been observed in cerium, uranium, and nowadays even in neptunium and plutonium compounds. Here, we present the results of several studies concerning the Fermi surface properties of the heavy fermion superconductors UPt_3 and $NpPd_5Al_2$, and of the ferromagnetic pressure-induced superconductor UGe_2, together with those of some related compounds for which fascinating anisotropic superconductivity, magnetism, and heavy fermion behavior has been observed.

RÉSUMÉ

L'effet de Haas–van Alphen, une méthode puissante pour explorer les propriétés de la surface de Fermi dans les solides, a été observé dans de nombreux composés du cérium, de l'uranium, du neptunium et du plutonium. Dans cet article, on présente les résultats obtenus pour les supraconducteurs à fermions lourds UPt_3 et $NpPd_5Al_2$, ainsi que pour le composé UGe_2 qui, soumis à une pression externe, devient supraconducteur en présence d'ordre ferromagnétique. On considère aussi certains systèmes analogues caractérisés par des états électroniques remarquables (supraconductivité anisotrope, magnétisme et comportement à fermions lourds).

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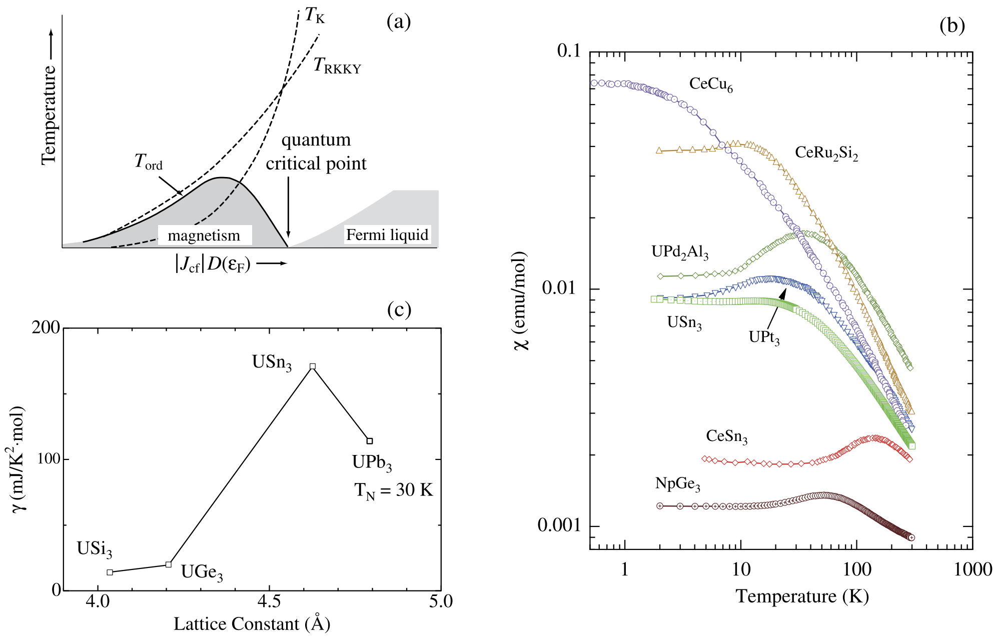

Fig. 1. (Color online.) (a) Doniach phase diagram, (b) the temperature dependence of the magnetic susceptibility in cerium, uranium and transuranium compounds, and (c) the γ vs lattice constant in UX_3 (X: Si, Ge, Sn, and Pb), cited from Ref. [5].

1. Introduction

In the presence of a strong magnetic field H, conduction electrons describe cyclotron orbits with discrete energy values, the so-called Landau levels. As the intensity of the magnetic field is increased, Landau levels cross the Fermi energy and the magnetic moment of the metal oscillates with a frequency F $(= c\hbar S_F/2\pi e)$ proportional to the extreme (maximum or minimum) cross-sectional area S_F of the Fermi surface. This is the well-known de Haas–van Alphen (dHvA) effect, a powerful method to image the Fermi surface and determine the effective cyclotron mass m_c^* and the scattering lifetime τ of conduction electrons. Magnetic moment oscillations are measured as a function of the magnetic field for different orientations of the sample, and from the angular dependence of the dHvA frequency f, obtained by fast Fourier transformation (FFT) of the oscillation curves, the topology of the Fermi surface can be determined with the help of energy-band calculations. The dHvA effect was first studied for the s and p electron systems, then for interacting electron systems based on the transition metal compounds, and eventually extended to strongly correlated electron systems of rare earth, uranium, and transuranium compounds [1–3].

The f electrons of cerium, ytterbium, uranium and transuranium compounds exhibit a variety of characteristic features, including spin and charge orderings, spin and valence fluctuations, heavy fermion and anisotropic (unconventional) superconductivity [1–3]. This variety is the result of the competition between the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction and the Kondo effect, as discussed by Doniach [4] and shown schematically in Fig. 1(a) as a function of $|J_{cf}|D(\varepsilon_F)$. $|J_{cf}|$ is the magnetic exchange interaction between conduction and f electrons, and $D(\varepsilon_F)$ is the density of states at the Fermi energy ε_F. The Doniach phase diagram is a good guiding principle to reach the quantum critical point (QCP), which is defined as the magnetic ordering temperature $T_{ord} \to 0$. Experimentally, $|J_{cf}|D(\varepsilon_F)$ is replaced by pressure P, and $T_{ord} \to 0$ is reached for $P \to P_c$ (P_c being the critical pressure). The heavy fermion state is formed in the QCP region.

The magnetic susceptibility χ of $CeCu_6$ and $CeRu_2Si_2$, as well as that of UPt_3, shown in Fig. 1(b), increases with decreasing temperature, following the Curie–Weiss law at high temperatures, and has a maximum at a characteristic temperature $T_{\chi\max}$. Below $T_{\chi\max}$, the susceptibility becomes almost temperature-independent, and the f-electron system is changed into a new electronic state, called the heavy fermion state. Here, $T_{\chi\max}$ approximately corresponds to the Kondo temperature T_K [5].

The heavy fermion state in the cerium compound is understood as follows. At low temperatures, the magnetic entropy of the ground-state doublet in the crystal electric field (CEF) scheme of the 4f levels, $R\ln 2$, is obtained by integrating the magnetic specific heat C_m in the form of C_m/T over the temperature. When C_m is changed into the electronic specific heat γT via the many-body Kondo effect, the following relations are obtained:

$$R\ln 2 = \int_0^{T_K} \frac{C_m}{T}\,dT \tag{1}$$