Studies in heavy-fermion systems

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We briefly review the study of heavy-fermion behaviour in rare earth and actinide compounds. Possible origin of the heavy-fermion behaviour and the Kondo effect in insulators are discussed.

One of the most exciting problems that has emerged within the condensed matter during the last decade is the study of heavy-fermion (HF) systems at low temperatures. These systems usually consist of certain lanthanide (Ce or Yb) or actinide (U or Np) based intermetallic compounds. In the case of normal metals, the heat capacity at low temperatures ($T \ll \theta_d$) can be written as $C = \gamma T + \beta T^3$, where γ is the electronic heat capacity coefficient and β is due to the phonons. For a normal metal like Cu the value of γ as $T \to 0$ is only 0.7 mJ/mole K^2. But in the case of these HF systems, the value of γ can be 2 or 3 orders of magnitude larger than that of Cu. This implies a large effective mass for the charge carriers in HF systems and hence the name. Confirmation of large effective mass has come from the de Haas- van Alphen studies on HF compounds such as $CeCu_6$, UPt_3 and $CeRu_2Si_2$ (ref. 1) in which the effective mass ranges up to 120 m_e. It is of interest to note that HF behaviour appears only in compounds with f–f spacing sufficiently large that by Hill's criteria[2] they should be strongly magnetic. Instead, the ground states of these compounds can be superconducting, or paramagnetic, or magnetic with small ordered moment. A large gamma corresponds to a large density of states at the Fermi level and consequently the system has a large value of Pauli paramagnetic susceptibility. HF phenomena are confined to temperatures well below a characteristic temperature T_{coh} of the order of few tens of degrees K. Temperatures well above T_{coh}, the effective masses are of the values expected for usual (s-, p-, d-) conduction electrons and there exists a well defined local magnetic moment from the partially filled 4f or 5f shells of the lanthanide or actinide atoms[1].

Although not termed as HF, such a behaviour was first observed in the heat capacity studies of dilute magnetic impurities in noble metals[3]. For instance, a small amount of Cr in Cu gives rise to a contribution to the γ which (when scaled to one mole of Cr) reaches an enormous value of 6 J/mole K^2. This and other systems of dilute magnetic moment in noble metals have stable moment only above a certain characteristic temperature T^* which can be observed by fitting the magnetic susceptibility (χ) to the Curie–Weiss expression, $\chi = C/(T+\theta)$ well above T^*. As the temperature is lowered, a negative exchange coupling between the local moments and the conduction electrons shields the magnetic moment and experimentally, one observes a transition from the Curie–Weiss susceptibility to an enhanced Pauli paramagnetism. This can be understood by a compensation of the magnetic moment via polarization of the conduction electron spins in the vicinity of the impurity. This compensation process is accompanied by an increase of the electrical resistivity with decreasing temperatures which is proportional to $-\ln(T/T^*)$. This dependence was first derived by J. Kondo and thereafter considered as a 'fingerprint' of a Kondo system. At low temperatures, the scattering of the conduction electrons due to the impurities gives rise to the formation of a narrow resonance in the electronic density of states close to the Fermi energy E_F. This is called the Abrikosov–Suhl[4] resonance and for single spin $-1/2$ Kondo impurity, the binding energy of the singlet and width of the resonance are determined by the Kondo scale which is given as, $k_B T_F = D \exp(-1/J\,N(E_F))$ where D is the bandwidth and $N(E_F)$ is the density of states of the non-interacting conduction band. Thus, viewed from the single impurity limit, it is easy to understand how a non-magnetic ground state in HF could develop, as well as a large γ and χ that are proportional of $1/T_K$.

Many of the HF compounds undergo magnetic ordering at low temperatures with reduced magnetic moment[1]. The ground state of a HF system at low temperature is determined by the relative strength of the RKKY interaction ($T_N \propto J^2 N(E_F)$) to the Kondo interaction ($T_K \propto \exp(-1/JN(E_F))$) in this system. It is possible to have local magnetic ordering as in the case of $CeAl_2$ or itinerant magnetic ordering observed in $NpSn_3$. Usually, many HFs adopt antiferromagnetic ordering between these two extreme types. A few of them also exhibit ferromagnetic ordering at low temperatures. UCu_5 seems to be an extraordinary sample which shows ordering at 1 K in addition to the already known antiferromagnetic ordering at 15 K (ref. 4). This is probably the first well-documented system where the gap opens in the heavy-electron excitation spectrum probably due to CDW (charge density wave) ordering. In URh_2Ge_2 (ref. 5), we have a HF system where the resistivity increases and saturates down to 20 mK. It is not known whether it could be due to inherent site disorder in this system.

Another interesting result is the observation of Kondo effect in insulators like CeSb (ref. 6) which show multiple magnetic transitions at low temperatures. One does not expect Kondo effect in insulators because T_K decreases rapidly with the concentration of conduction electrons. Many insulating compounds of Ce and Yb with non-metals like As, Sb and Bi show such anomalous Kondo effect[6].

One of the most unusual phenomena in HF compounds is the observation of superconductivity. Although many HFs exist today, only six compounds show superconductivity at low temperatures. At least in five of them magnetic ordering is already established. Early experiments on $CeCu_2Si_2$ by Steglich and co-workers[1] showed bulk superconducting ordering in this sample with large heat capacity jump which proved the participation of HFs in superconductivity. Another feature of these superconductors is the large value for the temperature derivative of the upper critical field near T_c (for UBe_{13}, $dHc_2/dT = -40\,T/K$) (ref. 7).

Many properties of the HF superconductors in the superconducting state (for instance, heat capacity (C_P), the ratio of the ultrasonic attenuation coefficients in the superconducting and normal state (α_S/α_N)) and spin-lattice relaxation) exhibit power law dependence unlike the exponential dependence predicted by the normal BCS theory. Hence, the BCS theory using electron–phonon interaction is thought to be inadequate to explain the superconductivity in these samples. In the case of normal superconductor, the superconducting order parameter is a scalar and it is related to the density of superconducting electrons. However, in HF superconductors, the order parameter is a (2×2) matrix defined at each point **k** on the Fermi surface. The detail form of the order parameter is restricted by the crystal symmetry because of the strong spin–orbit interaction in metals[8]. Many theories have been put forth to explain the superconductivity in $CeCu_2Si_2$, UBe_{13}, URu_2Si_2 and UPt_3 (which is a prime candidate for anisotropic order parameter) and none of them is completely successful in explaining all the superconducting properties of these two materials. At present, the debate is still on whether the order parameter in UPt_3 is an even or odd parity under the symmetry operations belong to certain irreducible group corresponding to the total symmetry of UPt_3. In UPd_2Al_3, a first observation of Fulde–Ferrel–Larkin–Ovchinnikov (FFLO) state has been reported which shows that the Cooper pairs can have net momentum in certain temperature region in the B–T phase[9]. Such a state is possible because the orbital critical field is greater than the Clogston–Chandrasekhar paramagnetic limiting field.

The discovery of HF compounds has certainly enriched the horizons of both theoreticians and experimentalists studying rare earths and actinides compounds. Unusual superconductivity and Kondo effect in insulators have certainly opened up new avenues for interaction among the physicists, chemists and metallurgists in studying these materials. The future holds much more promise in this field which requires a dedicated ultra low temperature (< 5 mK) setup and crystal growing facility for actinides in our country.

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