HEAVY FERMIONS

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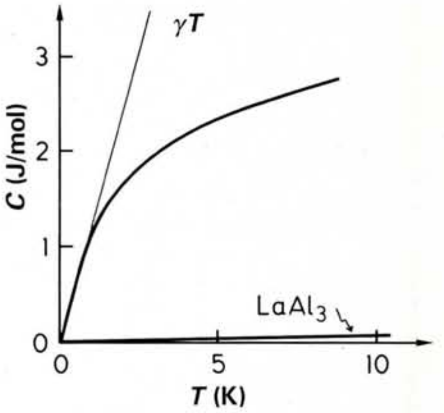

Schematic plot of the specific heat in $CeAl_3$. The linear behaviour at low T indicates a heavy Fermi liquid. For comparison, the curve for the related compound $LaAl_3$ is also included.

Over the past years, a new field has become established in metal physics which has already led to a number of interesting new phenomena. It deals with substances which have the characteristic feature that their low temperature thermodynamic properties are those of an ordering metal with very large electron masses. Generally the thermodynamics at low temperatures is determined by the quasiparticles of the system. These are excitations of the electronic system with energies $E \cong k_B T$ where T is the temperature and k_B is Boltzmann's constant. It is the mass of those quasiparticles which is found to be so large, in practice going up to more than 200 times the free electron mass m_e. The quasiparticles (or quasiholes) are therefore almost as heavy as μ mesons. Because they are fermions, these systems are called heavy fermion systems and at present approximately 15 heavy (or medium heavy) systems are known. They are predominantly Ce and U compounds and their number is steadily increasing.

It is clear that the large quasiparticle mass must result from strong electron correlations (many body effects). When an electron moves through the system, its motion requires rearrangements of other electrons in order to reduce the Coulomb repulsions. The quasiparticle, which can be considered as the complex consisting of an electron and its rearrangement cloud, moves then much more slowly than a free electron of the same energy. It acts therefore like a particle with a large mass.

Before discussing some of the characteristic properties of heavy fermion systems, let us see how one became aware of them.

In 1975 the obervation was made [1] that below 0.3 K the compound $CeAl_3$ had a linear specific heat $C = \gamma T$ with a Sommerfeld coefficient γ which is by three orders of magnitude larger than that of Na for example; γ is a measure of the conduction electron density of states which in turn is proportional to the effective mass m^*. An increase in γ therefore, must be interpreted as arising from an increase in the effective mass by nearly the same amount. The behaviour of $C(T)$ for $CeAl_3$ is shown schematically in Fig. 1.

One notices that the linear behaviour in T changes quickly as the temperature increases, and that at higher temperatures, $C(T)$ increases much more slowly. This indicates that the heavy quasiparticles exist only at temperatures $T < T^*$ where T^* is of the order of a few Kelvin. For $T >> T^*$ the quasiparticles lose their heavy masses and approach more and more the behaviour of free electrons. This is a characteristic feature of all heavy fermion systems and the rule is that the larger the low temperature m^* is, the smaller is T^*.

Another characteristic property of metals is a temperature independent Pauli paramagnetism. Like the specific heat coefficient γ, the magnetic susceptibility χ is also proportional to the density of states and therefore to the effective mass of the quasiparticles.

In accordance with this, $CeAl_3$ has a low temperature susceptibility which is constant and, by almost three orders of magnitude, larger than that of ordinary metals. The temperature independence of χ holds true though, only for $T < T^*$. For $T > T^*$, the susceptibility is Curie-like with a Curie constant as expected for a well localized 4f-electron per Ce site in a $J = 5/2$ multiplet. Therefore it appears that the magnetic moment of the Ce ions is quenched below T^* which reminds one of the Kondo effect (see separate panel). Since the ions with Kondo-like behaviour (*i.e.* the Ce ions) form a lattice, the heavy fermion Ce compounds are often also called "dense Kondo" or "Kondo lattice" systems.

The richness of the new physics opening up became clear after the surprising discovery of superconductivity in $CeCu_2Si_2$ [2]. This compound has an effective mass of $m^* = 220\ m_e$ below $T^* \cong 5$K and becomes superconducting at $T_c = 0.6$ K. The jump in the specific heat at T_c relates to the large specific heat coefficient γ and provides direct proof that the heavy quasiparticles are responsible for Cooper pair formation.

It was some time before it was generally accepted that $CeCu_2Si_2$ is a superconductor because Ce ions were known to destroy superconductivity. An example is Ce dissolved in $LaAl_2$ where the superconducting transition temperature is rapidly quenched as a function of the Ce concentration. This is due to the magnetic moments of the added Ce ions breaking up the Cooper pairs through their interaction with the conduction electrons.

In $CeCu_2Si_2$ the magnetic moments of the Ce ions are quenched at temperatures $T \leq T_c << T^*$. The related compound $LaCu_2Si_2$ is not superconducting and has no unusual effective mass, yet the only difference relative to $CeCu_2Si_2$ is the 4f-electron in the Ce ions. Therefore we must conclude that this 4f-electron is not only responsible for the heavy fermion behaviour of $CeCu_2Si_2$ but also for generating superconductivity in it.

After superconductivity in $CeCu_2Si_2$ became an undeniable fact, a considerable increase in research activity followed as a result of which a number of other heavy fermion systems were found to be superconductive, notably UBe_{13} and UPt_3. The experimental situation has been summarized in a recent review [3].

The following questions have been intensively discussed in the literature:

(a) what is the interaction mechanism between the quasiparticles which leads to their mutual attraction and therefore Cooper pair formation?

(b) what kind of Cooper pairs do form, *i.e.*, are we dealing with spin-singlet pairing as in ordinary superconductors or with spin-triplet pairing as in ^{3}He?

From careful Josephson current measurements it seems certain by now that superconducting $CeCu_2Si_2$ is in a singlet pairing state. For the U compounds the question is still undecided and further research is required. In any case the superconducting order parameter is expected to be anisotropic in momentum space, because the Fermi surface will be anisotropic in the heavy fermion systems.

Now that singlet pairing has been established in $CeCu_2Si_2$, there is little doubt that the mutual quasiparticle attraction leading to superconductivity is due to phonons in that substance. Again, for the U compounds this is still an open question and it is conceivable that there the quasiparticle-phonon interaction is unimportant for the Cooper pair formation. Instead, the quasiparticle attraction would have to result from Coulomb and exchange interactions within the electronic system, with the ion positions kept fixed.

The quasiparticle-phonon interaction in heavy fermion systems is an interesting problem in itself. Consider the Ce compounds for example. For $T > T^*$ the interactions between the 4f-electron and phonons are well understood (see *e.g.* Ref. 4). The 4f-electron of a Ce ion can be considered as well localized and its eigenstates are described by conventional crystal field theory. Lattice vibrations (phonons) change this crystal field and therefore the eigenstates of the 4f-electron. This provides a coupling mechanism between the two. Below T^* the 4f-electron must be considered as partially delocalized because a heavy fermion liquid forms. Then a deformation potential coupling between phonons and quasiparticles will take place as in any other metal. Only the coupling constant has to be determined anew. It turns out that it is determined by the pressure (or volume) dependence of T^*. This dependence can be measured experimentally and the quasiparticle-phonon interaction is therefore well characterized.

Let us now turn to a quantitative description of the quasiparticles. In particular we want to determine the dispersion $E(\mathbf{k})$, *i.e.* the energy bands of a quasiparticle. In the zero temperature limit, when the magnetic moment of the Ce ions has disappeared, we can characterize the ions of a heavy fermion system as in any other nonmagnetic metal by a scattering potential. An equivalent description is in terms of energy dependent phase shifts for different angular momenta ℓ. The problem consists then in determining these phase shifts. From the above discussion it is clear that the $\ell = 3$ or f-phase shift at the Ce sites must play a distinct role because it is the delocalization of the 4f-electrons which results in the heavy quasiparticles at low temperatures. Let us single out this phase shift and determine all the remaining phase shifts as in any other metal, *i.e.* by solving a one-particle Schrödinger equation with the potentials determined according to the local density approximation (LDA) to the density-functional method. Powerful linearized methods are available for performing such calculations even for large unit cells. This way one can determine all phase shifts with the exception of the one for $\ell = 3$ at the Ce sites. That phase shift cannot be determined by making a local density approximation because the latter cannot describe the many-body features which lead to the Kondo effect. Therefore one makes for it the simplest possible ansatz by expanding it around the Fermi energy ε_F:

$$\delta(\varepsilon) = \delta_o + \alpha(\varepsilon - \varepsilon_F). \qquad (1)$$

For $\ell = 3$ and $J = 5/2$ there are $2J+1 = 6$ scattering channels. Only those of the six channels which are known to form the crystal field ground state have a non-vanishing phase shift. They can be determined by inelastic neutron scattering experiments at $T > T^*$.

Eq. (1) contains two unknown parameters, i.e. δ_o and α. The parameter δ_o is determined by a sum rule due to Friedel which relates it to the 4f-electron occupancy $n_f \cong 1$. The other parameter α is adjusted so that in the end the right effective mass of the quasiparticles is obtained. One can set $\alpha = 1/T_K$ and define this way a Kondo temperature for the lattice. T_K is then approximately equal to T^* considered before.

When the Schrödinger equation is solved again, with the phase shift (1) taken into account, one finds the quasiparticle dispersion curves $E(\mathbf{k})$. The strong energy dependence of $\delta(\varepsilon)$ leads to a narrow resonance of width $k_B T_K$ at the Fermi surface which can describe the large effective masses of the quasiparticles.

Within the above computational scheme one can perform realistic calculations of quasiparticle-excitation bands. This has indeed been done for $CeCu_2Si_2$ [5]. One interesting result is that close to the Fermi surface there are excitations corresponding to heavy masses as well as light masses. The latter do not contribute appreciably to the specific heat and susceptibility because of their low density of states, but it is conceivable that they play an important role in the transport properties.

One is dealing here with a new class of metals which have extraordinary anisotropies. For example, the superconducting properties should be different for the heavy and light quasiparticles and we expect that the light ones will cause a vanishing energy gap in the single-particle tunnelling density of states. Presumably there will be many more investigations of this topic in the future.

The heavy quasiparticle excitations are almost entirely of f-character. However, the narrow bands close to the Fermi energy do not imply in any way a single-particle approximation for an f-electron wave function. The contrary is true. Photoelectron spectroscopy data demonstrate that it takes approximately 2 eV in order to knock out an f-electron from a Ce ion in $CeCu_2Si_2$. Yet, with respect to the low temperature thermodynamic properties, the f-electrons show up right at the Fermi surface. There is no contradiction though between these two facts, because in a strongly correlated system high frequency and low frequency excitations behave very differently.

In conclusion one may state that the field of heavy fermions or almost localized electrons has started to develop into a

THE KONDO EFFECT

The Kondo effect was discovered in 1964 [1]) by J. Kondo who considered a magnetic ion embedded in a sea of conduction electrons with which it interacted through an antiferromagnetic exchange interaction:

$$H_{int} = J_{ex}\mathbf{s}(0)\mathbf{S}.$$

Here $\mathbf{s}(0)$ is the conduction electron spin at the site of the magnetic ion which has a spin $\mathbf{S}$. He found that due to the internal degrees of freedom of the ion (it can flip its spin) a perturbation expansion in terms of H_{int} breaks down at low temperatures. The interacting magnetic ion-conduction electron system becomes an interesting many-body problem which requires complex theoretical methods for its solution. Exact solutions have been found only recently after many years of research (see *e.g.* Ref. 2). The magnetic susceptibility χ of the magnetic ion was shown to change from a Curie-like behaviour at high temperatures to saturation in the limit $T \rightarrow 0$. The cross-over occurs at a temperature T_K, the Kondo temperature. In the low temperature limit $\chi = \pi / T_K$. A quasiparticle description of the low temperature properties of the single-ion Kondo problem has been given [3]).

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fruitful field of research. Its present state is described in Ref. 5 which we recommend for further consultation.

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EPS Lecturer 1985/1986

The EPS Lecturer for 1985/86 is **Professor H. Haken** of the University of Stuttgart. He is well known especially for his original work on "Synergetics"* but he has also made basic contributions to the quantum field theory of the solid state, to statistical physics and to quantum optics. Professor Haken's lecture tour will consist of two parts: from 20 October until 7 November 1985 he will visit three Scandinavian countries and England, and then next year he will spend two-three weeks in January/February travelling through France, Portugal, Spain, Italy and Israel.

He will be presenting three lectures:
1. *Synergetics, an overview*
2. *Theory of non-equilibrium phase transitions, slaving principle and order parameters*
3. *Pattern formation in systems far from thermal equilibrium.*

Programme of the First Part

	Date, 1985	Location	Time	Lecture	Contact
Oct.	21	Helsinki	14.30	1	S. Stenholm
	22	Helsinki	10:30	3	S. Stenholm
	23	Turku	14:15	1	M. Punkkinen
	24	Turku	10:15	2	M. Punkkinen
	25	Stockholm	10:00	1	B. Nagel
	25	Stockholm	14:00	3	B. Nagel
	28	Göteborg	15:15	3	B. Lundqvist
	29	Göteborg	15:15	1	B. Lundqvist
	30	Lund	15:30	1	B.E. Svensson
	31	Lund	10:30	3	B.E. Svensson
Nov.	1	Lyngby	15:00	1	P. Christianssen
	4	Bristol	14:15	3	R.G. Chambers
	4	Bristol	17:00	1	R.G. Chambers
	6	Birmingham	17:00	1	W.F. Vinen
	6 or 7	Birmingham	14:15	2	W.F. Vinen

The programme of the second part will be published in the November/December issue of *Europhysics News*.

* see for example *Europhysics News* **7** (1976) 7/8, 9.

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