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Electronic instabilities in heavy-fermion compounds

A. de Visser[a], J. Flouquet[b], J.J.M. Franse[a], P. Haen[b], K. Hasselbach[b], A. Lacerda[b] and L. Taillefer[b]

[a]*Natuurkundig Laboratorium, Universiteit van Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands*
[b]*Centre de Recherches sur les Très Basses Températures, C.N.R.S., BP 166 X, 38042 Grenoble Cédex, France*

Invited paper.

We discuss a series of experiments that evidence that most of the heavy-fermion compounds are close to an electronic or magnetic instability. In the approach of the magnetic instability, the volume plays a major role, as follows from a Grüneisen parameter study. We illustrate our viewpoint by a study of the appearance of long-range magnetic order on doping in UPt_3 and $CeRu_2Si_2$ and, in particular by an extensive study of the metamagnetic-like transition in the latter compound. Finally, we draw attention to the possibility of an unconventional superconducting ground state in the U-based heavy-fermion superconductors.

1. Introduction

The experimentally observed large coefficient, γ, of the linear electronic specific heat in heavy-fermion systems is attributed to the low-temperature formation of a highly correlated electron band close to the Fermi level. Heavy-fermion behaviour is found in some selected Ce, Yb and U intermetallic compounds, as a result of the hybridization of the f electrons with the p or d orbitals of the ligand atoms. In the past few years, it has become clear that the degree of hybridization is extremely sensitive to shape and volume effects and that large changes, of the order of a factor 10–100, of the density of states can be achieved by applying an external or chemical pressure. Hence, the degree of delocalization of the f electrons can be tuned to a large extent and, as such, allows for a study of the competition between the local and itinerant character of the f electrons. Concurrently a wealth of physical phenomena can occur in such tunable heavy-fermion systems as a large diversity of electron excitations and magnetic interactions is brought about.

Among the ingredients that build up the correlated electrons are the Kondo screening, the RKKY interaction and the direct exchange J_{ij}. As a result, a number of energy scales with characteristic temperatures are observed experimentally: (i) the single ion Kondo temperature T_K (~100 K); (ii) the coherence temperature T_{coh} (of the order of a few K), below which coherent scattering at the correlated f electrons takes place; (iii) the (spin) fluctuation temperature T_{sf} (of the order of 10 K), below which antiferromagnetic intersite correlations are well stabilized; and (iv) the crystal field temperature $T_{cf} = \Delta / k_B$ (~100 K) where Δ is the energy separation between the ground state and the first excited level. However, the possible admixture of these interactions makes in many cases a clearcut experimental observation of the characteristic temperatures a difficult task. Furthermore, the admixture shades a clear theoretical description of the observed phenomena and makes a quantitative analysis of the experimental data arduous. This also holds for the problem of the ground state. Some heavy-fermion compounds remain a Pauli paramagnet down to the lowest temperatures investigated (~10 mK), others become an antiferromagnet ($T_N \sim 10$ K) or, most surprisingly, a superconductor ($T_c \sim 1$ K). While the occurrence of long-range anti-

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ferromagnetism (mostly of the spin density wave type) can be conceived from the forementioned presence of magnetic interactions, this is certainly not the case for the occurrence of superconductivity. The unusual properties of the superconducting state and the conjecture that an electron–electron mechanism, rather than an electron–phonon mechanism, mediates superconductivity has attracted much attention to the class of heavy-fermion compounds.

The aim of this paper is to review a number of trends or similarities in heavy-fermion compounds and to highlight these by a few prime experiments. It is organized as follows. In the first section we signalize the large volume effects that are related with the onset of the heavy-fermion behaviour as deduced from a Grüneisen parameter study. Next, we discuss the proximity of a magnetic instability. We illustrate this by alloying studies, that give rise to the occurrence of long-range magnetic order, and by a study of the metamagnetic-like transition observed in some of the compounds. Finally, we draw the attention to the appealing possibility of an unconventional superconducting state in the U based heavy-fermion superconductors.

2. Grüneisen parameters

An elegant way to probe the presence of different energy scales is by means of thermodynamic Grüneisen parameters. Crudely spoken, the Grüneisen parameter expresses the quotient of the pressure variation and the temperature variation of the entropy and can be determined experimentally from measurements of the coefficient of volume expansion and the specific heat. For practical purposes it is convenient to define a temperature dependent Grüneisen parameter

$$\Gamma_{\mathrm{eff}}(T) = \frac{V_{\mathrm{m}}\alpha_V(T)}{\kappa_s c_p(T)}\ , \tag{1}$$

where V_{m} is the molar volume, κ_s is the adiabatic compressibility and $\alpha_V(T)$ and $c_p(T)$ represent the temperature variation of the volume thermal expansion and specific heat at constant pressure, respectively. $\Gamma_{\mathrm{eff}}(T)$ has been investigated for a number of heavy-fermion compounds [1, 2]. In fig. 1 we show $\Gamma_{\mathrm{eff}}(T)$ for $CeCu_6$, $CeRu_2Si_2$, UPt_3 and UBe_{13}. It appears that $\Gamma_{\mathrm{eff}}(T)$ varies rapidly with temperature. In the low-temperature limit, we can define a heavy-fermion Grüneisen parameter that is connected to the linear terms in the specific heat, $c = \gamma T$, and thermal expansion, $\alpha_V = 3aT$,

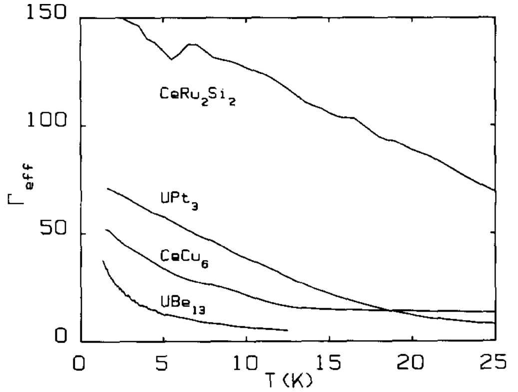

Fig. 1. Effective Grüneisen parameter for $CeCu_6$, $CeRu_2Si_2$, UBe_{13} and UPt_3. For the Ce compounds, the phonon contribution has been subtracted (after ref. [1]).

$$\Gamma_{\mathrm{hf}} = \lim_{T\to 0} \Gamma_{\mathrm{eff}} = \frac{3V_{\mathrm{m}}a}{\kappa_s\gamma} = -\frac{\partial \ln T^*}{\partial \ln V}\ , \tag{2}$$

where $T^*(V)$ is the characteristic temperature for the Fermi liquid. A common feature of the heavy-fermion compounds is that Γ_{hf} is anomalously large, i.e. one or two orders of magnitude larger than the electronic Grüneisen parameter in ordinary metals [1, 3]. Γ_{hf} amounts up to 57 for $CeCu_6$, 160 for $CeRu_2Si_2$, 25 for URu_2Si_2, 60 for UBe_{13} and 71 for UPt_3. Similarly large values have been reported for $CeAl_3$ (-200 [4]) and $CeCu_2Si_2$ (up to 80 [3]). The large value of Γ_{hf} will magnify any small volume change (δV) and thus gives rise to a fictitious volume change $\Gamma\,\delta V/V$. In many cases in solid state physics a change of a few percent in the volume induces drastic changes in the electronic and lattice properties. For $\Gamma_{\mathrm{hf}} \sim 100$, one thus might expect similar transitions for a bare volume change of the order of 10^{-4}. Thus the large Grüneisen parameter implies that the volume plays an important, if not major, role in the electronic and magnetic instabilities in heavy-fermion compounds.

3. Magnetic instabilities

An intriguing common feature of heavy-fermion compounds seems to be the occurrence of small ordered moments developing out of antiferromagnetic fluctuations at low temperatures. At present, it has been illustrated by various microprobe techniques (μSR, NMR and neutron scattering) that the heavy-fermion compounds URu_2Si_2 ($T_N = 17.5$ K [5]), $CeAl_3$ ($T_N \leq 1$ K [6]) and UPt_3 ($T_N = 5$ K [7]) (might) undergo such phase transitions. Long-range antiferromagnetism has also been reported for non-superconducting $CeCu_2Si_2$ ($T_N = 3.5$ K [8]), possibly for superconducting $CeCu_2Si_2$ ($T_N = 0.6$ K [9]) and, recently, for UBe_{13} ($T_N = 8.8$ K from magnetostriction measurements [10]). However, in the latter two compounds no evidence from microscopic measurements has been presented thus far. Apparently, only $CeRu_2Si_2$ and $CeCu_6$ remain in a Pauli paramagnetic state down to the lowest temperature investigated (~10 mK). However, the measured ordered moments are in most cases extremely small, i.e., in the order of $0.01\mu_B$/f-atom. The itinerant character of the magnetic order makes, furthermore, a direct observation of T_N by macroscopic techniques as specific heat very difficult as the involved entropy is correspondingly small. The appearance of an antiferromagnetic ground state with small ordered moments is certainly appealing, given our basic view point that the heavy-fermion systems are close to an electronic or magnetic instability, but, as a certain sample dependence is observed and as the different experimental probes not always lead to consistent results, the problem of the small ordered moment is not completely sealed experimentally yet. We illustrate this by the case of UPt_3.

A first indication of magnetic order in UPt_3 was deduced from μSR experiments [11], in which below 4 K very slow spin fluctuations, corresponding to an ordered moment of $10^{-3}\mu_B$, were observed. In subsequent neutron diffraction work, Aeppli et al. [7] showed that UPt_3 can be an antiferromagnet with an ordered moment of $(0.02 \pm 0.01)\mu_B$/U-atom and a Néel temperature $T_N = 5$ K. Although this has been confirmed by Hayden et al. [12] on a sample from a different origin, Frings et al. [13] performed neutron diffraction studies on two samples of different sources, and found that antiferromagnetic order was present in one of the samples only ($T_N = 5$ K, $|\vec{\mu}| = 0.01\mu_B$/U-atom). Also careful NMR measurements on annealed powders have not led to the detection of antiferromagnetism yet [14]. In that respect, it is interesting to note that the diffraction peaks are not resolution limited and that a magnetic coherence length of ~150 Å results [7]. The detection of antiferromagnetic order in UPt_3 is a consequence of preceding studies on the alloyed systems $U(Pt_{1-x}Pd_x)_3$ [15] and $U_{1-y}Th_yPt_3$ [16] in which antiferromagnetic order appears (with a maximum T_N of 6 K) for $0.02 \leq x \leq 0.10$ and $0.02 \leq y \leq 0.10$, respectively. The antiferromagnetic order, of the spin density wave type, was hinted [15, 16] by sharp anomalies in the specific heat and the resistivity and confirmed by neutron diffraction experiments on $U(Pt_{0.95}Pd_{0.05})_3$ [17] and $U_{0.95}Th_{0.05}Pt_3$ [18], with a resulting ordered moment of $(0.6 \pm 0.2)\mu_B$/U-atom pointing along the hexagonal *b* axis in both 5% compounds. In a search for antiferromagnetic fluctuations in pure UPt_3 along the *b* axis, Aeppli et al. and Frings et al. observed the forementioned weak magnetic Bragg scattering, with the same ordering vector, below $T_N = 5$ K. The magnetic phase diagram [19] (fig. 2) indicates that antiferromagnetism with large ordered moments occurs only in a limited range of substitutions. At present, it is not clear how the antiferromagnetism with small ordered moments, as observed for pure UPt_3, develops with Pd or Th concentration. A delicate Fermi surface nesting, explaining the different magnitudes of the moments observed in the pure and doped system, cannot be excluded. More detailed studies [20, 21] have shown that long-range antiferromagnetism also appears when UPt_3 is doped with 5 at.% Au, while 5% substitutions of Ir, Rh, Y, Ce and Os do not lead to

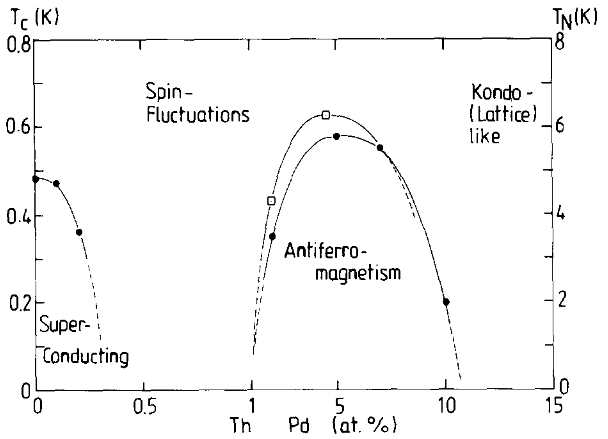

Fig. 2. Magnetic phase diagram for the $U(Pt_{1-x}Pd_x)_3$ (closed circles) and $U_{1-y}Th_yPt_3$ (open squares) compounds [19]. Note that long-range antiferromagnetism ($T_N = 5$ K) has also been reported for $x = y = 0$ (the scale up to 1 at.% is expanded).

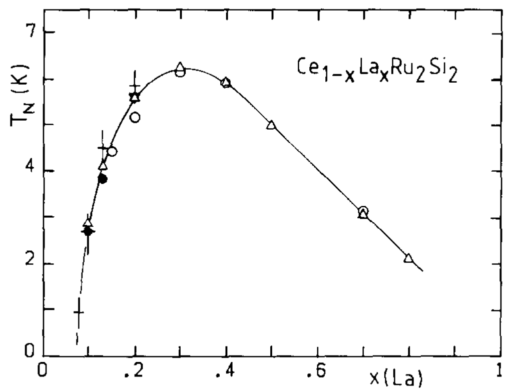

Fig. 3. Neél temperature as function of La concentration in $Ce_{1-x}La_xRu_2Si_2$ [24].

magnetic order. It has been suggested [20] that the change in the c/a ratio is here the dominant factor, indicating the strong influence of shape effects on the hybridization. The entropy associated with the magnetic order in the doped compounds amounts only to about $0.1R \ln 2$ [15] assuring the itinerant character of the ordered moments.

The proximity of the magnetic instability is also well illustrated by the sensitivity of $CeRu_2Si_2$ to substitution of, e.g. Ru by Rh [22] or Os and Si by Ge [23], or Ce by Y or La [24], which allows for a distinct γ variation and in some cases to the transition to a long-range ordered state. As an example, we present in fig. 3 the phase diagram for $Ce_{1-x}La_xRu_2Si_2$ [24], where long-range antiferromagnetism appears near a critical concentration of 7% La. The maximum T_N amounts to ~6 K for $x \simeq 0.30$, and the ordering vector is incommensurate [$\boldsymbol{k} = (0.309, 0, 0)$] [24]. It is not surprising that the intersite correlations observed for pure $CeRu_2Si_2$ by inelastic neutron scattering experiments [25] have the same $\boldsymbol{k}$ dependence. The appearance of long-range order in the doped $Ce_{1-x}La_xRu_2Si_2$ alloys is closely related to the change in volume on doping. For instance, in the case of La doping the volume increases, which first leads to an enhancement of the γ-value, but when a certain critical value [24] is attained (near 7% La) the system transits to the ordered state and only above this concentration the γ-value starts to drop. Below the critical concentration the hybridization is thought to inhibit the divergence of the magnetic correlation length and thus to prevent long-range order. However, and this is most important, in the ordered state magnetic fluctuations are still present as evidenced by neutron scattering experiments [26] and anomalies reminiscent of the metamagnetic-like transition (see the next section) found in the field induced paramagnetic phase by magnetization [27] and magnetostriction [28] experiments. The heavy-fermion behaviour also persists in the ordered state in the $U(Pt, Pd)_3$ alloys [15, 28]. A first study of the volume effects at the magnetic phase transitions in heavy-fermion systems [28] reveals a strong increase of the volume in the ordered state, consistent with alloying and external pressure experiments. Recent experiments on $CeCu_{6-x}Au_x$ [29], that reveal long-range order for $x \geq 0.1$, have been interpreted in a similar way.

4. Metamagnetism

Another way to clarify the nature of the magnetic interactions in the heavy-fermion compounds is by applying an external magnetic field. In general, if anomalies in the susceptibility (e.g.

maxima) are observed at an energy $k_B T^*$, a nonlinearity in the magnetization is observed at about the same energy μB^*. The compounds UPt_3 and $CeRu_2Si_2$ indeed show a maximum in χ at a temperature of 17 K [30] and 10 K [31], respectively, and a strong increase in the low-temperature magnetization at $B^* = 20$ T [30] and 8 T [31], respectively. Magnetoresistance measurements [31, 32] have revealed that $\rho(B)$ passes through a maximum at B^*, which strongly suggests that B^* coincides with the collapse of the antiferromagnetic correlations. Inelastic neutron scattering experiments in field [25] yield direct evidence for this in the case of $CeRu_2Si_2$: the intersite contribution to the magnetic signal is suppressed in fields above B^*, while the contribution from the on-site Kondo-type fluctuations is almost field independent (up to 10 T). The similarity of $\chi(T)$, $\rho(B)$ and $m(B)$ for $CeRu_2Si_2$ and UPt_3 suggests that an identical mechanism lies at the origin of the metamagnetic-like transition, the main difference being that in the case of $CeRu_2Si_2$ the transition occurs for a field along the tetragonal axis and thus has a unidimensional character, whereas for UPt_3 the transition takes place for a field in the basal plane (bidimensional character). As $B^* \sim 8$ T in $CeRu_2Si_2$, and thus is easily accessible experimentally, the transition has been studied in great detail.

An interesting aspect of the metamagnetic-like transition is its nature at $T = 0$ K, and, in particular the mass enhancement at B^*. Extensive magnetization, magnetostriction and thermal expansion measurements in field have been performed recently on $CeRu_2Si_2$ for $T > 100$ mK [33] in order to shed light on these questions. Several elucidating conclusions could be made. First, the temperature interval where the characteristic Fermi-liquid behaviour is observed ($c = \gamma T$, $\rho = AT^2$) drops rapidly on approaching B^*, and as a consequence measurements near B^* should be performed at very low temperatures ($T <$ 200 mK) in order to perform an adequate analysis. Secondly, the width of the transition as obtained by magnetostriction measurements becomes extremely small for $T \rightarrow 0$ (see fig. 4). At $T = 1.3$ K, the half width at the full maximum of λ'_V ($= V^{-1}$ dV/dB) amounts to 0.56 T, whereas at 130 mK ΔB equals only 0.04 T. The temperature variation of ΔB obtained [33] suggests that ΔB remains finite at $T = 0$ K for the investigated sample, and, therefore, the transition seems to remain continuous at $T = 0$ K. However, one cannot exclude that eventually the transition becomes of first order for two reasons. First, the demagnetizing effects become important in this narrow field range and we estimate that a proper correction sharpens the transition quite a bit. Secondly, a similar study on $Ce_{0.95}La_{0.05}Ru_2Si_2$ ($B^* = 5.3$ T) [33] shows that all the anomalies connected with B^* are considerably broadened. Since the $CeRu_2Si_2$ sample used in these investigations has a residual resistance ρ_0 of the order of 3 μΩ cm at B^*, a broadening ΔB due to sample inhomogeneities cannot be excluded. The phase diagram (T_m, B) that delimites the antiferromagnetically correlated phase from the field induced polarized phase is shown in fig. 5. T_m drops rapidly on approaching B^*. However, the exact shape of the phase boundary near B^* is not known yet and it is not clear whether a real phase transition occurs at $T = 0$ K. The possibility that quantum fluctuations present a phase transition at $T = 0$ K is appealing, but, given the present experimental results, difficult to proof. A third interesting aspect of this study is the mass enhancement as function of the applied field, $m_{eff}(B)$, that we take proportional to $\gamma(B)$. The mass enhancement has been determined in three

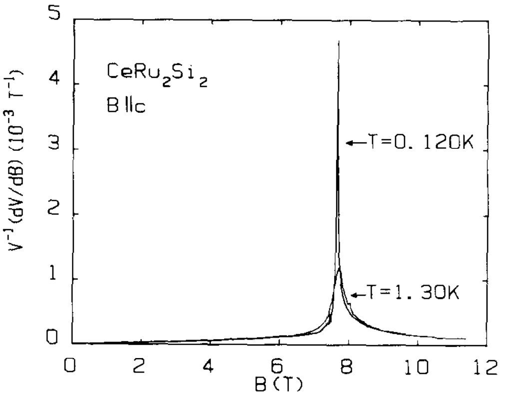

Fig. 4. Coefficient of volume magnetostriction for $CeRu_2Si_2$ for $B \| c$ at temperatures as indicated (after ref. [33]).

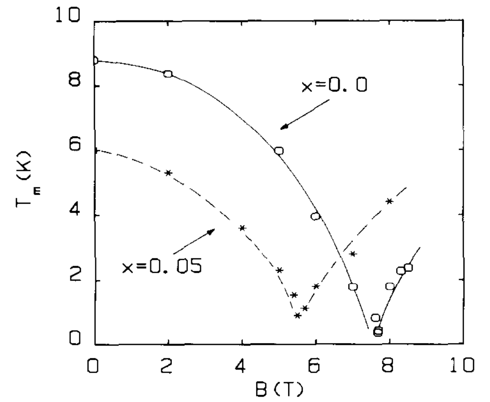

Fig. 5. Field dependence of the temperature T_m where the extremum in the volume expansion occurs for $B \| c$ for $Ce_{1-x}La_xRu_2Si_2$ for $x = 0$ (○) and $x = 0.05$ (*) (after ref. [33]).

ways: (i) experimentally by specific heat measurements in an applied field, but only few data are available [34]; (ii) from the field variation of the linear coefficient in the thermal expansion using scaling theory; and (iii) from the T^2 dependence of the magnetization via the Maxwell relation $\partial M/\partial T|_{p,B} = \partial S/\partial B|_p$. The three methods are in good agreement with each other, and the results obtained from the susceptibility data are shown in fig. 6, plotted as a function of the reduced variable $\delta = (B - B^*)/B^*$. Before leveling off as $\delta \rightarrow 0$, γ follows a linear $\sqrt{|\delta|}$ variation with an extrapolation $\gamma_c(B \rightarrow B^*) = 650\,\mathrm{mJ/mol\,K^2}$ (while γ equals $350\,\mathrm{mJ/mol\,K^2}$ at $B = 0$). Interestingly, this value is close to the maximum γ-value for $x = 0.05$ at B^* [33] and to the γ-value at which magnetic order appears for the doped compounds (see previous section). This strongly suggests that a critical γ-value is found at the magnetic instability in (Ce, La)Ru_2Si_2. In the case of UPt_3, γ increases from $425\,\mathrm{mJ/mol\,K^2}$ at $B = 0$ up to a value of $\sim 620\,\mathrm{mJ/mol\,K^2}$ at $B^* = 20\,\mathrm{T}$ [35]. The critical γ value for the appearance of long-range antiferromagnetism on doping with Pd is, however, considerably smaller: $\sim 500\,\mathrm{mJ/mol\,K^2}$ for 1% Pd atoms [15].

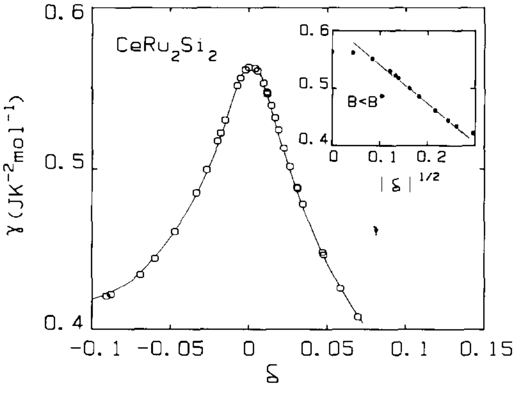

Fig. 6. The γ-value for $CeRu_2Si_2$ (calculated from the low temperature T^2 term in the magnetization) as function of the reduced variable $\delta = (B - B^*)/B^*$. The insert shows the γ value as function of $|\delta|^{1/2}$ for $B < B^*$. The solid lines are guides to the eye. At $B = 0$, γ equals $350\,\mathrm{mJ/mol\,K^2}$ (after [33]).

Another system that exhibits a strong field variation of the mass enhancement is $CeCu_6$ ($\gamma = 1600\,\mathrm{mJ/mol\,K^2}$). The magnetoresistance [36] measured for $B \| [0\,0\,1]$ has a shallow maximum at 2 T below ~300 mK. Low-temperature neutron scattering data in field [25] lend support for a drastic change of the intersite correlations at $B_{c1} = 2\,\mathrm{T}$ and a collapse at $B_{c2} \sim 4\,\mathrm{T}$. Low-temperature sound velocity [37] and magnetostriction [38] measurements give also evidence for the presence of two anomalies at ~2 and ~4 T. Furthermore, measurements [39] of the second derivative of the magnetization versus field, $\partial^2 M/\partial H^2$, indicate also such cross-over fields. The absence of maxima in the first derivative of the magnetization, $\partial M/\partial H$, (characteristic for the metamagnetic-like transition) in contrast to the previous cases of $CeRu_2Si_2$ and UPt_3, coincides with the weak magnetostriction effects at the cross-over fields [38].

5. Superconductivity

The discovery of a superconducting ground state in $CeCu_2Si_2$ ($T_c \sim 0.7\,\mathrm{K}$), UBe_{13} ($T_c \sim 0.8\,\mathrm{K}$), UPt_3 ($T_c \sim 0.5\,\mathrm{K}$) and URu_2Si_2 ($T_c \sim 1\,\mathrm{K}$) came rather unexpected, as the mass renormalization in the heavy-fermion systems arises from strong magnetic interactions. As also the upper critical field is unusually large for superconductors with such a low T_c (H_{c2} is in the order of a few tesla at $T = 0\,\mathrm{K}$), unconventional pairing models, based on an attractive electron–

electron interaction, rather than on an electron–phonon mechanism, have been proposed. Since then, a wide assortment of experimental and theoretical expertise has been applied to investigate whether the superconducting condensate is of an unconventional nature. The electronic excitation spectrum below T_c, as obtained from the electronic specific heat, the thermal conductivity, the acoustic attenuation and the nuclear relaxation time, was found to have a power law temperature dependence, instead of the usual exponential temperature dependence. This has been taken as evidence for a strongly anisotropic gap function, with nodes or lines of zero's, and an interpretation in terms of p or d wave superconductivity has been put forward. However, as the relevant temperature interval ($T \ll T_c$) has not been probed reliably yet, and as conflicting results are found in the literature, this interpretation is still controversial.

Recently, another type of evidence for unconventional superconductivity in some of the heavy-fermion superconductors has been reported, namely structures in the $H_{c2}(T)$ curve and notably the appearance of anomalies within the superconducting phase. Perhaps the most direct evidence comes from thermodynamic measurements, that in two cases revealed a double peak structure in the superconducting regime. On alloying UBe_{13} with Th, a second peak below T_c appears in a limited concentration range (~3% Th) [40]. μSR studies [11] have shown that a magnetic signal appears below the second transition, but, at present, it is not clear whether this signal arises from a magnetic phase with small ordered moments, or from a second superconducting phase possessing orbital or spin moments.

In the case of UPt_3, specific heat data [41, 42] taken on different types of samples clearly resolved a double transition, with a temperature separation of 60 mK, i.e. about $\frac{1}{10}T_c$. The smallness of the splitting has been taken as evidence for the presence of a symmetry breaking field. It has been proposed [43] that the symmetry breaking field in UPt_3 is provided by the weak magnetic order at 5 K. The magnetic order distorts the hexagonal symmetry, lifts the degeneracy of T_c, thus causing the double transition. From group theoretical work [43], it has been inferred that a multiplicity of superconducting phases can be brought about by a coupling of the magnetic and superconducting order parameters, and might give rise to unconventional superconducting phase diagrams. Extensive experimental studies of thermodynamic properties in field, as the specific heat [42, 44], the thermal expansion [44] and the sound velocity [45], have indeed led to the observation of such phase diagrams. In order to illustrate this we show in fig. 7 the H–T phase diagram for UPt_3, with a field along [44] and perpendicular [42] to the hexagonal axis. From fig. 7, it follows that the phase diagrams are rather similar. Three distinct superconduct-

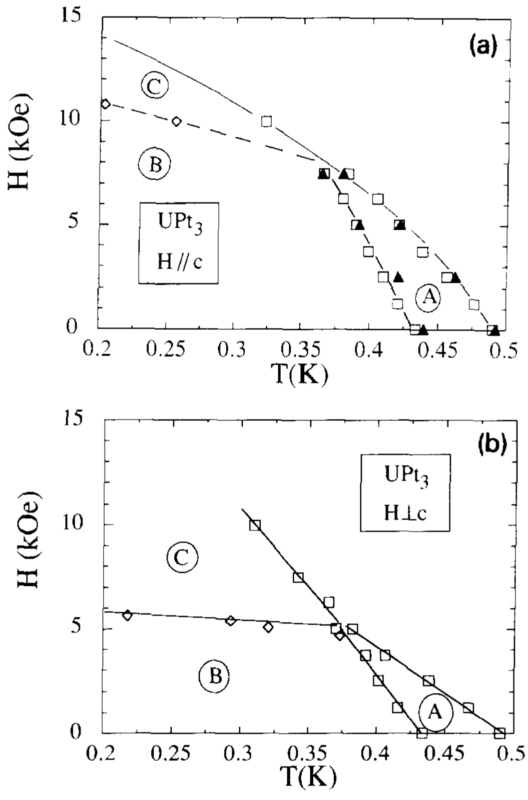

Fig. 7. Multicomponent phase diagram of superconducting UPt_3 as determined from specific heat (open squares) [42, 44], thermal-expansion (closed triangles) [44] and sound-velocity measurements (open diamonds) [45], in applied magnetic fields (a) along and (b) perpendicular to the hexagonal axis. The three distinct superconducting regions are labeled A, B and C (after [42, 44]).

ing regions occur. For a full discussion of the experimental results we refer to refs. [44] and [46]. The isotropy of the phase diagram with respect to the field orientation cannot be explained within the present theoretical models and urges for more theoretical insight, in particular in the role of the symmetry breaking field. A hard proof of the direct coupling between the splitting of T_c and the symmetry breaking field is still lacking. As the long-range weak magnetic order has not been observed in all the samples, and thus might be attributed to imperfections (impurities or defects), a similar conclusion for the double superconducting transition cannot be ruled out completely.

In the two remaining superconductors, $CeCu_2Si_2$ and URu_2Si_2, superconductivity also occurs within an antiferromagnetically ordered state (T_N equals 0.7 and 17.5 K, respectively). In the case of $CeCu_2Si_2$, decisive evidence for conventional singlet-type of superconductivity has been put forward [8], whereas the experimental situation in URu_2Si_2 is less clear, as no sharp thermodynamic superconducting transitions have been observed thus far. It is interesting to note that for $CeCu_2Si_2$ an electron–phonon pairing mechanism, based on the strong Grüneisen parameter coupling via the Kondo screening, has been proposed [47]. In the U based heavy-fermion superconductors

$$\frac{\partial \ln T_c}{\partial \ln V} \cong -\frac{\partial \ln T^*}{\partial \ln V} \tag{3}$$

(see, e.g. ref. [48] for data on UPt_3) suggesting a close connection between the Fermi-liquid and superconducting properties, and thus a pairing mechanism mediated by the electron–electron interactions, i.e., the antiferromagnetic spin fluctuations, is anticipated.

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