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$T_c$ for heavy fermion superconductors linked with other physical properties at zero and applied pressure

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Abstract

The superconducting transition temperature $T_c$ has earlier been correlated with coherence length and effective mass for a series of heavy fermion (HF) materials at atmospheric pressure. Here, a further physical property, the dc electrical conductivity $\sigma(T_c)$, is one focal point, another being the pressure dependence of both $T_c$ and $\sigma(T_c)$ for several HF materials. The relaxation time $\tau(T_c)$ is also studied in relation to an Uncertainty Principle limit, involving only the thermal energy $k_BT_c$ and Planck’s constant.

1. Introduction

In earlier work [1, 2], the superconducting transition temperature $T_c$ of several heavy fermion (HF) materials has been correlated with the effective mass $m^*$ (usually ~100 $m_e$, with $m_e$ the electron mass) and the coherence length $\xi$ by

$$k_BT_c = f(\epsilon_c),$$

where $\epsilon_c$ is a characteristic energy defined as [1]

$$\epsilon_c = \frac{\hbar^2}{m^*\xi^2}.$$ (2)

An approximate form of the relation between $k_BT_c$ and $\epsilon_c$, has been derived with the Bethe–Goldstone equation as the starting point [2]. One finds

$$\frac{\epsilon_F}{\epsilon_c} = \frac{4}{3}\xi^2 + \frac{\ell(\ell + 1)}{1 + x} \left(1 - \frac{x \ln x}{1 + x}\right),$$ (3)

where $2\epsilon_F = |\epsilon| \simeq k_BT_c$ is the binding energy of a Cooper pair, and $\epsilon_F$ is the Fermi energy [2]. Equation (3) manifestly depends on the quantum number $\ell$ of the pair angular momentum, which is usually employed to parameterize the anisotropic character of the superconducting order parameter, $\ell = 0, 1, 2$ corresponding to $s$-, $p$-, and $d$-wave symmetry, respectively. While this expression correctly reduces to the standard one for isotropic $s$-wave superconductors, in the case $\ell \neq 0$ it agrees qualitatively with the phenomenological dependence of $k_BT_c$ on the characteristic energy $\epsilon_c$, proposed in [1] for HF compounds as well as for high-$T_c$ cuprates. It should be pointed out, however, that equation (3) is qualitatively insensitive to different values of $\ell > 0$, the effect of a nonzero $\ell$ being mainly that of having $k_BT_c$ saturating to a finite value as $\epsilon_c \rightarrow \infty$, instead of diverging, as is the case with $\ell = 0$ [2].

Since this early work, we have uncovered in the literature further relevant data, for example on CeCoIn$_5$, CeIrIn$_5$, and CeRh$_2$Si$_2$ (see table 1 and references therein). Figure 1 then shows an updated correlation plot of $k_BT_c$ versus $\epsilon_c$, including the latter three new entries appearing at the two ends of the series of data, and with equation (3) used as the fitting function.

Motivated by the study of Homes et al [3] on high-$T_c$ materials (plus elemental metals Nb and Pb with relatively high $T_c$ values for such superconductors) and of Zaanen [4], it is useful in connection with table 1 to define a relaxation time $\tau(T_c)$ through [5]:

$$\sigma(T_c) = \frac{n_e\rho^2\tau(T_c)}{m^*},$$ (4)

where $\sigma(T_c) = \rho^{-1}(T_c)$ is the dc electrical conductivity at the transition temperature $T_c$, and $n_e$ is the carrier density.
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Table 1. Selected physical properties for uranium and cerium based HF materials. Where available, multiple entries separated by slashes refer to properties along different crystallographic directions. $T_N$ is the magnetic ordering (Néel) temperature, $\gamma$ denotes the Sommerfeld specific-heat coefficient, $\lambda_0$ the superconducting penetration depth extrapolated at $T = 0$, and $\omega_{pn}$ is the plasma frequency in the normal state. The last two columns are the ‘Uncertainty Principle’ relaxation time $\tau_{UP}$, equation (5), and the relaxation time $\tau(T_c)$ at $T_c$, equation (4) [4].

| Compound      | $T_c$ (K) | $T_N$ (K) | $\xi$ (Å) | $m^*/m_e$ | $\gamma$ (J mol$^{-1}$ K$^{-2}$) |
|---------------|-----------|-----------|-----------|-----------|-------------------------------|
| $\text{UPt}_3$ | 0.52, 0.48 | 5.0 [14, 13] | 100/120 [14] | 180 [14] | 0.450 [14] |
| $\text{UBe}_13$ | 0.87 [13] | 100 [14] | 260 [14] | 1.100 [14] |
| $\text{UNi}_2\text{Al}_3$ | 1.0 [14, 13] | 4.3–4.6 [14, 13] | 240 [14] | 48 [14] | 0.120 [14] |
| $\text{UPd}_2\text{Al}_3$ | 2.0 [14, 13] | 14.5 [13] | 85 [14] | 66 [14] | 0.145 [14] |
| $\text{URu}_2\text{Si}_2$ | 1–1.5 [13, 15] | 17–17.5 [14, 15] | 100/150 [14] | 140 [14] | 0.065–0.18 [14, 15] |
| $\text{CeCu}_2\text{Si}_2$ | 0.65 [13] | 1.3 [14] | 90 [14] | 380 [14] | 0.73–1.1 [14] |
| $\text{CeRh}_2\text{Si}_2$ | 0.35$^a$ [16] | 35–36 [16, 17] | 370 [16] | 220 [16] | 0.08 [16] |
| $\text{CePd}_2\text{Si}_2$ | 0.4$^b$ [18] | 10.2$^c$ [18] | 150 [18] | — | 0.13 [19] |
| $\text{CeCu}_2\text{Ge}_2$ | 0.64$^d$ [20] | — | 4.1 [20] | — | 0.4 [18] |
| $\text{CeNi}_2\text{Ge}_2$ | 0.22$^e$ [19] | — | — | — | 0.037 [15] |
| $\text{UPt}_3$ | 0.75 [22] | 2.2 [22] | 81–97 [22] | — | 0.23 [23] |
| $\text{CeNiGe}_2$ | — | 3 [23, 17] | — | — | 0.034 [24] |
| $\text{CeNiGe}_3$ | 0.48$^f$ [24] | 5.5$^g$ [24] | 130$^h$ [24] | — | 0.25$^i$ [28] |
| $\text{CeCoIn}_5$ | 2.3 [25] | 58 [26], 35/82 [27] | 83 [26], 5/49/87 [27] | 0.29 [25, 26] |
| $\text{CeIrIn}_5$ | 2.1$^j$ [28] | 3.8 [28] | 57$^k$ [7] | 0.40 [28] |
| $\text{CeIrIn}_5$ | 0.40 [29] | 0 [30] | 241 [26] | 140 [26], 20/30 [31] | 0.72–0.75 [29, 25] |
| $\text{CeIn}_3$ | 0.25$^l$ [28] | 10$^m$ [28] | — | $\leq 0.13^n$ [32, 6] |
| $\text{CePd}_3$ | — | — | — | — | 0.037 [15] |

| Compound      | $\rho(T_c)$ ($\mu\Omega$ cm) | $\lambda_0$ (Å) | $\omega_{pn}$ (eV) | $n_s$ (10$^{22}$ cm$^{-3}$) | $\tau_{UP}$ (ps) | $\tau(T_c)$ (ps) |
|---------------|-----------------|-----------------|------------------|-----------------|----------------|----------------|
| $\text{UPt}_3$ | 0.3–3 [14] | $> 15 000$ [13] | 2.6 [15] | 1.8 [33] | 13.9 | 11.8–118 |
| $\text{UBe}_13$ | 18 [14] | 11 000 [13] | 2.9 [34] | 0.61 [34] | 7.6 | 4.0 |
| $\text{UNi}_2\text{Al}_3$ | 7 [14] | 3300 [13] | 5.5 [35] | 1.9 [36] | 3.8 | 3.1 |
| $\text{UPd}_2\text{Al}_3$ | 4 [14] | 4000 [13] | 10000 [13] | 5.1–7.6 |
| $\text{CeCu}_2\text{Si}_2$ | 2–65 [14] | 5000 [13] | 11.4 [16] | 11.8 | 0.2–6.0 |
| $\text{CeRh}_2\text{Si}_2$ | 2 [16] | 19.7 [16] | 21.8 | 2.0 |
| $\text{CePd}_2\text{Si}_2$ | 1.4 [18] | 19.1 | 11.9 |
| $\text{CeNiGe}_2$ | $\approx 3$ [18] | 19.1 | 34.7 |
| $\text{CeRu}_2\text{Ge}_2$ | 1.0 | 19.1 |
| $\text{CePd}_3$ | 6.5 [22] | — | 15.9 |
| $\text{CeNiGe}_2$ | — | — | — |
| $\text{CeNiGe}_3$ | — | — |
| $\text{CeCoIn}_5$ | 7.21 [6] | 2810 [37] | 1.15 [26] | 3.3 | 3.55 |
| $\text{CeIrIn}_5$ | 5–7.5 [28, 7] | 2.67 [26] | 19.1 | 18.6 |
| $\text{CeIn}_3$ | 6.5 [22] | — | 2.3 [15] | — | — |

$^a$ At 0.9 GPa.
$^b$ At 2.71 GPa.
$^c$ At 0 GPa. $T_N$ vanishes at $p_c = 2.86$ GPa [18].
$^d$ At 0 GPa. $T_N$ vanishes at $p_c = 5.5$ GPa [24].
$^e$ At 6.5 GPa.
$^f$ At 1.5 GPa.
$^g$ At 4–10 GPa.
$^h$ At 2.5 GPa.
$^i$ At 1.7 GPa. $T_c$ reaches 2.2 K at 2.5 GPa [7].
$^j$ At 2.5 GPa.
$^k$ At 0.9 GPa.
$^l$ At 0 GPa.
$^m$ At 0 GPa.
in the normal state. For several materials, experimental data collected in table 1 for all the physical quantities appearing in equation (4) exist with the exception of the relaxation time $\tau(T_c)$. Table 1 therefore records the value of $\tau(T_c)$ extracted from equation (4) using experimental values for $\rho(T_c)$, $n^*$ and $m^*$. For comparison, we have also recorded the ‘Uncertainty Principle’ (UP) estimate $\tau_{UP}$ given by Zaanen [4], following the study of Homes et al [3]:

$$\tau_{UP} = \frac{\hbar}{k_B T_c}.$$  

(5)

In most cases, the values of $\tau(T_c)$ entered in table 1 are of the same order of magnitude as $\tau_{UP}$ given by equation (5), but no simple correlation exists between $1/\tau(T_c)$ and $T_c$ in the HF materials.

Figure 1. Measured superconducting transition temperatures $T_c$ for a variety of HF materials plotted against the characteristic energy $\epsilon_c$ defined in equation (2). Data for $T_c$, $m^*$, $\xi$ have been taken from table 1. The dashed curve is a phenomenological fit based on equation (3) [2].

Figure 2. Resistivity $\rho(T_c)$ at $T_c$ (solid curves) and ratio $\rho(T_c)/T_c$ (dashed curves) of CeCoIn$_5$ [6] and CeRhIn$_5$ [7]. Inset: plots $\rho(T_c)$ versus $T_c$ for CeCoIn$_5$ [6]. The curves are guides to the eye.

Figure 3. Experimental superconducting transition temperatures $T_c$ for CeNi$_2$Ge$_2$ (+ [38]), CePd$_2$Si$_2$ (× [18]), CeIn$_3$ (+ [18]), CeCoIn$_5$ (Ω [6], □ [8]), CeRhIn$_5$ (Ω [28], ● [7]), plotted as a function of pressure $p$. The curves are guides to the eye.

2. Pressure dependence of $T_c$ and $\rho(T_c)$

Of the HF materials referred to above, we next note that CeCoIn$_5$, which is a superconductor at atmospheric pressure ($p = 0$), has been studied over a pressure range out to about 3 GPa [6]. Figure 2 plots the variation of the normal state resistivity $\rho(T_c)$, together with the ratio $\rho(T_c)/T_c$ as a function of pressure. In contrast to the almost monotonous decrease of both these quantities with increasing pressure, we have also plotted available experimental data for CeRhIn$_5$ [7], which however starts superconducting at 1.7 GPa. The structure of both $\rho(T_c)$ and $\rho(T_c)/T_c$ as a function of pressure is marked, and they correlate. The inset shows $\rho(T_c)$ versus $T_c$ constructed from the set of data for CeCoIn$_5$ [6]. Over a range of $T_c$ from 2.2 to 2.5 K, the behaviour is rather linear, followed by a more sudden decrease of resistivity with increasing $T_c$.

3. Summary and future directions

Our findings to this point may be summarized as follows. The interlink between $T_c$ and the characteristic energy $\epsilon_c$ in figure 1 appears relatively robust, as evidenced by the addition of quite recent data. The classification of HF materials is clearly quite different from the high- $T_c$ regularity plus Nb and Pb discussed by Homes et al [3] and also by Zaanen [4]. However, the Uncertainty Principle relaxation time $\tau_{UP}$ is found to be of the same order of magnitude as that extracted from measured dc conductivity data plus effective masses at atmospheric pressure, namely $\tau(T_c)$. However, no inverse correlation between $\tau(T_c)$ and $T_c$ is found for an admittedly limited number of HF materials. In the same context, we have used the superconducting penetration depth $\lambda_0$ in table 1 to estimate the superfluid density $\rho_s$ as $\lambda_0^{-2}$. Then, following Homes et al [3], if we construct $\rho_s/T_c\sigma(T_c)$, then for all but one of the HF materials for which data are recorded in table 1, this ratio is at least a factor of seven greater than for high- $T_c$ materials, and with a huge scatter, confirming the above conclusion that HF materials are in a quite different category from high- $T_c$ materials plus the elemental BCS superconductors Nb and Pb.
As to future directions, we feel that further work, both experimental and theoretical, on applying pressure to HF materials should be illuminating. Thus, we have collected in figure 3 some available experimental data for $T_c$ as a function of pressure. The simplest example, and the only one shown which superconductors at $p = 0$, is CeCoIn$_5$ [6, 8], which has a relatively smooth variation of $T_c$ with pressure, exhibiting a single maximum. It is tempting for the future to study whether a link can be forged, for $p < p_{\text{max}}$, the latter corresponding to the maximum of $T_c$, with figure 1. However, whereas figure 1 relates $T_c$ to a single variable, i.e. the characteristic energy $\epsilon_c$, defined in equation (2), it may be that one must add further variables to describe the pressure dependence of $T_c$. For example, the detail of spin fluctuation [9–12], believed at present to be at least partially responsible for Cooper pair formation in this class of materials, may need inclusion. However, of course, some account is already present through the coherence length $\xi$, in which the size of the Cooper pair is manifested. Of course, for the remaining materials in figure 3, the pressure dependence of $T_c$ is more complex, including the fact that pressure is already needed to induce superconductivity.

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