Résumé. — Des expériences de magnétorésistivité montrent une relation simple quadratique $T_c$ de la résistivité de la phase normale juste au-dessus de la température superconductive $T_c$. La résistivité résiduelle dépend, elle, fortement du champ magnétique. Pour $12 \, T \approx H \approx 4 \, T$, la magnétorésistivité peut être décomposée en:

$$\rho(T,H) = \rho_0(H) + A(H)T^2$$

$ho_0$ et $A$ suivant des variations respectives en $\sqrt{H}$ et $H$. L'accent est mis sur la dualité particules légères et lourdes.

Abstract. — Very low temperature magnetoresistivity experiments exhibit a simple quadratic $T_c$ dependence of the resistivity just above the superconducting transition temperature $T_c$. Extrapolated residual resistivity depends strongly on the magnetic field. For $12 \, T \approx H \approx 4 \, T$, the magnetoresistivity can be fitted by:

$$\rho(T,H) = \rho_0(H) + A(H)T^2$$

$\rho_0$ and $A$ following respectively $\sqrt{H}$ and $H$ variations. Emphasis has been given on the duality between light and heavy particles.

The heavy fermion compounds (HFC) have the common property of showing huge values of the ration $C/T$ (the specific heat divided by the temperature). However, large differences occur among them, notably between the well known heavy fermion superconductors (HFS) UBe$_{13}$ [1], CeCu$_2$Si$_2$ [2] and UPt$_3$ [3]. The last two compounds have axial symmetry whereas UBe$_{13}$ has a cubic symmetry ; the U-U interdistance in UBe$_{13}$ larger ($d \approx 5.13 \, A$) is larger than the corresponding distance ($d \approx 4.1 \, A$) between the f atoms in the other two [4]. In zero applied field ($H$), in UBe$_{13}$ just above the superconducting transition $T_c \approx 0.9 \, K$, the resistivity $\rho(T_c') \approx 180 \, \mu\Omega\text{cm}$ is enormous and close to the maximum value of $\rho_H \approx 220 \, \mu\Omega\text{cm}$, which is reached for $T_M \approx 2.4 \, K$. For CeCu$_2$Si$_2$, $\rho(T_c') \approx \mu\Omega\text{cm}$, $\rho_H = 150 \, \mu\Omega\text{cm}$ and $T_M \approx 24 \, K$ while for UPt$_3$, $\rho(T_c') \approx 1.5 \, \mu\Omega\text{cm}$ and no resistivity maximum can be detected without phonon correction [4].

The strong scattering observed for UBe$_{13}$ at $T_c'$ precludes characterizing the low temperature properties of UBe$_{13}$ by an unique Fermi temperature $T_f \approx 8 \, K$ as chosen in the analysis of its specific heat and of
its magnetization. The latter is linear up to $H = 10$ T and quasi independent of temperature below $T = 4.2$ K [5]. A large negative magnetoresistivity has been already observed for UBe$_{13}$ [6]. New experiments performed down to 56 mK at fields up to 12 T, and down to 0.42 K at fields up to 24 T will be reported. The aim is to determine when simple laws, such as $T^2$ dependence, can be recovered in the resistivity of the normal phase. Data on the upper critical fields $H_c^2(T)$ will be briefly given for comparison with published results [6]. Previous experiments [6] were limited to fields up to 10 T and the data analysis were almost restricted to the superconducting transition. Finally magnetization measurements up to 24 T down to 1.3 K will be also reported.

**Experimental conditions.**

The sample was cut from the same batch as that sample recently used for performing thermal conductivity and thermoelectric power (TEP) measurements [7]. Four leads were soldered using indium and the resistivity was measured by an ac cryogenics bridge with a low power dissipation. The linear voltage output allows a continuous field sweep of the resistor at a constant temperature. The error bar on the resistivity data is less than 0.1 $\mu\Omega cm$. For $H < 12.5$ T the magnetic field was produced by a superconducting coil and the sample immersed in the mixing chamber of a dilution refrigerator (which reaches 56 MK). Between 12.5 T and 24.6 T the field was produced by a polyhelix type resistive magnet and temperatures were achieved in a $^3$He cryostat down to 0.42 K. In zero field, the temperature was measured with a Ge thermometer, which was calibrated on $^3$He vapour pressure, and was controlled with a capacitance under magnetic fields. DC magnetization ($M$) measurements show the strong linearity of $M$ with $H$ up to the highest applied field of 24 T at the lowest measured temperature of 1.3 K and the quasi independence of $M$ with the temperature below 4.2 K (Fig. 1).

**Magnetoresistivity.**

Figure 2 represents the magnetoresistivity for different temperatures and figure 3, at constant field, the temperature variation of the resistivity, measured up to 12.5 T, while figure 4 shows results obtained in resistive magnets. As was observed previously, the magnetoresistivity is large and negative [6,7]. The weak maximum in the temperature variation of $\rho$ at $T_c$ ~ 2.4 K for $H = 0$ clearly disappears for $H > 2$ T (for $H = 2$ T, $\rho$ is quasi constant for $2.4 < T < 3$ K). The drop of $\rho$ at $H = 21$ T has been observed with field increasing or decreasing; unfortunately, due to the failure of the magnet, it was not possible to repeat these high field experiments.

![Fig. 1. Magnetization of UBe$_{13}$ up to 24 T, down to 1.5 K.](image)

![Fig. 2. Magnetoresistivity of UBe$_{13}$ at different temperatures.](image)

Defining $T_c$ as the temperature corresponding to one half of the resistivity drop, the upper critical field phase diagram can be drawn (Fig. 5). The value found of $T_c$ ($H=0$) = 880 mK is slightly higher than the temperature $T_c (H=0)=854$ mK measured for a sample extracted from the same batch [7]; this difference may result from difficulties due to thermal gradients in the mixing chamber, when large power must be applied to stabilize the temperature. The low field regime I ($H < 20$ kOe) and high field regime II ($H > 20$ kOe) of the phase diagram correspond respectively to an enormous initial slope $\left(\frac{\partial H}{\partial T}\right)_c > -500$ kOe $/K$ and to a quasi linear temperature dependence down to 0 K with a slope $\left(\frac{\partial H}{\partial T}\right)_c \approx 0$.
-102 kOe/K, in excellent agreement with published data [1,6,7]. Contrary to other recent reported work [8], no departure from a field linearity of $H_{c2}(T)$ is observed at $T \to 0$ K; an extrapolation to $T \to 0$ K gives $H_{c2}(0) = 10.2$ T.

The main interesting feature is, that over all the field range $H < H_{c2}(0)$, $\rho(T_e')$ follows a $T_e^2$ dependence i.e. for $H < H_{c2}(0)$, $\rho(T_e')$ obeys the relation:

$$\rho(T_e') = \rho_0 + \alpha T_e^2$$

with $\alpha = 180 \mu\Omega cm K^{-2}$ and $\rho_0 = 38 \mu\Omega cm$ as shown in figure 6.

This relation between $\rho(T_e')$ and $T_e'$ is especially relevant taking into account the apparent enormous disorder scattering of the normal phase.

Figure 3 clearly shows that extrapolations to 0 K lead to residual resistivities which are strongly field dependent. For $H > 4$ T, $\rho(H)$ can be represented at very low temperature by the relation:

$$\rho(H) = \rho_0(H) + A(H) T^2$$

The striking results are: a) below $H_{c2}(0)$, dependences of $\rho_0$ and A in $\sqrt{H}$ and H respectively and b) above $H_{c2}$, the linear extrapolation to zero of $\rho_0$ for $H \sim 20$ T, i.e. near the field, where a drop in the resistivity has been observed (Fig.7). The $\rho_0(H)$ and A(H) curves intersect at low field for $H \sim 2$ T and in high field for $H \sim H_{c2}(0)$.

It is worthwhile mentioning that $\rho_0$ and $A(H)$ vary linearly with $H$ in the same field high regime $\Pi$. If a connection exists with the regimes I and II of the phase diagram, the crossing of $\rho_0(H)$ and A(H) must imply a characteristic temperature $T^* \sim 1$ K by homogeneity arguments ( $\rho_0$ in $\mu\Omega cm$, A in $\mu\Omega cm K^{-2}$). A similar temperature $T^* \sim 1$ K corresponds also to the mapping of the temperature dependence of the normalized magnetoresistivity by $H$ above 1 K in agreement with previous results (see ref. [4]).

**Discussion.**

Before discussing in more detail the experiments, let us underline, that the valence i.e. the nature of the magnetism carried by the U centres is not so well known [9], as for trivalent cerium ions in HFC. For example, in a cubic symmetry, a trivalent cerium ion (Kramer's ion) can only be in a non magnetic ground state via a Kondo

![Fig.3.- Temperature dependence of the resistivity at constant field.](image)

![Fig.4.- High field resistivity curve.](image)
case for paramagnetic impurities (Fig. 8). The strong temperature dependence of the magnetoresistivity contrasts with the independence of the magnetization with the temperature. That implies different characteristic energies in transport \( T^* \approx 1 \text{ K} \) and in magnetization measurements \( T_m \approx 8 \text{ K} \). On cooling, departure from the single ion behaviour increases since lattice effects become important below \( T_m \approx 2.4 \text{ K} \). However, the magnetoresistivity remains negative contrary to other HFC like \( \text{UPt}_3 \) [10,11], \( \text{CeAl}_3 \) [12], \( \text{CeRu}_2 \text{Si}_2 \) [13] and \( \text{CeCu}_2 \text{Si}_2 \) [14], where a positive contribution appears on cooling when the coherent lattice regime is approached.

![Fig. 5.- Upper critical field phase diagram.](image)

In \( \text{UBe}_3 \), a strong scattering of the itinerant electron by the U centres is observed almost down \( T_m \). This behaviour must be correlated with the weak value of \( T_m \approx 2.4 \text{ K} \) as compared to the Kondo temperature \( T_k \approx 8 \text{ K} \) necessary to explain the weak temperature dependence of its magnetization (Fig. 1). Further evidence is the strong scattering disorder found in TEP experiments, since a negative minimum of \( Q \) is not achieved for \( \text{UBe}_3 \) at \( T_m \) \( (H=0) \) [7]. Clearly, the band-width suitable to describe an ordering of the f electrons in the k space must be lower than \( 8 \text{ K} \). In constrast, as previously emphasized, in \( \text{CeCu}_2 \text{Si}_2 \), \( T_m \approx 24 \text{ K} > T_k \approx 5 \text{ K} \) and in \( \text{UPt}_3 \), \( T^* > T_m \) or \( T_{sf} \), the spin fluctuation temperature [15–17]; a negative minimum of the TEP occurs at 20 K for \( \text{CeCu}_2 \text{Si}_2 \) [18] and a positive maximum at \( T \approx 8 \text{ K} \) for \( \text{UPt}_3 \) [15]. The almost single ion behaviour of the U atoms in \( \text{UBe}_3 \) may be due to the fact that the U ions are strongly isolated from each other by the surrounding 13 Be atoms. Furthermore, the quasi independence of the U atom may be reinforced also from the large number \( n_s \approx 28 \) of f electrons per unit cell [19]. However, the relation between the number of f centres and the number of itinerant conduction electrons in the lattice properties is still an open question.

Basically, there are two types of particles involved in the problem: light electrons, given mainly by the Be atoms, and heavy f electrons of the U atoms. These last particles correspond to a weak delocalization of the f electrons by their Kondo like coupling with the itinerant electrons [20,21]. A two component picture of the normal phase has been already considered above \( T_c \) in thermal conductivity [21] and Hall effects experiments [22]. Here, it seems supported by a better linearity of the magnetoresistivity (\( \Delta T^* = \sigma(T)=\sigma(H=0) \)) than that of the magnetoresistivity in a plot \( \log \Delta T^* \) versus \( \log H \). Such a decomposition must fail when the phase of the two components must be mutually adjusted below \( T_c \) or when, in the normal phase, any auxiliary energy reservoir has collapsed. Clearly at \( H \to 0 \) from resistivity and TEP data [7] the temperature range of the coherent phase in the normal phase is very small, i.e. \( \ll T_c \). It has been observed that the A coefficient of the \( T^2 \) term of the resistivity can be scaled with the square of
the coefficient $\gamma$ of the specific heat [31]. The linear decrease of $A$ with the magnetic field suggests a $\mathcal{H}$ field decrease of $\gamma$.

The quadratic $T_c$ dependence of $\rho(T_c)$ shows that in the vicinity of the superconducting transition one has the temperature dependence usually observed for electron-electron interactions [23, 24], the magnitude $\alpha = 180 \mu \text{esu cm}^{-2}$ of the $T^2$ term is still larger than that found in the normal phases of HFC (for CeAl$_3$, $A = 35 \mu \text{esu cm}^{-2}$ [25] and for CeCu$_4$, $A = 120 \mu \text{esu cm}^{-2}$ [26, 27]). The superconductivity may follow some precursor coherence among the f electrons in the normal phase. Thus, at $T_c$, the $T^2$ law of the resistivity appears to correspond to coherence effects driven by the inset of the superconductivity. There is a mutual push-pull between superconductivity and interactions among particles. Correlatively, the disorder scattering enhances the upper critical fields. In regime I the large disorder observed in resistivity and TEP is associated with an enhancement of $\xi_{c2}(T)$ in agreement with the idea that the disorder enhances the paramagnon strength and weaken the pair breaking parameter [28]. Qualitatively, the important of localization effects agree also with the $\sqrt{\mathcal{H}}$ dependence of the residual resistivity $\rho_0$ found for $4 \text{ K} < H < H_{c2}(0)$ as a similar negative magnetoresistivity is observed for weak 3d localization [29].

$$\rho = \rho_0 + A(T^2)$$

**Fig. 7.-** Field variation of the coefficient $\rho_0$ and $A$, obtained by the fitting of the resistivity $\rho(T, H)$ by $\rho_0 + A(T^2)$.

$$\Delta \rho = \rho(0) - \rho(H)$$

The regime change in $\rho(H)$ for $H < H_{c2}(0)$ corresponds to a domain, where a $T^2$ law is obeyed up to $0.8 \text{ K} \cong T_0(H=0)$ and where a change in the sign of TEP seems to occur from negative to positive [7]. For $H = 0$, the electronic mean free path ($\lambda_e = 13 \text{ A}$ for $\rho \sim 130 \mu \text{esu cm}$) is smaller than the superconducting coherence length $\xi_e \sim \xi_{c2}(0)$. The interesting feature is that the large negative magnetoresistivity leads to an increase of the mean free path such that it becomes comparable to $\xi_e$ for $H \sim H_{c2}(0)$.

The applicability of the dirty limit approximation is doubtful for $\text{UBe}_13$ since a decrease of $\rho(T_c')$ by 30% [6] gives results similar to those reported here. Experiments on samples of different purities performed in the same apparatus to minimize experimental errors must be performed to clarify this point and also the interplay between localization, interaction and disorder. Finally up to $H < 24 \text{ T}$ and $T > 0.46 \text{ K}$ no re-entrant superconductivity has been found as recently proposed [30].

**Conclusion.**

The interplay between coherence effects of a lattice, localization and interaction effects is obvious for the specific case of $\text{UBe}_13$. The main interesting feature is the connection between superconductivity and the properties of the normal phase.
ducing the physics of HFC to the sole $f$ particles neglects the interesting problem of coupling between two interacting systems. Finally, the diversity of the hierarchy between basic parameters ($T_1, T_2$, anisotropy and crystal field effects) leads to drastic differences between HFS which needs to be understood via their normal phases.

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References


