Superconducting phase in UGe$_2$ by AC calorimetry

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Abstract.
We report on the detection of the superconducting transition $T_{sc}$ in the superconducting ferromagnet UGe$_2$ by AC calorimetry under pressure. Our results confirm the small value of the specific heat jump. We suggest that this observation is intrinsic in origin and does not arise from a distribution of $T_{sc}$ due to pressure gradient or sample defects.

1. Introduction
UGe$_2$ is a superconducting ferromagnet: the superconductivity is observed below a temperature $T_{sc}$ which is smaller than the Curie temperature $T_C$ [1]. The same succession of phase transitions is observed in URhGe [2] and UCoGe [3]. Contrary to these two last compounds, the superconductivity is not observed at ambient pressure in UGe$_2$ but it occurs in the range 1 − 1.5 GPa. The specific heat anomaly at the superconducting phase transition has been reported in ref. [4]. This experiment revealed a small yet distinct anomaly at $T_{sc}$. The largest anomaly was observed at 1.22 GPa: $\Delta C/(\gamma_n T_{sc}) \approx 0.29 \pm 0.06$ where $\Delta C$ is the specific heat jump at $T_{sc}$ and $\gamma_n$ is the value of $C/T$ just above $T_{sc}$. It is small compared to the weak coupling BCS value of 1.43. The residual $\gamma_0$ value obtained by the linear extrapolation of $C/T$ to 0 K is about 70% of $\gamma_n$. Despite experimental efforts, there is no other report of the specific heat anomaly on single crystals of UGe$_2$. In this paper, we report on the specific heat anomaly as a bulk superconducting transition by AC calorimetry measurements under pressure. Our results confirm the ones obtained by Tateiwa et al. although both reports show some discrepancies with resistivity, NQR and AC calorimetry experiments.

2. Experimental technique
The single crystal of UGe$_2$ was grown by the Czochralski pulling method in a tetra-arc furnace. The sample was cut by a spark cutter and checked by X-ray Laue diffraction, resistivity, thermal expansion, and specific heat measurements. The residual resistivity ratio is higher than 300, indicating the high quality of the samples. Pressure was applied via a NiCrAl-CuBe hybride piston-cylinder cell with Daphne oil 7373 as pressure transmitting medium. The pressure was determined by measuring the superconducting transition of Pb by AC susceptibility. The obtained temperature-pressure phase diagram is similar to previous reports. Magnetic field was applied along the a-axis in the orthorhombic structure, which corresponds to the easy magnetization axis.

In ref. [4], using the adiabatic heat pulse method, they measured the specific heat of a piston cylinder cell with a single crystal of UGe$_2$ inside, and substracted the signal of a piston cylinder...
cell without sample. The fact that no other report of the specific heat anomaly on single crystals of UGe$_2$ exists is a consequence of the experimental difficulty. We used the AC calorimetry method which is adapted to small samples and high pressure studies. The experimental setup is shown in fig. 1. It allows us for resistivity and AC calorimetry measurements. Four gold wires ($I^-$, $V^-$, $V^+$ and $I^+$) are spot welded on the sample for resistivity measurements. In addition, an Au-Fe(0.07%) wire is spot welded on a current contact ($I^+$) to constitute a thermocouple. An electrical current through two other contacts constitute a heater. It is assumed that the resistivity of the sample and wires is negligible compared to the contacts resistance. In the AC calorimetry method, the application of an AC power $P_0$ on the sample induces an oscillating temperature variation $T_{AC}$ of the sample at the same frequency. Since, in our setup, an excitation at a frequency $f$ will induce a Joule effect at a frequency $2f$, the response has to be measured at the second harmonic ($2f$). The AC signal of the thermocouple is measured with a Lock-In amplifier after being amplified by a factor 100 with a low noise transformer and by another factor 100 with a pre-amplifier. The sensitivity of the thermocouple has been calibrated in previous experiments.

![Figure 1. Experimental setup of the resistivity and AC calorimetry measurement under pressure on a single crystal of UGe$_2$.](image)

![Figure 2. Frequency characterization of the AC calorimetry experiment at 1.20 GPa at 115 mK. The dashed line is a fit from equation (1).](image)

A model of the AC calorimetry method has been developed in ref. [5]. Neglecting all the time constants between the sample, the heater and the thermometer, the model can be simplified so that:

$$T_{AC} \approx \frac{P_0}{2\pi fC} \frac{1}{\sqrt{1 + \left(\frac{\kappa_B}{2\pi fC}\right)^2}} = \frac{P_0}{\sqrt{\kappa_B^2 + (2\pi fC)^2}}$$

(1)

where $\kappa_B$ is the thermal conductivity to the thermal bath. In fig. 2, we show that this model is valid at low frequencies (below $\sim 300$ Hz). Below $\sim 30$ Hz, the system is dominated by the thermal conductivity to the bath: $T_{AC} \approx \frac{P_0}{\kappa_B}$. Therefore, we performed our measurements at higher frequencies, namely at 37 and 87 Hz.

The anomaly at the superconducting transition can be observed at these different frequencies of the excitation. In fig. 3, we show the inverse of the measured signal ($1/T_{AC}$) as a function of temperature. The superconducting transition is revealed by a hump below 680 mK. Using equation 1, measurements at several $f$ allows one to extract the temperature dependence of $C/T$. The different values of $f$ have to be chosen in the range where the simple model seems to be valid, and not too close, so that the specific heat part is not canceled. Another difficulty
with the measurement under pressure is that the environment of the sample contributes to the measured specific heat. This effect is considered to be more important at low frequency, but the simple model is anyway not valid at high frequency. By subtracting the signal at two different frequencies, it can be assumed that the effect of the environment is canceled in the first approximation.

![Figure 3. Temperature dependence
of the signal in the form 1/T_{AC} measured at different frequencies of the excitation at 1.20 GPa. The anomaly at the superconducting transition can be observed around 0.7 K.](image)

The obtained temperature dependence of $C/T$ is shown in fig. 4. The rather small size of the anomaly should not be ascribed to the AC calorimetry method, since this technique usually shows well defined superconducting transition [6]. Moreover, our result is similar to the biggest anomaly reported in ref. [4] by the adiabatic technique. This indicates that our signal is very close to detect correctly the heat capacity anomaly. The fact that the techniques are different suggests that the small value of the specific heat jump $\Delta C/(\gamma n T_{sc}) \approx 0.3$ is a reliable result: it cannot arise from experimental precision or hazards which would depend on the employed method.

3. Discussion

The value of $\Delta C/(\gamma n T_{sc})$ is around 0.6 in the other ferromagnetic superconductor URhGe [2] and around 0.7 in UCoGe [3]. Note that in URhGe and UCoGe, the measurements can be done at ambient pressure with adiabatic technique. One can think that the pressure inhomogeneity or the pressure dependence of $T_{sc}$ can be taken as an explanation of the smaller anomaly observed in UGe$_2$. In order to find out the distribution of $T_{sc}$ from our AC calorimetry measurements, we first determined $T_{sc} \approx 685 \pm 5$ mK such that the entropy is conserved as drawn by a dashed line in figs. 4 and 5. In the superconducting phase, we used a line node gap as proposed for the specific heat of URhGe [7], nuclear spin lattice relaxation rate in UGe$_2$ [8, 9] and UCoGe [10]. We note that, in our AC calorimetry measurements on UGe$_2$, it is necessary to add a background signal assumed to be proportional to the temperature in order to obey the entropy conservation. Such background signal depends on the choice of frequencies used in the AC calorimetry measurement, indicating the limit of the simple model. We convolved the curve with a gaussian distribution of $T_{sc}$ in order to reproduce the data, as drawn by a full red line in fig. 5. The distribution of $T_{sc}$ can be taken as a gaussian with characteristic width of $\sim 65$ mK. A similar value is obtained in high quality single crystal of UCoGe although the specific heat jump at the superconducting transition is more than 2 times larger (see fig. 5). Therefore, we
conclude that the small specific heat jump observed at the superconducting transition of UGe$_2$ is intrinsic and cannot be explained by the distribution of $T_{sc}$ due to pressure gradient or sample defects.

The smaller value of the specific heat anomaly in UGe$_2$ with respect to UCoGe is more likely related to the larger residual term. In our AC calorimetry measurements and in ref. [4], the residual term is more than 60% of the normal state. As already remarked in ref. [4], the contribution from the self-vortex state due to the coexistence of the ferromagnetism and the superconductivity is too small to account for the large residual term.

Another possibility is that the energy splitting between the majority and the minority spin band can result in an almost ungapped band [7, 9]. We suggest the residual term to arise from the majority band in agreement with the fact that $T_{sc}$ is expected to be higher for the minority band than for the majority one [11]. Measurements at lower temperatures are necessary for a better estimation of the residual part.

In summary, we have performed AC calorimetry measurements under pressure. We confirm the small value of the specific heat anomaly at the superconducting transition, and thus suggest that it is intrinsic in origin.

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