Low temperature AC susceptibility of UCoGe crystals

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Abstract.
The recent discovery of the magnetic ordering and the superconductivity in the UCoGe motivate the more detailed investigation of its properties. In this paper we study three single crystals prepared by different techniques by means of the AC susceptibility. For this measurement the Physical Property Measurement System (PPMS) from Quantum Design was used, using the simple self–made extension allowing transparent (for the user) measurement of AC susceptibility with the 3He option (major aspect will be discussed). Our results show strong dependence of the single crystal physical properties (possible suppression of superconductivity and magnetism) on the method used for sample preparation.

1. Introduction
Recently, the coexistence of magnetism and superconductivity at ambient pressure was reported in UCoGe [1]. The ferromagnetism was classified as weak, with the Curie temperature $T_C \sim 3$ K and a small ordered moment of $0.03 \mu_B$. The superconductive transition was reported to be approximately $T_s \sim 0.8$ K based on the resistivity measurements.

Consequently, several subsequent papers were published on the samples of different quality and measured by different methods. Nevertheless, the nature of the superconductive state still remains unknown, as the UCoGe compound is on the verge of magnetic stability and two explanations are proposed — superconductivity stabilized by long range ferromagnetic order and their coexistence below $T_s$ ([1], [2] and references therein) or the existence of ferromagnetic fluctuations and the presence of the robust superconductive regime independent to the long–range ferromagnetic ordering ([3] and [4]).

In this paper we will present the investigation of the AC magnetic susceptibility measured on single crystalline samples prepared by different techniques in temperatures down to 0.35 K. Also, we will briefly describe the necessary modifications allowing such measurement using the He3 insert in PPMS apparatus.

2. Instrumental part
The PPMS devices from Quantum Design allow measurement of various physical properties in the basic temperature range from 2 K up to 400 K. There are several possible extension to lower (3He option, heat capacity, electrical resistivity) or higher temperatures (VSM Oven,
magnetization), nevertheless, the possibilities for the study of magnetism or superconductivity at low temperatures (below 1.8 K) are limited, especially when there is a need for the study of bulk appearance of superconductivity where AC susceptibility is of irreplaceable importance.

As mentioned earlier, the magnetic anomaly in the UCoGe compound is located around 3 K and at the superconducting transition is at $\sim 0.8$ K, consequently, only scarce information about the physical properties can be obtained using PPMS. Therefore, we decided to extend the possible obtainable information by measuring the AC magnetic susceptibility using the 3He option.

The principles of the measurement of the AC magnetic susceptibility is well known — the primary coil is generating the alternating magnetic field and the response from the sample is read as a change of the voltage induced on the secondary coil. In order to increase precision the secondary coil has two parts wound in opposite directions and the sample is placed in the center of one of them.

In order to simplify the measurement procedure and increase the sensitivity of obtained data we decided to use the ACMS preamplifier and the ACMS electronics as well. In order to do it, an adapter has to be placed between PPMS probe head and ACMS preamplifier allowing amplification of the signal and proper transmission of the He3 thermometer wiring (for detail concerning this part, possibilities in the data evaluation and results of test measurements see [5]). As a result, the AC magnetic susceptibility in arbitrary units is obtained and the scaling/comparison with other apparatus in the overlapping region is useful.

**Figure 1.** The temperature evolution of the AC magnetic susceptibility for sample No. 1.

**Figure 2.** The temperature evolution of the AC magnetic susceptibility for sample No. 2. The line is a guide for an eye.

**Figure 3.** The temperature evolution of the AC magnetic susceptibility for sample No. 3. The line is a guide for an eye.
3. Results

The measurements were done on three crystals prepared by different techniques. First one, denoted as No. 1, was prepared by arc melting of stoichiometric amount of pure elements and the single crystalline part of sample was found within the polycrystalline button. This sample is identical to the one used in reference [3]. Second sample (No. 2) was isolated from large block of the UCoGe material after the solid state electrotransport purification procedure. Last sample (No. 3) was grown in the optical furnace. All samples have approximately same volume of about 1-2 mm$^3$, theirs crystallinity was check by the X—ray Laue method, the composition by the microprobe analysis. First sample was annealed with resulting RRR=15. Second sample (RRR $\approx$ 4) was used as cast (i.e. with respect to preparation conditions no subsequent annealing procedure was used). In the case of the sample No. 3 the annealing does not lead to an improvement in the RRR (approx. 4) nor in the change of the superconductive properties.

For the measurement above 1.8 K the SQUID based magnetometer MPMS from Quantum Design was used, for the low temperature measurements we used approach described earlier. In all measurements a special care was taken in order to suppress the possible residual field present in the superconductive magnets (based on our experience with this magnet we expect to have residual field below 0.3 mT).

The results are summarized in the figures 1-3. All measurements very well corresponds to the measurements from the MPMS in the overlapping temperature region. Also, the observations of the fact, that the bulk appearance of the superconductivity is significantly lower that the onset of superconducting state as deduced from the resistivity measurements is in agreement with the original investigation of the superconductivity in this system [1].

First two samples behave similarly in the magnetic anomaly temperature region (around 2 K), whereas the third sample has a peak in the AC susceptibility centered at significantly lower temperature ($\approx$ 0.45 K).

The bulk superconductivity was not observed down to 0.36 K in samples No. 2 and 3, which is in agreement to resistivity measurement on these samples, indicating transition temperatures to be significantly lower than in the sample No. 1.

The application of the magnetic field in the case of the first sample does not lead to the increase of the temperature of the superconductive transition contrary to the conclusion based from the measurements of the electrical resistivity [3]. This may not be in contradiction as the resistivity reflects only creation of superconductive percolation paths whereas the AC susceptibility is sensitive to the bulk superconductivity.

Our results show that the choice of the method of single crystal preparation has significant influence to the resulting both magnetic and superconductive properties, comparable to the application of the annealing procedure [6]. Both these approaches indicate, that the thermodynamics during the preparation of single crystalline samples of the UCoGe compound plays an important role in the determination of the final properties of this material and should be studied in detail.

4. Conclusions

In this paper we presented the application of the extension of the PPMS 3He insert to the measurement of the AC magnetic susceptibility in temperatures below 2 K. As an application example we used several different crystals of the UCoGe compound where a coexistence of magnetic and superconductive behavior occurs. Our results are generally in good agreement with previously published data and measurement of other properties and indicate strong sensitivity of both magnetism and superconductivity to the preparation conditions.
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