Alternating-field magnetoresistance measurements on $Sr_3Ru_2O_7$

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Abstract

We apply an alternating-field (af) magnetoresistance technique to investigate the temperature–field (T–H) phase diagram of the bilayer ruthenate $Sr_3Ru_2O_7$ in close vicinity of the metamagnetic quantum critical end point. The out-of-phase component of the af magnetoresistance is extremely sensitive to hysteresis effects. Clear peaks are observed when entering the bounded regime at low temperatures. They mark two separate first-order phase transitions ending at 0.7 and 0.45 K, respectively. No indication for hysteresis is observed inside the bounded regime.

Keywords: Quantum criticality; Metamagnetism; $Sr_3Ru_2O_7$

The bilayer ruthenate $Sr_3Ru_2O_7$ has recently attracted much interest because of itinerant electron metamagnetism leading to quantum critical behavior [1]. It has been shown that the field angle with respect to the tetragonal c-axis acts as control parameter for tuning the end point of a metamagnetic transition towards absolute zero temperature [2] for $H\|c$. However, the detailed investigation of very high quality single crystals has revealed that the quantum critical end point at $\mu_0 H_c \approx 8T$ is in fact hidden by a "phase" with anomalous properties [3]. Here, the electrical resistivity is strongly enhanced and almost temperature independent, indicating dominating elastic scattering and a strong reduction of the mean free path. The latter points to some kind of domain formation. It has been proposed that these domains may result from a spin-dependent Pomeranchuk deformation of the Fermi surface [3]. However, the thermodynamic analysis has revealed an enhanced entropy within the new "phase", in contrast to the expectation for a symmetry-breaking phase transition [4]. Alternatively, real space phase separation scenarios have been proposed [5,6]. Thus, further experimental characterization of the bounded region is needed.

In this paper, we use an alternating-field (af) technique for the detection of the magnetoresistivity which compared to conventional static magnetoresistance measurements gives additional information on hysteresis effects. We first provide a brief description of this technique and afterwards discuss our results close to the new "phase" in $Sr_3Ru_2O_7$. For a time (t) dependent magnetic field $H(t) = H_{DC} + h_0\cos(\omega t)$, with constant ($H_{DC}$) and alternating ($h_0$) components, the resistivity is given by

$$\rho(t) = \sum_{k=0}^{\infty} N'_k \cos(k\omega t) + N''_k \sin(k\omega t), \qquad (1)$$

with Fourier coefficients N'_k and N''_k. For small amplitudes $h_0 \ll H_{DC}$ the first Fourier coefficients N'_1 and N''_1 are proportional to the real and imaginary part of the af magnetoresistance $\left(\frac{\partial\rho}{\partial H}\right)_{\mathrm{af}} = \left(\frac{\partial\rho}{\partial H}\right)' + \mathrm{i}\left(\frac{\partial\rho}{\partial H}\right)''$ (in close analogy to the magnetic ac-susceptibility $\chi_{ac} = \chi' + \mathrm{i}\chi''$) and can be de-

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tected using a lock-in amplifier. From the definition of the coefficients, it follows that the real part of this property probes the slope of $\rho(H)$, whereas the imaginary part

$$\left(\frac{\partial\rho}{\partial H}\right)'' = \frac{1}{\pi h_0^2}\oint \rho(H)\mathrm{d}H \tag{2}$$

is proportional to the area of the minor hysteresis loop of the magnetoresistance, similar as the imaginary ac-susceptibility is proportional to a hysteresis loop of the magnetization $M(H)$. In contrast to χ'', the imaginary magnetoresistance can be both positive and negative, depending on the sign of $\mathrm{d}\rho/\mathrm{d}H$ (cf. Fig. 1b and c). For our measurements, we use an alternating-field $h_0 = 0.2$ mT with a frequency of 1.1 Hz.

Fig. 1a shows our $\rho(H)$ data which are consistent with previous measurements [3,7]. Two sharp changes in slope, indicated by the arrows, are observed which coincide with two metamagnetic transitions [3]. In order to search for tiny hysteresis effects, not detectable in the $\rho(H)$ measurement, we have performed af magnetoresistance measurements with the parameters given above.

Fig. 2 shows an exemplary curve taken at 0.2 K. The real part of the af magnetoresistance directly probes the slope of $\rho(H)$ and three anomalies are observed at 7.5, 7.81 and 8.05 T corresponding to three peaks in the magnetic susceptibility [3]. The imaginary part is sensitive to hysteresis effects and thus suited to detect first-order phase transitions. In the imaginary part, we observe two peaks which result from hysteresis loops indicated in Fig. 1b and c. This observation suggests two first-order (meta-

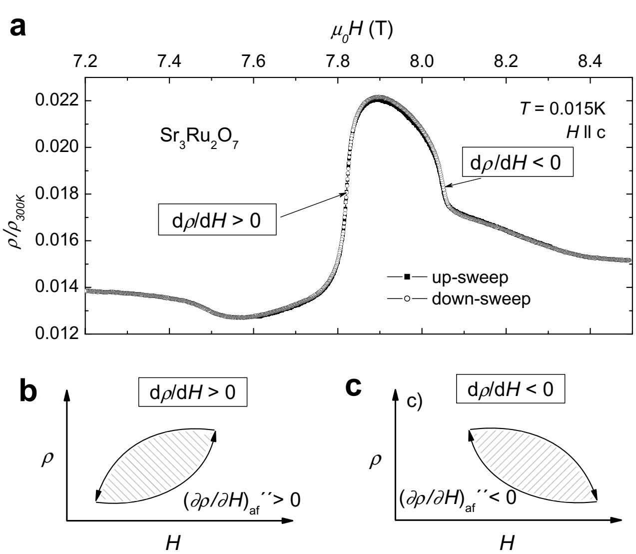

Fig. 1. (a) Magnetic field dependence ($H \| c$) of the electrical resistivity divided by the value at room temperature as $\rho/\rho_{300\,\mathrm{K}}$ of $Sr_3Ru_2O_7$ at 0.015 K. Closed and open symbols indicate data taken for increasing and decreasing field, respectively. Arrows indicate positions of steepest magnetoresistivity, with $\mathrm{d}\rho/\mathrm{d}H > 0$ and $\mathrm{d}\rho/\mathrm{d}H < 0$. The corresponding schematic hysteresis loops are sketched in (b) and (c), see text.

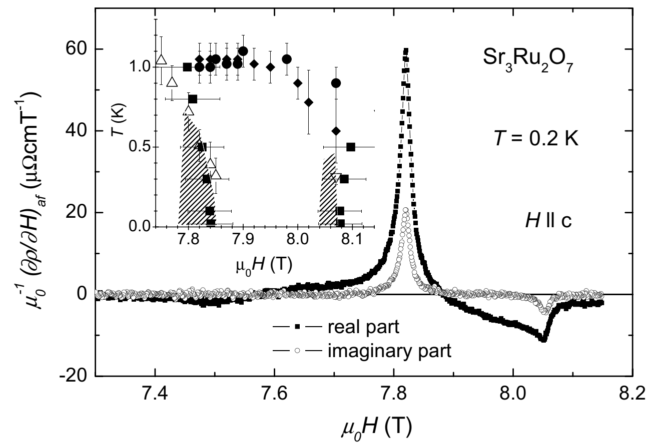

Fig. 2. Real and imaginary part of the alternating-field (af) magnetoresistance $\left(\frac{\partial\rho}{\partial H}\right)_{\mathrm{af}} = \left(\frac{\partial\rho}{\partial H}\right)' + \mathrm{i}\left(\frac{\partial\rho}{\partial H}\right)''$ of $Sr_3Ru_2O_7$ at 0.2 K. Note the two peaks in the imaginary part, which correspond to the hysteresis loops displayed in Fig. 1b and c. The inset shows the T–H phase diagram close to the bounded regime as determined previously from magnetostriction (squares) thermal expansion (circles and triangles) and resistivity (diamonds) measurements, see [4]. The shaded areas label the regions of non-zero imaginary part of the af magnetoresistance.

magnetic) phase transitions, in agreement with previous ac-susceptibility measurements [3]. Upon increasing the temperature, we have found that these peaks vanish at 0.7 and 0.45 K, respectively. Furthermore, we have performed temperature scans at constant H. Upon entering the bounded regime at constant H by decreasing the temperature from 1.5 K, the imaginary part of the af magnetoresistance remains zero. This proves, that hysteresis effects are confined to the close vicinity of the two lines of first-order transitions ending at separate critical end points. Inside the bounded regime, no hysteresis is detectable.

To summarize, we have applied a new alternating-field magnetoresistance technique for the study of the bounded regime in $Sr_3Ru_2O_7$. Our results confirm the existence of two first-order transition lines, ending at separate critical end points. No indication for hysteresis in the electrical resistivity is observed within the bounded regime.

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