Low-temperature magnetostriction of $Sr_3Ru_2O_7$

P. Gegenwart[a,b,*], F. Weickert[a], R.S. Perry[b,c,d], Y. Maeno[c,d]

[a] *Max-Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany*
[b] *School of Physics and Astronomy, University of St. Andrews, Fife KY16 9SS, Scotland*
[c] *International Innovation Center, Kyoto University, Kyoto 606-8501, Japan*
[d] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

Abstract

Itinerant-electron metamagnetism in the bilayer ruthenate $Sr_3Ru_2O_7$ is studied by *c*-axis magnetostriction measurements on a high-quality single crystal in magnetic fields up to 18 T and at temperatures down to 20 mK. The positive linear magnetostriction coefficient suggests an initial decrease of the magnetization under *c*-axis uniaxial pressure. A highly enhanced magnetic Grüneisen parameter $\Gamma_H = 106$ indicates a strong magnetoelastic coupling. The system is particularly sensitive to *c*-axis strain.

Keywords: Quantum criticality; Metamagnetism; $Sr_3Ru_2O_7$

The coupling of magnetic and lattice degrees of freedom leads to interesting phenomena such as incommensurate lattice distortions in spin-Peierls systems [1] or first-order metamagnetic transitions in metals [2]. Recently, the bilayer ruthenate $Sr_3Ru_2O_7$ attracted much interest because of a new type of quantum critical point that arises from the continuous suppression of the critical temperature T_c of a first-order itinerant-electron metamagnetic transition towards absolute zero [3,4]. In this specific case, the field angle acts as tuning parameter and the quantum critical end point occurs for a magnetic field of about 8 T applied along the *c*-axis. Subsequent investigations on high-quality single crystals ($\rho_{res} = 0.4\,\mu\Omega\,cm$) have revealed an anomalous region of enhanced and temperature-independent electrical resistivity, which is bounded by two first-order transitions at 7.85 and 8.07 T and possibly related to novel phase formation linked to quantum critical fluctuations [5].

In this paper, we use high-resolution capacitive dilatometry to study the magnetoelastic coupling in $Sr_3Ru_2O_7$. The linear magnetostriction $\Delta L_c(H, T = \text{const.})/L_c$ along the *c*-axis has been measured on a high-quality single crystal at temperatures down to 20 mK and fields $H \parallel c$ up to 18 T. The magnetostriction coefficient $\lambda_c(B) = d(\Delta L_c/L_c)/d(\mu_0 H)$ is determined from the differential length change in field intervals of 0.01 T.

The magnetostriction is displayed in Fig. 1. In the metamagnetic region near 8 T, three step-like increases of the length are resolved, whose positions in field perfectly match with those of peaks in the real part χ' of the ac-susceptibility [5]. Whereas the first anomaly is possibly a cross-over, clear peaks in χ'' at the second and third anomalies are indicative of (weak) first-order transitions. They mark the boundaries of a state in which the electrical resistivity is highly enhanced and almost temperature-independent indicative of dominating elastic scattering [5].

The Maxwell relation $\lambda_c V_m = -\partial M/\partial P_c|_{P_c \to 0}$ with the molar volume V_m and *c*-axis uniaxial pressure P_c relates the magnetostriction coefficient to the uniaxial pressure dependence of the magnetization in the limit of zero pressure [1]. Since $\lambda_c > 0$, the magnetization *initially* decreases under uniaxial pressure along the *c*-axis and the system is tuned away from the metamagnetic quantum critical end-point towards the paramagnetic regime. Interestingly, a first-order pressure-induced ferromagnetic

*Corresponding author. Max-Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany. Tel.: +49 351 4646 2324; fax: +49 351 4646 2360.

E-mail address: gegenwart@cpfs.mpg.de (P. Gegenwart).

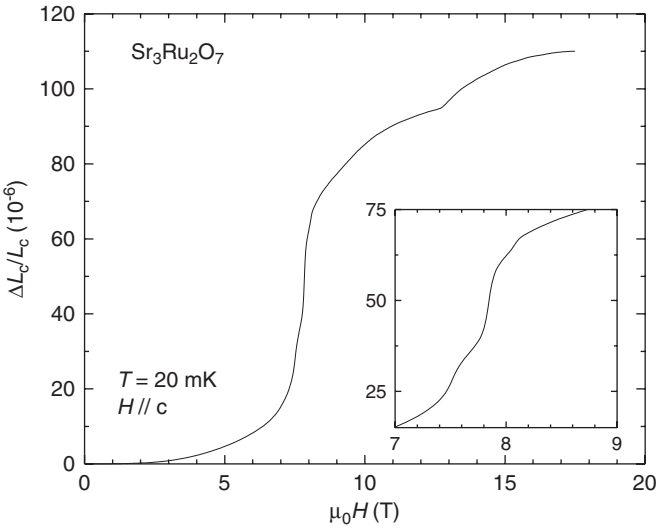

Fig. 1. Linear magnetostriction $\Delta L_c/L_c$ of $Sr_3Ru_2O_7$ measured at $T = 20\,\mathrm{mK}$ for $H \parallel c$ along the c-axis. Inset enlarges metamagnetic transitions.

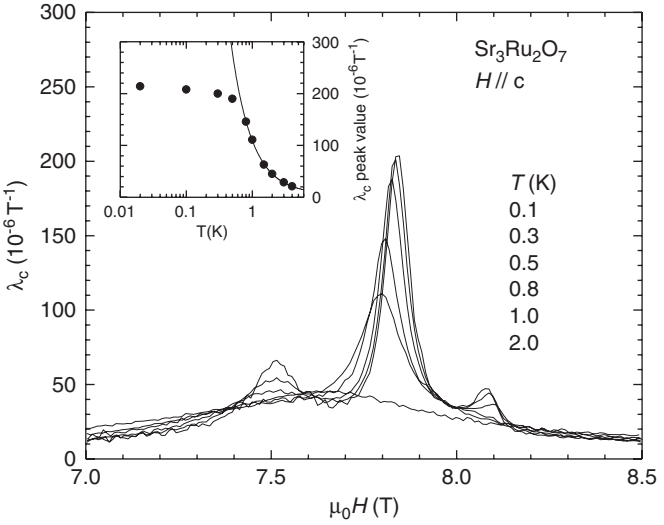

Fig. 2. Linear c-axis magnetostriction coefficient λ_c of $Sr_3Ru_2O_7$ vs field $H \parallel c$ at various different temperatures. Inset displays temperature dependence (on a log-scale) of λ_c at main peak. Solid line indicates $T^{-1.5}$ divergence.

ordering transition at $T_c \approx 80\,\mathrm{K}$, probably related to a change in the RuO_6 octahedron rotation angle, has been observed at a small c-axis uniaxial pressure of only 0.1 GPa [6]. Thus, $Sr_3Ru_2O_7$ is very sensitive to structural modifications.

Fig. 2 displays the linear magnetostriction coefficient $\lambda_c(B)$ at various temperatures for fields close to the metamagnetic region. The field and temperature dependence of λ_c strongly resembles that of the real part of the ac-susceptibility [5] and differential magnetization [7]. The low-temperature λ_c value at the main peak is of the same order of magnitude as that observed at the metamagnetic cross-over in $CeRu_2Si_2$ [8,9] providing evidence for a similar strong magnetoelastic coupling in both systems. In $CeRu_2Si_2$, the λ_c peak value follows a smooth T^2 dependence below 1.5 K, indicative of a cross-over that saturates in a Fermi-liquid ground state [9]. In contrast, for $Sr_3Ru_2O_7$ a $T^{-1.5}$ divergence is cut off around 0.7 K (see inset of Fig. 2) in agreement with a critical point at that temperature [5].

We now turn to the analysis of the magnetic Grüneisen parameter that is defined as $\Gamma_H = -(\mathrm{d}\log H^\star/\mathrm{d}\log V)_S$ and quantifies at constant entropy the volume dependence of a characteristic field $H^\star$. For $Sr_3Ru_2O_7$, using the isothermal compressibility $\kappa_T = 6.7 \times 10^{-12}\,\mathrm{Pa}^{-1}$ [10] and hydrostatic pressure dependence of the metamagnetic field $\mu_0\,\mathrm{d}H_\mathrm{m}/\mathrm{d}p = +5.6\,\mathrm{T/GPa}$ [11], the magnetic Grüneisen ratio equals $\Gamma_H = (\kappa_T \cdot H_\mathrm{m})^{-1}(\mathrm{d}\,H_\mathrm{m}/\mathrm{d}p) = +106$. Γ_H can also be derived from the ratio of the volume magnetostriction to the magnetic susceptibility: $\Gamma_H = V_\mathrm{mol}/(\kappa_T\mu_0 H)\cdot\lambda_V/\chi$. At present, we cannot investigate ab-plane length changes upon applying the field along the c-axis. If the volume magnetostriction is determined by λ_c only, using the differential susceptibility data of [7], a value of 160 ± 30 that exceeds Γ_H is obtained. Thus, the in-plane magnetostriction coefficient must be negative and around five times smaller in magnitude than λ_c. This also suggests an increase of the lattice anisotropy upon tuning through the metamagnetic transitions.

To summarize, a highly enhanced magnetic Grüneisen parameter indicative of a strong magnetoelastic coupling has been observed in $Sr_3Ru_2O_7$. The system is particularly sensitive to c-axis length changes.

We thank A. P. Mackenzie for helpful discussions and the Deutsche Forschungsgemeinschaft and Royal Society (UK) for financial support.

References

[1] U. Ammerahl, et al., Z. Phys. B 102 (1997) 71.
[2] T. Goto, K. Fukamichi, H. Yamada, Physica B 300 (2001) 167.
[3] S.A. Grigera, et al., Science 294 (2001) 329.
[4] S.A. Grigera, et al., Phys. Rev. B 67 (2003) 214427.
[5] S.A. Grigera, et al., Science 306 (2004) 1154.
[6] S.-I. Ikeda, et al., J. Phys. Soc. Japan. 73 (2004) 1322.
[7] T. Tayama, R.S. Perry, T. Sakakibara, unpublished results.
[8] A. Lacerda, et al., Phys. Rev. B 40 (1989) 8759.
[9] F. Weickert, et al., Physica B 359–361 (2005) 68.
[10] H. Shaked, et al., Phys. Rev. B 62 (2000) 8725.
[11] M. Chiao, et al., Physica B 312–313 (2002) 698.