# Anisotropy of the low-temperature magnetostriction of $Sr_3Ru_2O_7$

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We use high-resolution capacitive dilatometry to study the low-temperature linear magnetostriction of the bilayer ruthenate $Sr_3Ru_2O_7$ as a function of magnetic field applied perpendicular to the ruthenium-oxide planes ($B \parallel c$). The relative length change $\Delta L(B)/L$ is detected either parallel or perpendicular to the $c$-axis close to the metamagnetic region near $B = 8$ T. In both cases, clear peaks in the coefficient $\lambda(B) = \mathrm{d}(\Delta L/L)/\mathrm{d}B$ at three subsequent metamagnetic transitions are observed. For $\Delta L \perp c$, the third transition at 8.1 T bifurcates at temperatures below 0.5 K. This is ascribed to the effect of an in-plane uniaxial pressure of about 15 bar, unavoidable in the dilatometer, which breaks the original fourfold in-plane symmetry.

**1 Introduction** The bilayer ruthenate $Sr_3Ru_2O_7$ has recently attracted much interest, because of itinerant electron metamagnetism and the possible formation of a nematic electron fluid close to a quantum critical point near 8 T for fields applied perpendicular to the ruthenium-oxide planes, i.e., parallel to the tetragonal $c$-axis [1–4]. Early studies of the magnetic susceptibility of single crystals have suggested quantum criticality to arise from the suppression of the critical temperature of a first-order metamagnetic transition by tuning the field angle towards $B \parallel c$ [2]. Subsequent studies on high-quality single crystals ($\rho_0 = 0.4\,\mu\Omega$cm) have revealed a fine structure in the $T$–$B$ phase diagram, bound by two metamagnetic transitions at 7.85 and 8.07 T which are of first-order for temperatures below 0.7 and 0.5 K, respectively [3, 5]. Within this regime, the electrical resistivity peaks and becomes temperature independent, indicating an increase of elastic scattering, possibly due to the formation of some kind of domains [3], whereas outside this region the thermal expansion behavior was found to be compatible with metamagnetic quantum criticality [6]. An in-plane anisotropy of the electrical resistivity arises when the applied magnetic field is tilted by 13° off the $c$-axis, indicating a spontaneously broken fourfold rotational symmetry in the ab plane perpendicular to the $c$-axis [4]. The coupling of this presumed "electronic nematic state" to the lattice could be studied most sensitively by capacitive dilatometry. Previously, a strong magnetoelastic coupling with highly enhanced magnetic Grüneisen parameter has been found in linear magnetostriction measurements along the $c$-axis in $Sr_3Ru_2O_7$ [3, 7]. Since in the novel phase the fourfold symmetry is broken, length measurements perpendicular to the $c$-axis are of particular interest. In this paper, we compare for $B \parallel c$ the magnetostriction along and perpendicular to the $c$-axis.

**2 Experiment** For our experiments, we have used one piece of about $(1.5\,\mathrm{mm})^3$ dimension of the same high-quality single crystal, grown by the floating zone technique [8], which has been studied previously in thermal expansion and magnetostriction along the $c$-axis [3, 6, 7] (the original crystal has broken in two pieces).

The magnetostriction has been determined by a miniaturized capacitive dilatometer, which is small enough to be mounted in parallel and perpendicular configuration in a dilution refrigerator with an 18 T superconducting magnet. For our measurements, we have applied the field parallel to the $c$-direction, similar as previously. The linear magnetostriction has been detected in two separate runs first parallel

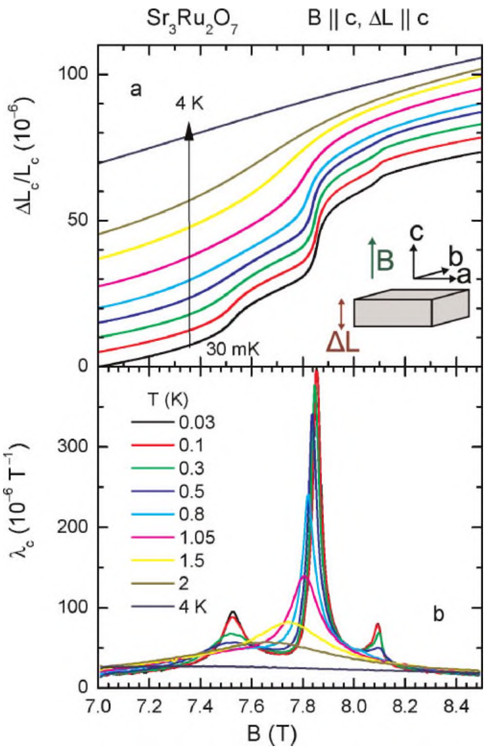


**Figure 1** (online color at: www.pss-b.com) (a) Linear magnetostriction $\Delta L_c/L_c$ along the $c$-axis of $Sr_3Ru_2O_7$ measured at various temperatures for $B \parallel c$, as indicated in the sketch. (b) Respective magnetostriction coefficient $\lambda_c(B)$.

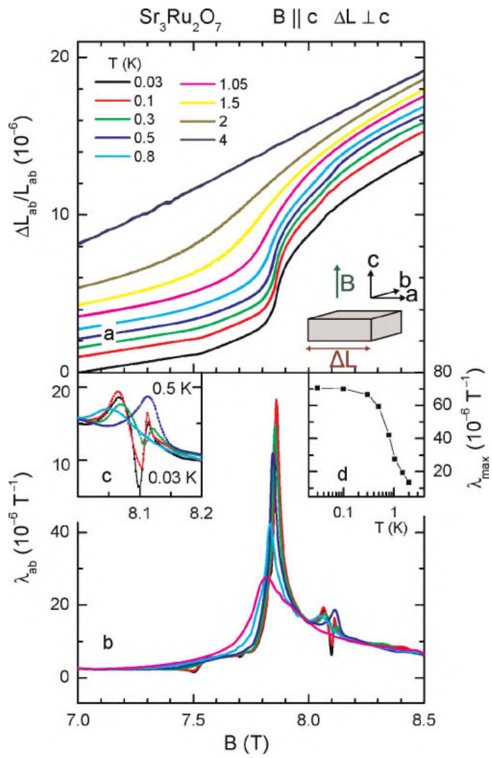


**Figure 2** (online color at: www.pss-b.com) (a) Linear magnetostriction $\Delta L_{ab}/L_{ab}$ of $Sr_3Ru_2O_7$ measured perpendicular to the $c$-axis at various temperatures for $B \parallel c$, as indicated in the sketch. (b) Respective magnetostriction coefficient $\lambda_{ab}(B)$. Inset c enlarges region close to upper metamagnetic transition. Inset d displays temperature dependence (on a log scale) of maxima in $\lambda_{ab}$ at the central metamagnetic transition.

to the applied field, i.e., $\Delta L \parallel B \parallel c$ as sketched in Fig. 1a, and subsequently perpendicular to the field, $\Delta L \perp B \parallel c$ (Fig. 2a)[1]. The magnetic field is varied with a rate of 1 T/h for temperatures between 30 mK and 4 K. No hysteresis larger than 2 mT could be detected similar as previously [7]. The magnetostriction coefficient $\lambda = \mathrm{d}(\Delta L/L)/\mathrm{d}B$ has been obtained by linear fits on 20 mT field intervals.

**3 Results** The length change parallel to the field and to the $c$-axis, $\Delta L_c/L_c$ between 7 and 8.5 T, displayed in Fig. 1a, is similar as observed previously [3, 7]. However, the three peaks in the coefficient $\lambda_c(B)$ are narrower and larger, indicating sharper transitions in this piece of the original single crystal used in Refs. [3, 7]. This may be related to the first-order nature of the metamagnetic transitions. The height of $\lambda_c$ at the central peak saturates at low-$T$, similar as found previously [7] and similar as observed for $\lambda_{ab}$ (inset d of Fig. 2).

Figure 2 shows corresponding magnetostriction results transverse to the applied field. In this configuration, the length change $\Delta L_{ab}/L_{ab}$ between 7 and 8.5 T is about five times smaller compared to the former case. The central peak in $\lambda_{ab}$ is qualitatively similar as found for $\lambda_c$, including its temperature dependence. However, the two other metamagnetic transitions display very different signatures. The 7.5 T crossover is visible as a distinct *minimum* in $\lambda_{ab}(B)$ at lowest temperatures. Furthermore, a splitting of the 8.1 T transition is observed below 0.5 K, resulting in a sharp minimum close to 8.1 T in $\lambda_{ab}(B)$ at lowest temperatures (cf. inset c of Fig. 2). As discussed below, we ascribe this anomaly to the small uniaxial pressure generated by our dilatometer.

Figure 3 displays a $T$–$B$ phase diagram with the positions of maxima in the linear magnetostriction coefficients $\lambda_{ab}(B)$ and $\lambda_c(B)$ indicated by blue circles and red triangles, respectively. Besides the bifurcation of the 8.1 T peak for measurements perpendicular to the $c$-axis at temperatures below 0.5 K, we also note the small shift of the central peak towards larger $B$ for this configuration.

**4 Discussion** The sign of the linear magnetostriction is related by the Maxwell relation $\lambda V_m = -(\mathrm{d}M/\mathrm{d}P)_{P\to 0}$ to the uniaxial pressure dependence of the magnetization ($V_m$: molar volume). Since $\lambda > 0$ for both orientations for the main metamagnetic transition, the magnetization decreases with increasing pressure, in qualitative agreement with the shift of the metamagnetic field under hydrostatic pressure [10].

[1] The sample edges are parallel to the axes of the pseudotetragonal crystal structure with $a \approx b \approx 3.89$ Å [9].

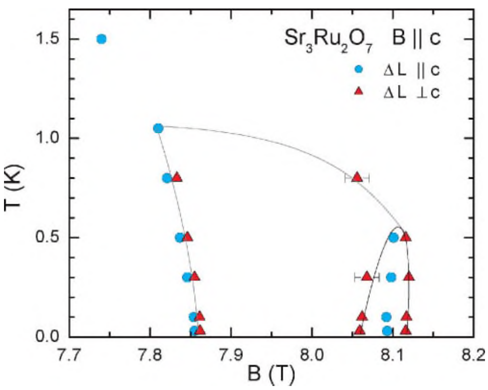


**Figure 3** (online color at: www.pss-b.com) *T*–*B* phase diagram for $Sr_3Ru_2O_7$, $B \parallel c$. Blue circles and red triangles indicate positions of maxima in $\lambda_c$ and $\lambda_{ab}$. Black and gray lines indicate bifurcation of 8.1 T transition in $\lambda_{ab}$ measurement and boundary of proposed symmetry-broken phase [3], respectively.

Positions of transitions in *T*–*B* phase space can generally not depend on the direction along which magnetostriction has been measured (for similar field orientation). Since the *same* crystal has been used, the only reason for the observed differences in the positions of the metamagnetic transitions is the effect of a weak uniaxial pressure in these measurements. The two parallel flat springs of our dilatometer exert a force of approximately 3 N on the sample's cross-section along the measurement direction, corresponding to a uniaxial pressure of roughly 15 bar for the studied crystal. Using the estimated uniaxial pressure dependence of the central metamagnetic transition [7], this pressure causes a shift of approximately 0.01 T, only, which is of similar size as a possible field offset due to remanence in the superconducting magnet. However, for the $\lambda_{ab}$ measurements the uniaxial pressure acts *perpendicular* to the *c*-axis and therefore breaks the fourfold in-plane symmetry. Such symmetry breaking could have a strong effect on the low-*T* properties. Most interestingly, the 8.1 T transition is found to bifurcate below 0.5 K, i.e., at temperatures below which this metamagnetic transition is of first order [3]. The comparison with the magnetostriction experiments along the *c*-axis indicates that this splitting arises from the in-plane uniaxial pressure. Interestingly, a bifurcation of two metamagnetic transitions has also been found for a high-quality $Sr_3Ru_2O_7$ single crystal at $B \perp c$, for temperatures below 0.5 K [11]. In this case, the field applied perpendicular to the *c*-axis breaks acts symmetry breaking.

To summarize, we have studied the anisotropy of the low-temperature magnetostriction of $Sr_3Ru_2O_7$ by capacitive measurements along and perpendicular to the applied field $B \parallel c$. $\Delta L_c/L_c(B)$ is about five times larger than $\Delta L_{ab}/L_{ab}(B)$. Remarkably, we observe a splitting of the metamagnetic transition at 8.1 T for the measurement perpendicular to the *c*-axis that is ascribed to a symmetry breaking uniaxial pressure of about 15 bar in this experiment.

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