Anisotropy of the low-temperature magnetostriction of Sr$_3$Ru$_2$O$_7$

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We use high-resolution capacitive dilatometry to study the low-temperature linear magnetostriction of the bilayer ruthenate Sr$_3$Ru$_2$O$_7$ 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 $\lambda(B) = d(\Delta L/L)/dB$ 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$_3$Ru$_2$O$_7$ has recently attracted much interest, because of itinerant electron metamagnetism and the possible formation of a nematic electron fluid close a quantum critical point near 8 T for fields applied perpendicular to the ruthenium-oxide planes, i.e. parallel to the tetragonal $c$-axis.\cite{1,2,3,4,5}. 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 $B \parallel c$.\cite{2,5,6,7}. Subsequent studies on high-quality single crystals ($\rho_0 = 0.4 \mu \Omega \cdot cm$) 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.\cite{5,6,7,8,9}. 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.\cite{5,6,7,8,9} whereas outside this region the thermal expansion behavior was found to be compatible with metamagnetic quantum criticality.\cite{5,6,7}. An in-plane anisotropy of the electrical resistivity arises when the applied magnetic field is tilted by $13^\circ$ off the $c$-axis, indicating a spontaneously broken fourfold rotational symmetry in the ab plane perpendicular to the $c$-axis.\cite{4,9}. 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$_3$Ru$_2$O$_7$.\cite{3,7,9}. Since in the novel phase the four-fold 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 mm)$^3$ dimension of the same high-quality single crystal, grown by floating zone technique, which has been studied previously in thermal expansion and magnetostriction along the $c$-axis.\cite{3,6,7,8} (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 18 T superconducting magnet. For our measurements, we have applied the field parallel...
Figure 1 a: Linear magnetostriction $\Delta L_c/L_c$ along the $c$-axis of Sr$_3$Ru$_2$O$_7$ measured at various temperatures for $B \parallel c$, as indicated in the sketch. b: Respective magnetostriction coefficient $\lambda_c(B)$.

to the $c$-direction, similar as previously. The linear magnetostriction has been detected in two separate runs first parallel to the applied field, i.e. $\Delta L \parallel B \parallel c$ as sketched in Figure 1a, and subsequently perpendicular to the field, $\Delta L \perp B \parallel c$ (Fig. 2a). 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 $\lambda = d(\Delta L/L)/dB$ 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 Figure 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 [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 be-
low, 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 $\lambda_c$ and minima in $\lambda_{ab}$. Black and gray lines indicate bifurcation of 8.1 T transition to the uniaxial pressure dependence of the magnetization and boundary of proposed symmetry-broken phase [3], respectively.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3}
\caption{$T$-$B$ phase diagram for Sr$_3$Ru$_2$O$_7$, $B \parallel c$. Blue circles and red triangles indicate positions of maxima in $\lambda_c$ and maxima and minima in $\lambda_{ab}$. Black and gray lines indicate bifurcation of 8.1 T transition in $\lambda_{ab}$ measurement and boundary of proposed symmetry-broken phase [3], respectively.}
\end{figure}

\section{Discussion}

The sign of the linear magnetostriction is related by the Maxwell relation $\lambda_{ab} = -(dM/dP)_{P=\text{constant}}$ to the uniaxial pressure dependence of the magnetization ($V_m$: molar volume). Since $\lambda > 0$ for both orientations for the studied crystal, the magnetization decreases with increasing pressure, in qualitative agreement with the shift of the metamagnetic field under hydrostatic pressure [10].

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 samples 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 [2], 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$_3$Ru$_2$O$_7$ 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$_3$Ru$_2$O$_7$ 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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