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Forced magnetostriction of samarium metal up to 33 Tesla

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Combining the highest steady magnetic fields with the best resolution for measuring length changes clearly pushes the frontiers of experimental physics. The design of a miniaturized capacitance dilatometer that can be used in the 33 T magnet of the National High Magnetic Field Laboratory allows magnetostriction measurements with unprecedented resolution. We present the first investigation of the forced magnetostriction of samarium metal.

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I. INTRODUCTION

The measurement of magnetostriction is the most powerful macroscopic method to study the interaction of electronic and lattice degrees of freedom. Combining the highest steady magnetic fields with the best resolution available for measuring length changes clearly pushes the frontiers of experimental physics. Recently, there has been great activity in the area of the magnetostriction of antiferromagnets (see, for instance, the review[1]). In contrast to ferromagnets, in antiferromagnets a large variety of magnetic structures can be stabilized at different temperatures and magnetic fields, which allows us to separate and distinguish the different mechanisms of magnetostriction.

There are some pure rare earth metals, for which the forced magnetostriction has not been reported, as, for instance, for the antiferromagnetic Sm metal. Sm is a *c*-axis antiferromagnet with magnetic order of the moments on the hexagonal and cubic site of the rhombohedric structure at 106 K and 14 K, respectively.[2–4] Some magnetic properties of Sm have already been studied in 1974 (Ref. 5) by magnetization measurements in pulsed magnetic fields. These measurements revealed the existence of a magnetic transition for a field parallel to the crystallographic *c* axis at about 28 T. We demonstrate the power of forced magnetostriction measurements by the data of a Sm single crystal.

II. DESCRIPTION OF THE EXPERIMENTAL METHOD

The design of a miniaturized capacitance dilatometer (outer diameter 22 mm)[6] allows the measurement of longitudinal as well as transversal components of magnetostriction with unprecedented resolution and field range. Therefore, the complete magnetostriction tensor can be analyzed. The dilatometer was installed in the 33 T Bitter magnet of the National High Magnetic Field Laboratory (Tallahassee, FL) equipped with a ^{4}He cryostat. For the best resolution of about 10^{-6}, it is important to damp mechanical vibrations and electric noise. The results shown in Fig. 1 were obtained by averaging the signals obtained for increasing and decreasing fields. No systematic hysteresis effects have been observed. The error bars include the effects of mechanical noise and the differences between increasing and decreasing field data. To verify the high-field results, the measurements were also performed in a 14 T superconducting magnet.

To exclude effects caused by the crystal growing process, two different high-quality Sm crystals were used: The first

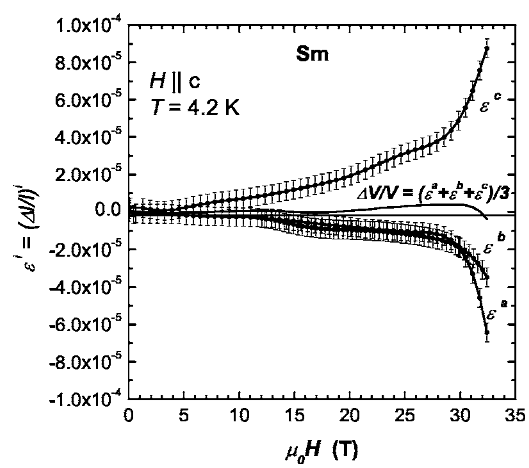

FIG. 1. Magnetostriction of a Sm single crystal with the magnetic field applied along the *c* direction.

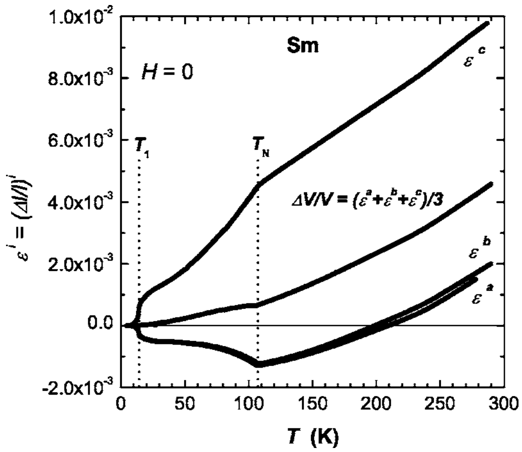

FIG. 2. Thermal expansion of a Sm single crystal in a zero magnetic field.

crystal, grown at the University of Birmingham (UK), has a cuboid shape of $1.6\times1.7\times1.2$ mm^3. It was prepared by solid state crystal growth techniques with the sample sealed under argon within a tantalum container to prevent the loss of material by volatilization. The crystal was oriented and the quality was checked using back-reflection x-ray Laue techniques. The second crystal, from the Ames Laboratory (USA), is nearly cubic, $2.27\times2.34\times2.38$ mm^3. It was prepared by a strain annealing process and was also characterized by the Laue technique. To avoid oxidization influences, the surfaces were cleaned before the experiment. The magnetostriction results of both crystals are identical in the limit of the experimental error.

III. THE MAGNETOSTRICTION OF SAMARIUM METAL

We now present the first investigation of the forced magnetostriction of samarium metal. Figure 1 summarizes the experimental data obtained in magnetic fields up to 33 T parallel to the c axis. It clearly reflects the phase transition, which has been observed in the pulsed field magnetization measurements and that has been attributed to a reorientation of the magnetic moments at the quasicubic sites leading to a field-induced ferromagnetic state.[5]

The magnetoelastic behavior of the crystal is anisotropic. When the magnetic field is applied parallel to c, the c axis expands, whereas the plane perpendicular to the c axis shrinks. The volume magnetostriction effect is small. This anisotropic behavior is also reflected by the zero-field data of thermal expansion, which is shown in Fig. 2. On cooling, the c axis contracts at T_N, whereas the a and b axes expand. The spontaneous volume magnetostriction at the Néel temperature T_N and at the ordering temperature T_1 of the moments at the quasicubic sites is very small. The application of a magnetic field along the easy direction reverses the effect of cooling, i.e., the c axis expands and the a and b axes contract. Such behavior is in line with the expectations from the exchange striction model.[1]

The spontaneous magnetostriction is of the order of 10^{-3}. When the magnetic moments are aligned parallel by an external field we expect a similar order of magnitude for the forced magnetostriction (see, e.g., Ref. 7). In order to investigate this point and determine the saturation magnetostriction above the metamagnetic transition, the field range of the experiment has to be extended further.

In agreement with the magnetization measurements,[5] no spin flop transition is observed in our data, when the field is applied perpendicular to the c axis. In fields parallel to the a direction, the magnetostriction is very small and does not exceed a value of 5×10^{-6} up to 33 T. The same behavior was found for the b direction.

Note that the observed magnetostriction effects disagree with the crystal field striction model, which would suggest small effects for the magnetic field along the easy axis and large effects for fields along the hard axes.[1] Therefore we infer from our data that the magnetostrictive properties of Sm metal are dominated by the exchange striction mechanism.

In addition, in order to explain a negligible magnetostriction for fields along the hard axes, the two-ion magnetoelastic constants have to be anisotropic. In order to see this we note that, for example, the field dependence of the magnetoelastic strain ϵ^a is described within the exchange striction model by the expression (compare Ref. 1)

$$\sum_{ij} \frac{\partial \mathcal{J}_{cc}(ij)}{\partial \epsilon^a} \langle \mathbf{J}_i^c \mathbf{J}_j^c \rangle_{T,\mathbf{H}} + \frac{\partial \mathcal{J}_{aa}(ij)}{\partial \epsilon^a} \langle \mathbf{J}_i^a \mathbf{J}_j^a \rangle_{T,\mathbf{H}}. \tag{1}$$

In the expression (1), $\mathcal{J}_{aa}(ij)$ and $\mathcal{J}_{cc}(ij)$ denote the components of the two-ion interaction tensor describing the magnetic interaction between the ions i and j. This tensor is assumed to be diagonal and (1) is valid for the magnetic field $\mathbf{H}$ along the a axis. The field dependence of the magnetoelastic strain ϵ^a is contained in the static two-ion correlation functions $\langle \mathbf{J}_i^\alpha \mathbf{J}_j^\alpha \rangle_{T,\mathbf{H}}$ (here $\mathbf{J}_i^\alpha$ denotes the α component of the angular momentum operator of ion i and $\langle\,\rangle_{T,\mathbf{H}}$ denotes the thermal expectation value).

When two antiferromagnetically aligned moments are turned into the a direction by the external magnetic field, the correlation function $\langle \mathbf{J}_i^c \mathbf{J}_j^c \rangle_{T,\mathbf{H}}$ is negative and approximately equal to $-|\langle \mathbf{J}_i^c \rangle_{T,\mathbf{H}}|^2$. On the other hand, $\langle \mathbf{J}_i^a \mathbf{J}_j^a \rangle_{T,\mathbf{H}}$ is positive and equal to $|\langle \mathbf{J}_i^a \rangle_{T,\mathbf{H}}|^2$. The magnetization measurements indicate[5] that the magnitude of the moments does not change significantly, when these are turned into the basal plane, i.e., $|\langle \mathbf{J}_i^a \rangle_{T,\mathbf{H}}|^2 + |\langle \mathbf{J}_i^c \rangle_{T,\mathbf{H}}|^2 = \text{const}$. Therefore the small-field dependence of the magnetostriction (1) can only be explained if the magnetoelastic constants $\partial \mathcal{J}_{\alpha\alpha}(ij)/\partial \epsilon^a$ fulfill approximately

$$\frac{\partial \mathcal{J}_{aa}(ij)}{\partial \epsilon^a} \sim -\frac{\partial \mathcal{J}_{cc}(ij)}{\partial \epsilon^a}. \tag{2}$$

Such a relation is not expected if the two-ion interactions are dominated by the isotropic mechanisms such as Heisenberg or RKKY types of exchange. In this sense our magnetostriction experiments indicate an anisotropic mechanism in the magnetic two-ion interactions of Sm metal. To our knowledge the only investigation of anisotropic interactions in a Sm-based system has been done for $SmCu_2$.[8]

IV. CONCLUSION

Magnetostriction measurements on Sm metal have been performed. For an external field parallel to *c* they show the occurrence of a structural distortion, which is associated with the high-field transition, where the moments at the quasicubic sites undergo a spin flop transition. Spontaneous and forced magnetovolume effects are small in Sm metal. However, large anisotropic strains have been observed. The magnetostriction data suggest exchange striction as the dominant magnetoelastic interaction mechanism in Sm metal and indicate anisotropy in the magnetic two-ion interactions.

The feasibility to do magnetostriction measurements using the capacitance method in steady magnetic fields up to 33 T has been demonstrated. By optimizing the cell design and reducing mechanical vibrations as a source of noise it is possible to obtain data of extremely high quality. Phase transitions and magnetoelastic strains can be determined with unprecedented precision in magnetic fields above 20 T.

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