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Michael Leonard
*Southern Illinois University Carbondale*

Shibaji Saha
*Southern Illinois University Carbondale*

Naushad Ali
*Southern Illinois University Carbondale*



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# Magnetic properties of $RTSb_3$

Michael Leonard, Shibaji Saha, and Naushad Ali[a)]
*Department of Physics and Molecular Science Program, Southern Illinois University at Carbondale, Carbondale, Illinois 62901*

Magnetization, electrical resistivity, and thermal expansion measurements have been performed on polycrystalline $RTSb_3$ (R=La, Ce, Pr, Nd, Gd, Tb, and Dy; T=Cr, V) samples in order to study their magnetic properties. Depending on the rare-earth element, $RTSb_3$ has been found to have either a purely ferromagnetic (or antiferromagnetic) phase or combination of antiferromagnetic (lower-temperature) and ferromagnetic (higher-temperature) phases. The antiferromagnetic order evolves from the ferromagnetic order as a result of the competition between $R^{3+}$ and $Cr^{3+}$ ions. As R is changed from La to Dy, the antiferromagnetic ordering of the $R^{3+}$ ions becomes more prominent and predominate over the ferromagnetic ordering of $Cr^{3+}$ for R=Gd, Tb, and Dy. Thermal expansion measurements show that the antiferromagnetic transition accompanies a drop in the sample dimension. The order of the ferromagnetic transition is found to be of the second order.
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## INTRODUCTION

The intermetallic alloys formed by combining the magnetic properties of the $4f$ metals (large magnetocrystalline anisotropy, R) and the $3d$ metals (large exchange coupling, T) in $RTSb_3$ present an interesting class of magnetic material both for the study of their basic magnetic behavior and for their possible applications. It is mentioned that the rare-earth metal is useful in stabilizing low-dimension features such as layers or chains[1] (seen in $CeCrSb_3$). Successive layering of such compound allows for the control of the magnetic aspect through interlayer coupling.

Previous results on the magnetic properties of the $RTSb_3$ system with T=Cr and V show that the Cr atoms which order ferromagnetically, correspond to two unpaired spins, whereas the V has one uncompensated spin.[2] The lowered Curie temperatures for $RTSb_3$ (T=Cr) are attributed to the R–T coupling where R orders antiferromagnetically. In the same way as the atomic radius decreases from La to Lu, it was found that substitution of heavier rare earths for La in $LaTSb_3$ causes the structure of the compound to contract.[1] The contraction of the structure is accompanied by changes in the magnetic properties of the system. This led us to extend the study of the magnetic properties of $RTSb_3$ with R=La, Ce, Pr, Nd, Gd, Tb, and Dy.

## EXPERIMENTAL DETAILS

Polycrystalline $RTSb_3$ samples were synthesized by are melting of the proper amounts of the constituent elements in an Ar atmosphere. An excess amount (10%) of Sb was added to compensate for its weight loss during melting. The purities of the elements were 99.9% for all the rare-earth elements, 99.99% for Cr, 99.9% for V, and 99.999% for Sb. Samples were annealed in an evacuated quartz tube at 600 °C for two days and at 800 °C for eight days. Magnetization measurements were carried out by means of a superconducting quantum interference device magnetometer (Quantum Design, CA) over the temperature range of 5–400 K and in an applied magnetic field up to 5.5 T. Thermal expansion measurements were made using a capacitance dilatometer over the temperature range of 4.2–200 K. Electrical resistivity measurements were done using the standard four-probe method over the temperature range of 5–300 K.

## RESULTS AND DISCUSSIONS

Figure 1 shows the magnetization behavior of the $RCrSb_3$ (with R=La, Ce, Pr, Nd, Gd, and Tb) compounds as a function of temperature. Unless specified, all samples were cooled in zero applied magnetic field from room temperature and magnetization measurements were done in an applied field of 0.01 T while raising the temperature. Figure 1(a) shows that $LaCrSb_3$ is ferromagnetic with a Curie temperature of 144 K. The transition temperature was determined from the first derivative of $M$ vs $T$ data. The $T_c$ found by Hartjes *et al.*[2] for $LaCrSb_3$ is 125 K, which was determined from the lowest point of the $1/\chi$ vs $T$ plot. In Fig. 1(b) $CeCrSb_3$ shows ferromagnetic ordering with $T_c=140$ K. This is much higher than that found by Hartjes *et al.*[2] The inset shows the magnetization data of $CeCrSb_3$ at 1 T. It shows that there is another ordering below 30 K. Interestingly, the $PrCrSb_3$ sample [Fig. 1(c)] shows antiferromagnetism below 16 K while it is ferromagnetic at higher temperatures with $T_c=142$ K. A comparison of the low-temperature ordering in $CeCrSb_3$ [the inset of Fig. 1(b)] with the low-temperature antiferromagnetic ordering in $PrCrSb_3$ suggests that in $CeCrSb_3$ there is an onset of an antiferromagnetic phase at low temperature. Temperature-dependent magnetization of the $NdCrSb_3$ [Fig. 1(d)] sample is similar to that of $PrCrSb_3$. For $NdCrSb_3$, transition temperatures of $T_N=18$ K and $T_c=141$ K were found. The overall magnetic behavior of the samples presented in Figs. 1(a), 1(b), 1(c), and 1(d) agree with those found by Hartjes *et al.*[2]

We now turn our attention to new systems in the $RTSb_3$ series, namely, $GdCrSb_3$, $TbCrb_3$, $DyCrb_3$, and $DyVSb_3$.

a)Electronic mail: nali@physics.siu.edu

 

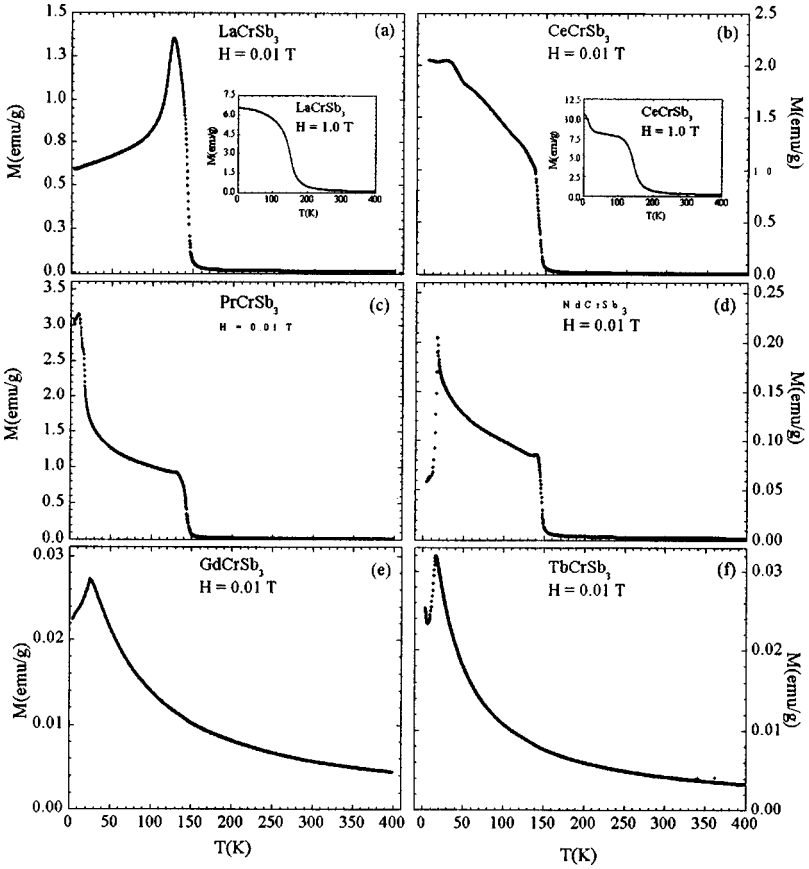


FIG. 1. Magnetization as a function of temperature of $RCrSb_3$ samples: (a) $M$ vs $T$ of $LaCrSb_3$ at 0.01 T; the inset shows the data taken at 1 T. (b) $M$ vs $T$ of $CeCrSb_3$ at 0.01 T; the inset shows the data taken at 1 T. (c) $M$ vs $T$ of $PrCrSb_3$ at 0.01 T; the inset shows the data taken at 1 T. (d) $M$ vs $T$ of $NdCrSb_3$ at 0.01 T. (e) $M$ vs $T$ of $GdCrSb_3$ at 0.01 T. (f) $M$ vs $T$ of $TbCrSb_3$ at 0.01 T.

In Fig. 1(e), $GdCrSb_3$ shows an antiferromagnetic ordering with $T_N = 26$ K. $GdCrb_3$ does not show the ferromagnetic ordering found in all the $RCrSb_3$ for R lighter than Gd. $TbCrSb_3$ shows a clear antiferromagnetic phase with $T_N = 17$ K [Fig. 1(f)]. It is known that the ferromagnetic ordering in $LaCrSb_3$ is due to the ordering of the Cr atoms. According to Czachor,[3] the antiferromagnetic order in $RCrSb_3$ compounds is due to the antiferromagnetic ordering of the $R^{3+}$ ions. In the present study, the evolution of an antiferromagnetic order from ferromagnetic order in $RCrSb_3$ as we changed R from La to Dy, is most likely due to favorable antiferromagnetic ordering of the $R^{3+}$ ions over the ferromagnetic order of the Cr atoms. This, most likely, has a connection with the changes in the lattice parameters due to the lanthanide contraction.

Magnetization data of $DyCrSb_3$ are plotted in Fig. 2(a). It shows that $DyCrSb_3$ orders antiferromagnetically below 12 K. Field-dependent magnetization data in the antiferromagnetic phase are plotted in Fig. 2(c) for $DyCrSb_3$. It clearly shows that the sample is antiferromagnetic below 12 K; more importantly, the sample transforms to a ferromagnetic phase with higher field showing a metamagnetic behavior of the sample. The critical field is found to be $H_C = 1.9$ T at 5 K. The critical fields have been determined from several field-dependent magnetization measurements at different constant temperatures. An $H-T$ phase diagram is shown in the inset of Fig. 2(c). Hartjes *et al.*[2] also found a metamagnetic transition in $PrVSb_3$ and $NdVSb_3$. Since $DyCrSb_3$ showed metamagnetism, we also studied $DyVSb_3$. Figure 2(b) shows the magnetization of $DyVSb_3$ as a function of temperature. It is antiferromagnetic with $T_N = 12$ K. Figure 2(d) shows the magnetization as a function of applied field at 5, 7, and 8 K where it is clear that $DyVSb_3$ also shows metamagnetic behavior. The inset of Fig. 2(d) shows the $H-T$ phase diagram for $DyVSb_3$.

Thermal expansion measurements were done on selected samples to determine the order of the ferromagnetic transitions and also to investigate any dramatic dimensional

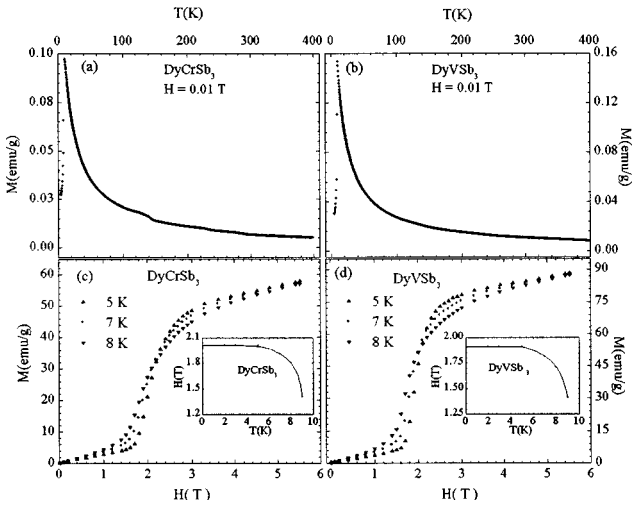


FIG. 2. Magnetization of $DyCrSb_3$ (a) and $DyVSb_3$ (b) samples as a function of temperature at an applied field of 0.01 T. Magnetization as a function of applied field at different constant temperatures of $DyCrSb_3$ (c) and $DyVSb_3$ (d) samples; the insets show the $H-T$ phase diagrams.

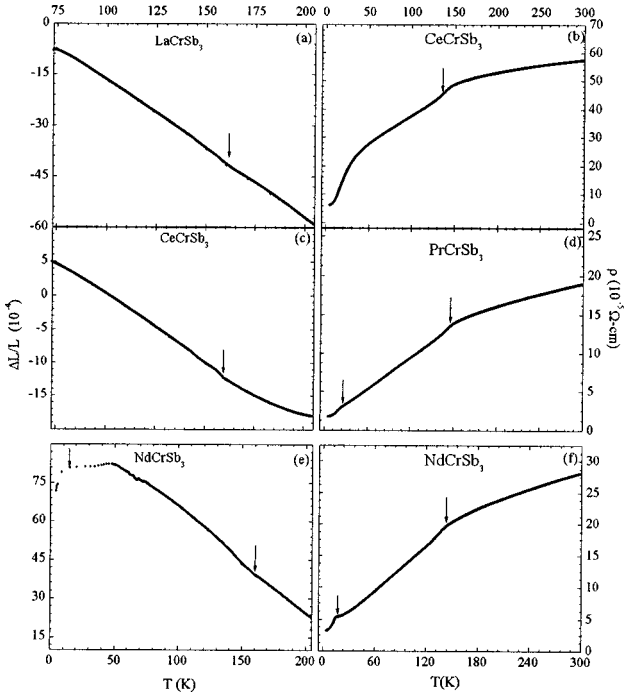


FIG. 3. Respective relative thermal expansivity $\Delta l/l$ of $RCrSb_3$ (R=La, Ce, Nd) are given in (a), (c), and (e) as a function of temperature. Electrical resistivity of $RCrSb_3$ (R=Ce, Pr, Nd) are shown in (b), (d), and (f), respectively, as a function of temperature.

changes associated with the magnetic transitions. Thermal expansion data for $LaCrSb_3$, $CeCrSb_3$, and $NdCrSb_3$ are given in Figs. 3(a), 3(c), and 3(e), respectively. In the data for $LaCrSb_3$, a slope change occurs near the ferromagnetic transition which suggests a second-order transition. In the $CeCrSb_3$ sample a slope change occurs near the ferromagnetic transition, which again suggests a second-order transition. A drop in sample dimension appears, near $T_N = 18$ K, the antiferromagnetic transition of $NdCrSb_3$, at higher temperatures, the data suggests a second-order ferromagnetic transition at $T_c = 141$ K.

Electrical resistance measurements on selected samples of $RCrSb_3$ were made to identify features in resistance which would correlate with the transitions observed in the magnetization measurements. Resistivity data on $CeCrsb_3$, $PrCrSb_3$, and $NdCrSb_3$ are shown in Figs. 3(b), 3(d), and 3(f), respectively. All samples show metallic character. In $CeCrSb_3$ the transition marked by an arrow corresponds to the ferromagnetic transition observed in the magnetization data. The two transitions found in the resistivity data of both $PrCrSb_3$ and $NdCrSb_3$ correspond to the antiferromagnetic and ferromagnetic transitions in the magnetization data.

## SUMMARY

Magnetization, thermal expansion, and electrical resistivity measurements have been made on $RTSb_3$ samples. $RCrSb_3$ samples show ferromagnetic order for R=La; antiferromagnetic and ferromagnetic orders for R=Ce, Pr, and Nd, and antiferromagnetic order for R=Gd, Tb, and Dy. The variety of magnetic order clearly depends on the size of the rare-earth elements. A drop in the sample dimension is found to occur near the Néel temperatures. The ferromagnetic transitions in $RCrSb_3$ are found to be second order. Transitions in electrical resistivity data corresponded to those in magnetization data.

## ACKNOWLEDGMENT

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[2] K. Hartjes *et al.*, J. Magn. Magn. Mater. **173**, 109 (1997).
[3] A. Czachor, J. Magn. Magn. Mater. **139**, 355 (1995).