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MAGNETIC TRANSITIONS IN THE TERNARY COMPOUNDS NdRu$_2$Si$_2$, NdRu$_2$Ge$_2$ AND NdCo$_2$Ge$_2$

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Abstract. – Heat capacity and electrical resistivity studies have been performed on the tetragonal ternary NdRu$_2$Si$_2$, NdRu$_2$Ge$_2$ and NdCo$_2$Ge$_2$ compounds. Two magnetic phase transitions are observed at temperatures 10 K and 23 K for NdRu$_2$Si$_2$ and at 10 K and 17 K for NdRu$_2$Ge$_2$. One transition is seen for NdCo$_2$Ge$_2$ (at 28 K).

The intermetallic compounds of the formula NdT$_2$X$_2$, where T is 3d, 4d or 5d metals and X is Si or Ge exhibit interesting magnetic behaviours [1]. These compounds crystallize in the ThCr$_2$Si$_2$-type, tetragonal structure with I4/mmm space group [2]. NdCo$_2$Ge$_2$ has the collinear antiferromagnetic structure of AFI type [3] below $T_N = 26.5$ K [4]. The magnetometric measurements indicate the additional phase transition at temperature $T = 10$ K [5].

Neutron diffraction study performed on NdRu$_2$Ge$_2$ indicate the antiferromagnetic ordering below 17 K and ferromagnetic ordering below 10 K [6]. A very similar behaviour is observed for NdRu$_2$Si$_2$ (two magnetic transitions at 24 K and 10 K) [7].

In this paper we report the specific heat and electrical resistivity for these three compounds. The samples were prepared by melting the rare-earth metals, the Co or Ru metals and Ge or Si in an induction furnace. They were annealed in an argon-filled quartz tube at 800 °C for 100 h. The single-phase nature of the compounds was established by X-ray analysis using FeK$_x$ radiation. In the case of NdCo$_2$Ge$_2$ and NdRu$_2$Si$_2$ all the observed lines could be indexed assuming a tetragonal ThCr$_2$Si$_2$ type structure. For NdRu$_2$Ge$_2$ minor impurity phases corresponding to NdGe and NdRu$_2$ were observed.

Heat capacity data were taken down to temperatures of 0.1 K (from 50 K) in a $^3$He–$^4$He dilution refrigerator using a semiaadiabatic calorimeter described previously [8]. Resistivity measurements were carried out (1.7 – 300 K) using a standard four-probe ac technique in a gas-flow cryostat.

The specific heat data for the three compounds are shown in figure 1. For NdCo$_2$Ge$_2$ compound we observe a single peak at 28 K, which corresponds to the magnetic transition temperature ($T_N = 26.5$ K). We do not see any anomaly around 10 K.

In the temperature range below 10 K the specific heat data were analysed assuming the following formula:

$$C_p (T) = C_{\text{latt.}} + C_{\text{cond.}} + C_{\text{n}} + C_{\text{M}}$$

FIG. 1. – (a) Heat capacity vs. temperature for NdCo$_2$Ge$_2$. (b) Magnetic heat capacity of NdRu$_2$Si$_2$. (c) Magnetic heat capacity of NdRu$_2$Ge$_2$.

$C_{\text{latt.}}$ = lattice contribution (given by the Debye function $\beta T^3$)

$C_{\text{cond.}}$ = conduction electron contribution (of the form $\gamma T$)

$C_{\text{n}}$ = nuclear contribution (observed only at very low temperature – of the form: $aT^{-2}$)

$C_{\text{M}}$ = magnetic contribution (given by function $cT^{3/2}$ for ferromagnets and by $dT^2$ for antiferromagnets).
In the $C_p/T$ vs. $T^2$ graphs we observed a linear dependence for NdCo$_2$Ge$_2$ and NdRu$_2$Ge$_2$ compounds (in the temperature range 3-7 K) but because of the magnetic contribution we are not able to extract the $\beta$ and $\gamma$ values.

In the second step we analyzed the magnetic part of the specific heat.

In the case of NdRu$_2$Si$_2$ and NdRu$_2$Ge$_2$ the magnetic term $C_M$ of the specific heat was obtained by subtracting the data of LaRu$_2$Si$_2$ [9] and LaRu$_2$Ge$_2$ [10] respectively (Fig. 1). For NdRu$_2$Si$_2$ we observed the jump at 10 K which corresponds to the F-AF phase transition and the second maximum at $T = 23$ K which corresponds to the AF-paramagnetic state transition. We also observed one bump (at 29 K) which corresponds probably to the Schottky anomaly due to the crystal field levels. For NdRu$_2$Ge$_2$ the maximum corresponding to the F-AF phase transition is observed at 10 K, whereas the maximum (at 17 K) corresponds to the AF-paramagnetic phase transition. The calculated magnetic entropy reaches 66% and 31% of $R\ln 2$ for NdRu$_2$Si$_2$ and NdRu$_2$Ge$_2$ compounds respectively at the peak position.

The magnitude of the Schottky anomaly due to the nuclear hyperfine splitting (Fig. 2) suggests that the magnetic moment in the crystal ground state is about 80% of the free-ion value of Nd$^{+3}$ for the NdRu$_2$Ge$_2$ compound and is equal to the free-ion value in the case of NdRu$_2$Si$_2$ and NdCo$_2$Ge$_2$ compounds.

![Fig. 2. Low-temperature heat capacity of NdCo$_2$Ge$_2$, NdRu$_2$Ge$_2$ and NdRu$_2$Si$_2$. The dotted and solid lines correspond to the theoretical curves of the full and 80% of the full free-ion value of Nd$^{+3}$ respectively.](image)

The temperature dependences of the electrical resistivity at low temperatures are shown in figure 3. Our data indicate the magnetic phase transitions at 10 K and 23 K for NdRu$_2$Si$_2$, 10 K and 17 K for NdRu$_2$Ge$_2$ and 28 K for NdCo$_2$Ge$_2$.

![Fig. 3. Electrical resistivity vs. temperature for NdCo$_2$Ge$_2$, NdRu$_2$Ge$_2$ and NdRu$_2$Si$_2$.](image)

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