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Induced Magnetic Phase Transitions in Rare-Earth Intermetallic Compounds $R\text{Mn}_2\text{Ge}_2$ in Ultrastrong Magnetic Fields


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Abstract—The differential magnetic susceptibility of intermetallic compounds $R\text{Mn}_2\text{Ge}_2$ ($R = \text{Gd, Tb, Dy, Ho, Y}$) with a layered tetragonal structure is measured in pulsed magnetic fields up to 130 T. It is found that all these compounds undergo a first-order magnetic phase transition in strong magnetic fields. The nature of this transition is discussed, and it is found that a change in the magnetic state of the manganese sublattice is responsible for the transition. © 2001 MAIK “Nauka/Interperiodica”.

The intermetallic compounds $R\text{Mn}_2\text{Ge}_2$ ($R$ stands for rare-earth metals (REMs), yttrium, uranium, etc.) have a tetragonal crystal structure (space group $I4/mmm$) consisting of alternating atomic layers $R$–Ge–Mn–Ge–$R$... normal to the tetragonal axis [1]. From the magnetic point of view, these compounds have two magnetic subsystems, one of which is formed by REM atoms and the other by Mn atoms. Numerous investigations (see [1] and the references therein) have shown that the Mn–Mn ferromagnetic exchange in a layer is the strongest in $R\text{Mn}_2\text{Ge}_2$. The interlayer Mn–Mn exchange interaction is approximately an order of magnitude weaker than the exchange in an Mn layer. The exchange interaction between the manganese and the rare-earth subsystems has nearly the same order of magnitude. The exchange within the rare-earth subsystems is still weaker by an order of magnitude. The exchange interaction between the Mn layers and between Mn and REM layers are both antiferromagnetic in intermetallic compounds with heavy REMs and yttrium.

The hierarchy of the exchange interactions described above determines the peculiarities of the magnetic properties of the $R\text{Mn}_2\text{Ge}_2$ compounds with heavy REM. The manganese subsystem in these compounds becomes ordered at temperatures of 350–450 K. This ordering is antiferromagnetic; the magnetic moments in adjacent ferromagnetic layers of manganese are antiparallel [1]. The magnetic rare-earth subsystem remains paramagnetic in this case, because the effective fields of the two adjacent manganese layers acting on this subsystem neutralize each other.

With decreasing temperature, the rare-earth subsystem of certain intermetallic compounds (with gadolinium, terbium, dysprosium) undergoes a first-order phase transition to the ferromagnetic state [1]. In this case, the manganese subsystem is also transformed to the ferromagnetic state due to the REM–manganese exchange interaction. Since this interaction is antiferromagnetic, the magnetic moments of the rare-earth and the manganese subsystems are antiparallel, and hence the magnetic structure on the whole is ferrimagnetic. In intermetallic compounds with holmium, erbium, and thulium, the REM–Mn exchange interaction is weaker and, hence, the manganese subsystem in these compounds remains in the antiferromagnetic state to the lowest temperatures [1].

The behavior of $R\text{Mn}_2\text{Ge}_2$ compounds in a magnetic field has been studied much more sparingly. Phase transitions induced by a magnetic field were detected in a number of intermetallic compounds (with dysprosium and gadolinium in Gd–Y and Gd–La systems) [2–6] and attributed to a change in the nature of magnetic ordering in the manganese subsystem. However, the nature of these transitions has not been established unambiguously so far. It should be emphasized that even in the strongest magnetic fields (up to 40 T) employed in those experiments, the magnetization of the investigated compounds was considerably lower than the theoretical saturation magnetization for a parallel orientation of the magnetic moments of the rare-earth and manganese subsystems, leading to the assumption that additional field-induced magnetic phase transitions can be observed in stronger fields.

In this work, we report on the attempts to detect these transitions by measuring the magnetic properties of the intermetallic compounds $R\text{Mn}_2\text{Ge}_2$ in ultrastrong magnetic fields.
Polycrystalline samples of compounds $\text{RMn}_2\text{Ge}_2$ ($R = \text{Gd, Tb, Dy, Er}$) were smelted from constituent elements in an induction furnace in an argon atmosphere under quasi-levitation conditions. For better homogenization, the samples were remelted three times and annealed in a dynamic vacuum at 750°C for 170 h. X-ray diffraction analysis was carried out to verify the single-phase nature of the samples.

Measurements were made on powdered samples with a particle size of about 10 μm at 5–7 K in pulsed magnetic fields up to 150 T generated by the inductive discharge of a bank of capacitors through a one-turn solenoid (the duration of the first half-period of the pulse was 6 μs). Note that considerable spurious signals are generated in this technique due to the noise of the capacitor bank discharge, decompensation of the measuring coils, mechanical vibrations of the system of measuring coils, etc. This makes it difficult to isolate the desired signal. For the small magnitudes of this signal, we made repeated measurements. The criterion for the correct isolation of the desired signal was its detection in both increasing and decreasing fields. Detection was impossible for most spurious signals. Finally, we made auxiliary measurements using the explosive compression technique to obtain an ultrastrong field [7] in the case of the gadolinium intermetallic compound, which produced the weakest signal during the phase transition in our experiments. All these measures enabled us to reliably determine the fields $H_c$ for the induced magnetic phase transitions in the investigated compounds.

The signal induced in the measuring coils can be described by the formula

$$V = (a + B\chi)dH/dt. \quad (1)$$

Here, $dH/dt$ is the time derivative of the field; the first term in parentheses describes the decompensation signal from the measuring coils and the second, the signal from the sample; $\chi$ is the differential magnetic susceptibility of the sample; and $a$ and $b$ are constants associated with the parameters of the coils (number of turns and cross-sectional areas) and of the sample (mass and geometrical size), respectively. In the critical magnetic field $H_c$ for the first-order magnetic phase transition, the susceptibility $\chi$ passes through a maximum. Consequently, a peak in the voltage $V$ induced in the measuring coils is observed in this region. Note that the fields corresponding to the peaks of the dependences $V(H)$ and $\chi(H)$ will coincide only in the case of $dH/dt = \text{const}$. Estimates show that this condition is fulfilled in comparatively weak fields (for a sinusoidal time dependence of the field pulse, for approximately $H < 0.5H_{\text{max}}$). Appropriate corrections must be made for transitions occurring in stronger fields. For this reason, we determined the value of $H_c$ from the field dependence of the quantity $V/(dH/dt)$ in the region where no such correction was required. The corresponding dependences are shown in Fig. 1. It can be seen that the magnetization of all the investigated compounds undergoes a diffuse metamagnetic transition in strong fields. The values of the critical fields are different for transitions in increasing and decreasing fields, which is characteristic of first-order phase transitions. Note that the width of the hysteresis loop is apparently affected by relaxation effects associated with the pulsed nature of...