Dependence of the Curie Temperature on the Effective de Gennes Factor in Ferromagnets with Exchange Frustration

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Abstract—Considering the magneto-diluted gadolinium-containing Adamian alloys, it is shown that the dependence of the Curie temperature on the de Gennes factor \( \xi = c(g - 1)J(J + 1) \) can be expanded for ferromagnets with the exchange frustration. It is shown that in this case it is necessary to replace \( J \) by \( S_{\text{eff}} \) and that the linear dependence of \( T_C \) on \( \xi_{\text{eff}} \) remains up to the pure spin-glass state with \( S_{\text{eff}} = 0 \).

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Temperatures of magnetic transition into the magnetically ordered ferro- or antiferromagnetic states \( (T_{\text{Curie}} \equiv T_C, T_{\text{Neel}} \equiv T_N) \) in rare-earth metals (Re) and their alloys are proportional to the atomic concentration of magnetic ions \( c \) and are well described by the de Gennes factor \( \xi = c(g - 1)J(J + 1) \), where \( g \) is the Lande factor and \( J \) is the total angular momentum [1]. Some experimentally observed deviations of \( T_C \) and \( T_N \) from a linear dependence can be explained by changes in the lattice parameter [2] as well as by the variation of the band structure of rare-earth alloys [3]. It is evident that both mechanisms influence the Curie temperature. We believe that the dependence of \( T_C \) on the lattice parameter is more essential because the exchange interactions between localized rare-earth ions, which are realized by the conduction electrons (the Ruderman–Kittel–Kasuya–Yosida mechanism [4]), directly depend on the distance between them.

In [5] V. Adamian has proposed a method to obtain intermetallic solid solutions with a CsCl crystal structure, in which the cubic lattice constant \( a_0 \) remains unchanged with variations of the alloy composition. All distances between magnetic ions are determined by means of \( a_0 \). Adamian and coworkers have synthesized and investigated a number of pseudobinary gadolinium-contained alloys \([\text{Gd}]_{1-x}[(\text{La}, \text{Y})_x][\text{M}]_{1-y}[\text{M}_2]_y\]

\[ \text{A system} \equiv [\text{Gd}_{0.22}(\text{La}_{1-x}\text{Y}_x)_{0.78}][\text{Zn}_{1-x}\text{Cd}_x], \quad 0 \leq x \leq 1, \]

\[ \text{E system} \equiv [\text{Gd}_{0.22}(\text{La}_{1-x}\text{Y}_x)_{0.78}][\text{Zn}_{1-x}(\text{In}_{0.5}\text{Cu}_{0.5})_x], \quad 0 \leq x \leq 0.5, \]

\[ \text{D system} \equiv [\text{Gd}_x(\text{La}/\text{Y})_{1-x}][\text{Zn}_{0.15}\text{Cd}_{0.85}], \quad 0.22 \leq x \leq 1. \]

In these alloys only the Gd\(^{3+}\) ions \( (L = 0, S = 7/2) \) are magnetic, while the other ions \( (\text{La}^{3+}, \text{Y}^{3+}, \text{In}^{3+}, \text{Zn}^{2+}, \text{Cd}^{2+}, \text{and Cu}^{1+}) \) are diamagnetic. The constant value of \( a_0 \) in the A and E systems is achieved by simultaneous substitutions of ions in the rare-earth and metallic sublattices \( (\text{Zn}^{2+} \text{by Cd}^{2+} \text{or by (In}^{3+} + \text{Cu}^{1+}) \text{in combination with La}^{3+} \text{by Y}^{3+} \). The constancy of the lattice parameter in the D system is achieved by the variation of the Y/La ratio at the variation of the gadolinium concentration. For all three systems of alloys the measured cubic lattice constant \( a_0 = (3.741 \pm 0.001) \). In the A and E systems the concentration of the magnetic Gd\(^{3+}\) ions is constant \( (c = 0.22) \), while in the D system it changes in the range of \( 0.22 \leq c \leq 1 \) \( (c \equiv x) \).
Fig. 1. Dependences of the Curie temperature $T_C$ and spontaneous magnetization $\mu_{s0}$ on the concentration of Gd$^{3+}$ ions $c$: $\Delta - D = [\text{Gd}_{0.22}(\text{La}_{1-x}\text{Y}_x)_{0.78}]\text{[Zn}_{0.15}\text{Cd}_{0.85}]$, $0.22 \leq c \leq 1$; ○ - $A = [\text{Gd}_{0.22}(\text{La}_{1-x}\text{Y}_x)_{0.78}]\text{[Zn}_{1-x}\text{Cd}_x]$, $0 \leq x \leq 1$; ▲ - $E = [\text{Gd}_{0.22}(\text{La}_{1-x}\text{Y}_x)_{0.78}]\text{[Zn}_{1-x}([\text{In}_{0.5}\text{Cu}_{0.5}])]$, $0 \leq x \leq 0.5$.

Figure 1 presents the $c$-dependence of $T_C$ for all three systems. The linear dependence of $T$ on $c$ (the de Gennes dependence) is well obeyed for the D system. However, for the A and E alloys, for which $c = 0.22$, one observes different $T_C$ depending on the composition of diamagnetic ions $x$. In the A system $T_C$ varies from 13 K to 50 K, while in the E system it changes from 13 K to 0 K. Figure 1 shows also the $c$-dependence of the spontaneous magnetization $\mu_{s0}$ at $T = 0$ K. The dependences of $T_C$ and $\mu_{s0}$ on $x$ at $c = 0.22$ are presented in Fig. 2. In [6–8] we have shown that the “magnetic anomalies” in the A and E systems are caused by the alloying effects, i.e., by the dependences of the mean free path of electrons and electron effective mass on $x$. Note also that the Gd$^{3+}$ ions concentration $c = 0.22$ in the A and E alloys is close to the percolation threshold and that the essentially different dependences of $T_C$ and $\mu_{s0}$ at the range of $x \sim 0.5$ (a collinear ferromagnet with $\mu_{s0} = 7\mu_B$ and $T_C = 50$ K in the A system and a spin glass with $\mu_{s0} = 0$ and $T_C = 0$ K in the E system) are determined by the compositional disorder of nonmagnetic ions at isoelectronic substitutions in the first case and by the charge disorder at nonisoelectronic substitutions in the second case [7, 8]. In both systems we observe in fact the ferromagnetism, which is partially suppressed due to the frustration of exchange interactions (ferromagnetism with the exchange frustration).

Fig. 2. Dependences of $T_C$ and $\mu_{s0}$ on $x$ in the A and E systems at $c = 0.22$. 