Thermal expansion and magnetic transformations of $Mn_{1-x}Cr_xSb$ alloys

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The nature of the magnetic phase transitions of the alloys $Mn_{1-x}Cr_xSb$ in the concentration range $0 \leqslant x \leqslant 0.8$ has been studied by measuring their thermal expansion and magnetization and by differential thermal analysis. The magnetic phase diagram, in which the lines of the ferromagnetic (T_C) and antiferromagnetic (T_N) transformations intersect in the region of $x = 0.5$, is obtained for these alloys. It is established that the ferromagnetic transitions are of second order for all the concentrations x studied, while the antiferromagnetic transitions are of first order both at the point of intersection of the $T_C(x)$ and $T_N(x)$ lines and far from that point. On the basis of the experimental results obtained and the exchange-striction theory of Bean and Rodbell the reasons for the appearance of first-order magnetic phase transitions are discussed and effects related to the shift of T_N with pressure are evaluated.

INTRODUCTION

There has recently been a great deal of interest in investigations of the effect of critical fluctuations on the character of the magnetic phase transition. For a number of antiferromagnets (see, e. g., Ref. 1), it has been shown that the phase transitions, which, according to the Landau theory, (ignoring fluctuations) should be second-order transitions, become first-order transitions because of critical fluctuations. This theoretical conclusion has been confirmed experimentally.[2]

For systems with mixed ferromagnetic and antiferromagnetic exchange interactions the critical behavior has received considerably less experimental study. The magnetic phase diagram of such a system is characterized by a singular point (a polycritical point) formed by the intersection of the lines of the ferromagnetic and antiferromagnetic transitions. According to the Landau theory, this polycritical point can be bicritical or tetracritical. Theories[3–5] which take into account fluctuations of the order parameters on the basis of the renormalization group and Wilson's ε-expansion lead to the conclusion that second order phase transitions at the point of intersection of the lines of the magnetic transformations are not possible. In this case, according to Refs. 4 and 5, there should be a first order phase transition which can be very much washed out in the mixed systems mentioned above.

As far as we know, these theoretical conclusions have not been tested experimentally; accordingly, our purpose in the present investigation is to make such a test using by way of example the alloys $Mn_{1-x}Cr_xSb$.

The solid solutions $Mn_{1-x}Cr_xSb$ are formed from the ferromagnetic compound MnSb and the antiferromagnetic compound CrSb. According to neutron diffraction data,[6] as the manganese in MnSb is replaced by chromium there is a continuous transition from ferromagnetic ($x = 0$) to antiferromagnetic ($x = 1$) ordering, with the formation of a canted magnetic structure in the intermediate range of concentrations $0.05 < x \leqslant 0.8$. The Curie temperature T_C and the Néel temperature T_N of these alloys are lowered as the transition element is substituted and at the middle of the phase diagram ($x = 0.5$) the lines of the magnetic transformations intersect. In a wide range of concentrations, with the exception of $x = 0.5$, an increase in temperature brings about the following sequence of magnetic structures: canted–collinear–paramagnetism, while for the alloy of composition $x = 0.5$ there should be a direct transition from the canted to the paramagnetic phase. All of these magnetic transformations occur within the same crystallographic structure–the NiAs-type hexagonal lattice (space group $P6_3/mmn$).

Attempts have been made[7,8,4] to construct theoretically the magnetic phase diagram of $Mn_{1-x}Cr_xSb$ on the basis of various models of the exchange interactions, but good agreement with existing experimental data was not obtained. We shall show below that all-inclusive investigations of the magnetic phase transitions give additional information on the exchange mechanisms and can be very helpful in the study of the mechanisms in complex magnetic systems.

To determine the character of the magnetic phase transitions we have, in this investigation, studied the thermal expansion of the alloys $Mn_{1-x}Cr_xSb$ of various chemical compositions ($0 \leqslant x \leqslant 0.8$), as well as thermal effects and the field and temperature dependences of the magnetization and the magnetic susceptibility.

ALLOY PREPARATION AND EXPERIMENTAL METHOD

The $Mn_{1-x}Cr_xSb$ alloys were synthesized by heating in evacuated quartz ampoules thoroughly mixed chemically pure powders of Mn (99.8%), Cr (99.7%), and Sb (99.99%), which were taken in the required proportions and pressed into the shape of bars at pressures 3.7–4.2 tons/cm^2. The thermal treatment during the synthesis was similar to that described in Ref. 9: slow heating to 920 K, holding at this constant temperature for one hour, sintering[1)] at 1050–1150 K for 24 h and then lowering the temperature at an average rate of 40 deg/h. The MnSb alloy was obtained by cooling from the sintering temperature at 15 deg/h. To obtain more homogeneous alloys, the cycle described above was repeated twice. Taking into account the dependence, noted in Ref. 9, of the magnetic properties on the thermal treatment in the

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preparation of the alloys, we also prepared and studied alloys produced by quenching in water from the sintering temperature. It should be noted that the alloys with a high chromium concentration were very fragile, and therefore it was not possible to make a suitable sample with concentration $x = 0.9$.

X-ray diffraction and microstructural phase analyses showed the presence of a small amount of Sb (about 3–5% by volume) in addition to the principal $Mn_{1-x}Cr_xSb$ phase.[2)] The x-ray diffraction patterns were taken for powder samples in an RKD-57.5 camera by the asymmetric method using copper and iron radiation. All the diffraction lines in the x-ray patterns, taken at room temperature, were indexed on the basis of the NiAs-type hexagonal lattice. The results of the x-ray diffraction tests on the alloys we produced are reported in Ref. 10. The results indicate that the phase of $Mn_{1-x}Cr_xSb$ is a homogeneous solid solution. The values of the lattice parameters a, c, and c/a, and the volume of the unit cell of $Mn_{1-x}Cr_xSb$ as well as the variation of these parameters with x are in good agreement with published data.[6]

The thermal expansion was measured with a specially designed and constructed vacuum quartz dilatometer in which the displacement sensor was a 6MKh1S movable electrode tube having a high current sensitivity to displacements and linear electronic-mechanical characteristics over the range $\pm$ 50 μm. The sensitivity of the dilatometer to elongation was better than 10^{-6} cm. The measurements were carried out on samples 5 mm in diameter and 3–6 mm long at two heating rates, 20 and 6 deg/min. The relative error in the measurements was 8%.

Thermal effects were studied by means of differential thermal analysis. The thermograms were taken on a DO-102 optical derivatograph in an argon atmosphere, using annealed aluminum oxide as a standard. This instrument allowed us to measure, in addition to the thermal effects, changes of weight of the sample during heating.

The magnetic measurements were made with a Domenicali-type pendulum magnetometer in magnetic fields up to 16 kOe. The Curie temperature was determined by the well-known method of thermodynamic coefficients[11] from the measured magnetization isotherms in the vicinity of T_C. To stabilize the sample temperature we used a Gappler ultrathermostat, which made it possible to maintain a constant temperature with a precision of 0.02 °C. The temperature was measured with a copper-constantan thermocouple tightly attached to the sample. The samples were spherical, with a diameter 2–3 mm.

RESULTS OF MEASUREMENTS

The temperature dependence of the relative elongation $\Delta l/l$ of the polycrystalline $Mn_{1-x}Cr_xSb$ alloys ($0 \leqslant x \leqslant 0.8$) was measured from 77 K to 830 K for both the annealed and the quenched samples.

Figure 1 shows the results of the measurements of the linear thermal expansion. From this figure it can be seen that in the regions of the magnetic transition temperatures T_C and T_N there are large anomalies in the thermal expansion of

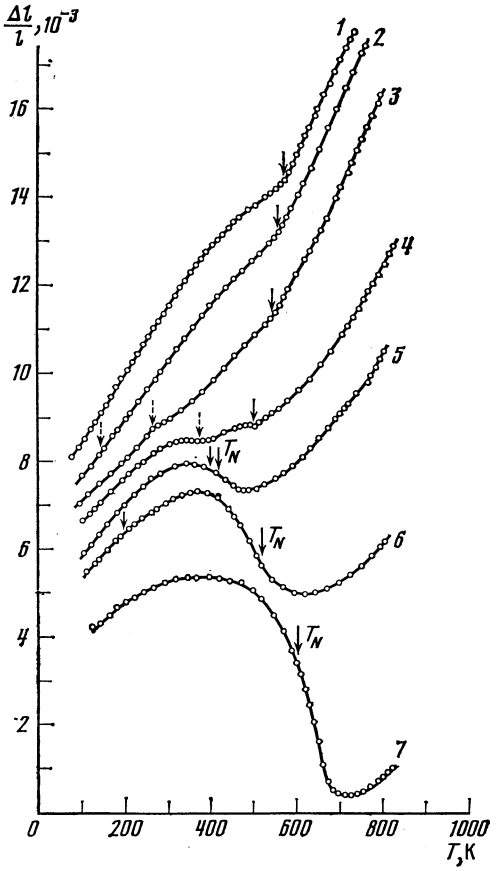

FIG. 1. Temperature dependence of linear thermal expansion of $Mn_{1-x}Cr_xSb$ alloys. 1) $x = 0$; 2) $x = 0.1$; 3) $x = 0.25$; 4) $x = 0.4$; 5) $x = 0.5$; 6) $x = 0.7$; 7) $x = 0.8$. The arrows show T_C according to the magnetic measurements; T_N and the temperatures of the canted-structure–ferromagnetic transition (dashed arrows) are determined from neutron diffraction data.[6]

the annealed alloys. However, the anomalies in the temperature dependence of $\Delta l/l$ near T_C and T_N have a considerably different character. The ferromagnetic alloys with $x = 0$, 0.1, and 0.25 (curves 1, 2, and 3) have a kink typical of ferromagnets in the curve of $\Delta l/l$ at the Curie point. This kink indicates a second-order phase transition and a positive spontaneous magnetostriction, which corresponds to a downward shift in the Curie point of these alloys under pressure[10]: $dT_C/dP < 0$. It should be noted that the values of T_C determined from the temperature dependences of $\Delta l/l$ and from the magnetic measurements by means of the method of thermodynamic coefficients are in very good agreement with each other.

In the alloys with high chromium concentration, $x = 0.5$, 0.7, and 0.8 (curves 5, 6, and 7 of Fig. 1) there is an abrupt change in $\Delta l/l$ at the Néel point, indicating a first order phase transition. The data show that the volume change $\Delta V/V$ at the antiferromagnetic–paramagnetic transition increases with x and is 0.5% at $x = 0.5$ and 1.5% at $x = 0.8$. The change in volume at T_N is accompanied by a thermal effect which is associated with the absorption of heat and which was observed in the differential thermal analysis thermograms for all the alloys in the concentration range $0.5 \leqslant x \leqslant 0.8$. According to the Clausius-Clapeyron re-

lation

$$\frac{dT}{dP} = \frac{T(\Delta V/V)}{Q},$$

the sign of dT_N/dP for endothermic transformations ($Q > 0$) is determined by the sign of $\Delta V/V$, i.e., by whether the volume increases or decreases at the phase transition. From the data we have obtained ($\Delta V/V < 0$), we can expect that the Néel temperature should decrease with pressure. It would be desirable to check this conclusion by direct measurements of T_N under hydrostatic pressure. There exist published values of dT_N/dP only for CrSb[12,13] and these are in disagreement with each other.

Using our data for the thermal expansion and from the magnetic measurements we have plotted in Fig. 2 the temperatures of the magnetic transformations as a function of the chemical composition of the alloys $Mn_{1-x}Cr_xSb$. In the same figure the dashed lines show the magnetic phase diagram for these alloys determined by neutron diffraction studies.[6] From the data presented here it can be seen that in the T–x phase plane the lines which separate the paramagnetic phase from the magnetically ordered ferromagnetic and antiferromagnetic phases (curves 1 and 2) as well as the transitions of these phases into the canted phase (curves 1′ and 2′) are in good agreement with the results of the neutron diffraction investigations.[6] We did not study the transformations, observed in Ref. 6, resulting from a change in the magnetic crystallographic anisotropy.

Curve 1 of the magnetic phase diagram of the $Mn_{1-x}Cr_xSb$ alloys (Fig. 2) is the line of the Curie temperatures T_C, the values of which decrease linearly with increasing x in the concentration range $0 \leqslant x \leqslant 0.4$. With further increase in x the dependence $T_C(x)$ is no longer linear, and at $x = 0.5$ curve 1 goes over into curve 1′, which characterizes the canted-ferromagnetic–antiferromagnetic transformation. Although the transitions at the Curie point and the canted–ferromagnetic–antiferromagnetic transitions are related to different kinds of magnetic transformations—order-disorder and order-order—nonetheless we have observed no difference in the character of the magnetic transformations

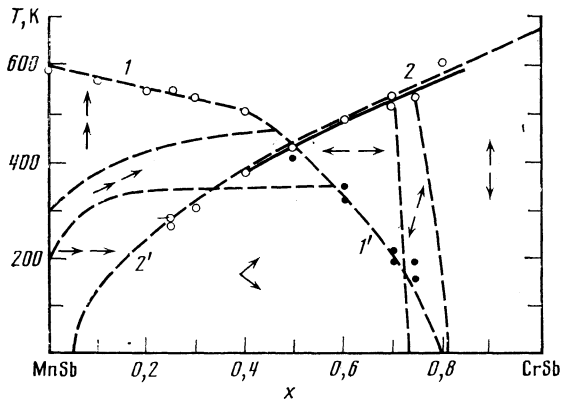

FIG. 2. $Mn_{1-x}Cr_xSb$ magnetic phase diagram plotted from the temperature dependence of $\Delta l/l$ (○) and from the magnetic measurements (●). The solid curve corresponds to first-order phase transitions, the dashed curves to second-order phase transitions.[6]

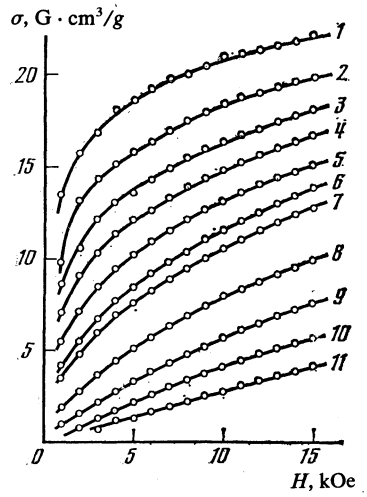

FIG. 3. Magnetization curves of $Mn_{0.4}Cr_{0.6}Sb$ in the vicinity of the canted-ferromagnetic–antiferromagnetic transition. Temperatures in K are: 1) 290; 2) 298; 3) 303; 4) 308.3; 5) 313; 6) 318; 7) 323; 8) 333; 9) 343; 10) 353; and 11) 368.

determined by the curves 1 and 1′. The magnetization isotherms, $\sigma(H)$ measured both in the region of curve 1 and of curve 1′ could be described by the magnetic equation of state $A\sigma + B\sigma^3 = H$, just as in ordinary ferromagnets near T_C.

Figure 3 shows by way of example the field dependences of the magnetization of the annealed alloy of concentration $x = 0.6$, measured in the vicinity of the canted-ferromagnetic–antiferromagnetic transition. From these data we plotted the dependences of H/σ on σ^2 shown in Fig. 4, which allowed us to determine the temperatures of the canted-ferromagnetic–antiferromagnetic transitions by the method of thermodynamic coefficients. It was established that the canted-ferromagnetic–antiferromagnetic transformations are associated with the loss of spontaneous magnetization and are second order phase transitions. The temperature dependences of the magnetization of the alloys of concentration $x = 0.6$ and $x = 0.75$, measured in a field $H = 8$ kOe and shown in Fig. 5 (curves 2 and 3) may serve as illustrations of this point.

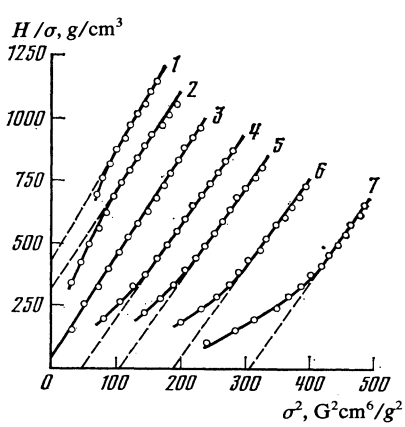

FIG. 4. Dependence of the ratio H/σ on σ^2 for $Mn_{0.4}Cr_{0.6}Sb$ in the vicinity of the canted-ferromagnetic–antiferromagnetic transition. Temperatures in K are : 1) 323; 2) 318; 3) 313; 4) 308.3; 5) 303; 6) 298; and 7) 290.

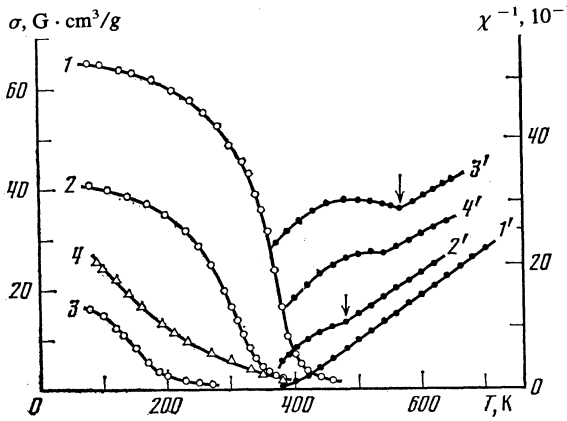

FIG. 5. Temperature dependence of specific magnetization and inverse susceptibility, χ^{-1} (curves denoted by primed numbers) for the $Mn_{1-x}Cr_xSb$ alloys measured in a field of 8 kOe for the annealed alloys: 1 and 1') $x = 0.5$; 2 and 2') $x = 0.6$; 3 and 3' $x = 0.75$; and for the quenched alloy: 4 and 4' $x = 0.7$. The arrows indicate T_N.

The distinction between the canted-ferromagnetic–ferromagnetic transformations from the ferromagnetic transformations exists only at high temperatures and is due to the existence of antiferromagnetic ordering in the high-temperature phase of the alloys of composition $0.5 < x < 0.8$. The Néel temperature T_N of these phases can be determined both from the temperature dependences of $\Delta l/l$, as has already been discussed, and from measurements of the temperature dependence of the magnetic susceptibility, as can be well seen from the graphs of $\chi^{-1}(T)$ shown in Fig. 5, curves 2' and 3'. It is noteworthy that the first order phase transition at the Néel point for the $Mn_{1-x}Cr_xSb$ alloys does not produce any large anomalous changes in $\chi^{-1}(T)$.

Another feature of the canted-ferromagnetic–antiferromagnetic transitions is the strong dependence of the temperature of this transition on the thermal treatment of the alloys of composition $0.5 < x \leqslant 0.8$. Thus, for, e. g., the quenched alloys it was not possible to determine the temperature of the canted-ferromagnetic–antiferromagnetic transition: the dependence $\sigma(T)$ in this case was smeared out (curve 4 of Fig. 5). Nevertheless, the antiferromagnetic–paramagnetic transformations of the quenched alloys were similar to those of the annealed alloys with this difference: that the volume change $\Delta V/V$ at T_N was, as a rule, 1.5–2 times larger than in the annealed alloys. The high-temperature magnetic susceptibilities of the annealed and the quenched alloys did not differ very much from each other, as can be seen from the plots of $\chi^{-1}(T)$, shown in Fig. 5.

Curve 2 in the magnetic phase diagram (Fig. 2) is the line of the Néel points T_N; for $x < 0.5$ this line goes over into curve 2', which defines the canted-ferromagnetic–ferromagnetic transformations. The solid line on curves 2 and 2' show the first-order phase transitions which we have determined for T_N in the concentration range $0.5 \leqslant x \leqslant 0.8$ and for the canted-ferromagnetic–antiferromagnetic transition in the alloy of composition $x = 0.4$. The results of the thermal expansion measurements (see Fig. 1) indicate that for the alloys with $x < 0.5$ the magnetic transformation becomes progressively less sharp with decreasing x and there is a decrease in the volume change at the canted-ferromagnetic–antiferromagnetic transitions, the temperatures of which are shown by the dashed arrows on curves 4, 3, and 2 in Fig. 1. In the alloys with low chromium concentrations ($x \leqslant 0.2$) these magnetic transformations do not show up in the temperature dependences of $\Delta l/l$ (see curve 2, Fig. 1). It should be noted that with the exception of the alloy with $x = 0.4$ (for which there was a very weak anomaly in the differential thermal analysis thermogram) we observed no thermal effects for the canted-ferromagnetic–antiferromagnetic transitions and found no changes in the character of the magnetization isotherms or in the curves of $\sigma(T)$ in the region of the canted-ferromagnetic–antiferromagnetic transitions. These regularities were observed both for the annealed and the quenched alloys.

In the alloy with $x = 0.5$, the concentration of which corresponds to the intersection point of the $T_C(x)$ and $T_N(x)$ lines of the phase diagram (Fig. 2), two magnetic transformations occur almost simultaneously and take place independently of one another. These are a ferromagnetic and an antiferromagnetic transformation, where the transformation at the Néel point T_N is a first-order phase transition. This can be seen from the results of the measurements of the temperature dependence of the thermal expansion $\Delta l/l$ (curve 5, Fig. 1), which indicate that there is a volume change in the vicinity of T_N accompanied by a thermal effect. The transformation at the Curie point T_C is of second order, as is indicated by the magnetic measurements: the $\sigma(H)$ isotherms for the alloy with $x = 0.5$ are similar to those shown in Fig. 3, while the temperature dependence of the magnetization is shown in Fig. 5 (curve 1). Fig. 5 also shows $\chi^{-1}(T)$ (curve 1'), which follows the Curie-Weiss law over the entire temperature range investigated.

DISCUSSION OF RESULTS

The difficulty of interpreting the magnetic properties of $Mn_{1-x}Cr_xSb$ stems from the lack of a clear understanding of the exchange interaction mechanism in these alloys. In earlier works the theoretical investigations of the magnetic phase diagrams of these alloys were based on models of a six-sublattice ferrite[7] and the double exchange model of de Gennes,[8] and these models did not lead to good agreement with neutron diffraction data.[6,9]

Subsequently, the magnetic phase diagrams and the critical behavior of similar systems have been studied on the basis of a model of a disordered alloy with mixed ferromagnetic and antiferromagnetic interactions, both for the case of random bonds[4] and random sites.[3,5] In these cases the general form of the phase diagrams that were obtained (ignoring anisotropy) agreed with that shown in Fig. 2. Nevertheless, it was still not clear to what extent this model was applicable to $Mn_{1-x}Cr_xSb$, since there was very little experimental data unambiguously identifying these alloys as a mixed ferromagnetic-antiferromagnetic system with competing exchange interactions. We may note that there has been only a single work concerned with the study of exchange anisotropy and rotary hysteresis in $Mn_{1-x}Cr_xSb$ of concentration $x = 0.5$, 0.6 and 0.7.[14]

The results obtained in this set of experiments on magnetic transformations may serve as additional evidence that the $Mn_{1-x}Cr_xSb$ alloys belong to the above-mentioned class of magnets with mixed exchange. The evidence is: a) the mutual independence of the ferromagnetic and antiferromagnetic phase transformations, b) the strong effect of thermal treatment on T_C of alloys with a high chromium concentration ($0.5 < x \leqslant 0.8$); this effect is a manifestation of short range magnetic order in a disordered system having exchange of opposite signs, c) the increase in the volume change $\Delta V/V$ with increasing x at the Néel point for alloys of concentration $0.5 \leqslant x \leqslant 0.8$; this indicates that the number of antiferromagnetic interactions increases with the chromium concentration.

From the experimental data we have obtained we can conclude that there is no change in the character of the phase transition at the intersection point of the $T_C(x)$ and $T_N(x)$ curves or on either side of it ($x \geqslant 0.5$). Over a wide range of concentrations x the magnetic transformations at the Curie point are second order phase transitions, while at the Néel point they are first order. This indicates that the ferromagnetic and antiferromagnetic phases are largely independent, as may be expected on the basis of the experimental data on the exchange anisotropy of the $Mn_{1-x}Cr_xSb$ alloys[14] and the theoretical predictions[3-5] of a sharp increase in the associated ferromagnetic and antiferromagnetic order parameters in the vicinity of the critical concentrations. It should be noted that the theoretical conclusions[3-5] pertaining to the change in the character of the magnetic transformation at the polycritical point of a mixed system refer to the case where the magnetic transitions of the initial phases (both ferromagnetic and antiferromagnetic) are second order transitions. The critical behavior of systems similar to the $Mn_{1-x}Cr_xSb$ alloys (with different type of the ferromagnetic and antiferromagnetic phase transformations) has not yet been studied theoretically.[3)]

The question arises as to why the antiferromagnetic–paramagnetic transition in $Mn_{1-x}Cr_xSb$ is of first order. Evidently this cannot be explained by the increase in the fluctuations in the vicinity of T_N, for we would then expect that the ferromagnetic–paramagnetic transformation would also be of first order. This conclusion follows from the fact that the ferromagnetic (MnSb) and antiferromagnetic (CrSb) phases of $Mn_{1-x}Cr_xSb$ are Ising magnets and have the same type of crystal structure, so that theoretically[17] the critical behavior of the ferromagnetic and antiferromagnetic systems must be the same in this case.

We have attempted to study the observed first order antiferromagnetic–paramagnetic phase transitions on the basis of Bean-Rodbell exchange striction theory,[18] which takes into account the dependence of the exchange interaction on the interatomic spacings. Following Ref. 19, we evaluate the effects related to the shift of T_N with pressure:

$$\frac{dT_N}{dP} = \left(\frac{\Delta V}{V} + \Delta\alpha T_N\right) V_0 \Big/ \frac{3}{2}\left(\frac{j}{j+1}\right) Nk\left(\frac{\sigma}{\sigma_0}\right)^2,$$

using our measured values of T_N and $\Delta V/V$, where $\Delta\alpha$ is the difference in the volume expansion coefficients of the paramagnetic and antiferromagnetic states, V_0 is the volume of the unit cell at $T = 0$ K in the absence of exchange interactions, and σ/σ_0 is the magnetization at the transition temperature relative to the magnetization at $T = 0$ K as determined by the Brillouin function for $j = 3/2$. Here N is the number of magnetic ions per unit volume and k is Boltzmann's constant. The calculated values of dT_N/dP were used to calculate the important parameters of the theory:

$$\beta = \frac{dT_N/dP}{\varkappa T_N},$$

which characterizes the variation in the bulk energy with compression (here $\varkappa$ is the compressibility) and

$$\eta = 2{,}2Nk\varkappa T_N\beta^2,$$

which defines the character of the magnetic phase transition: if $\eta > 1$ it is a first order transition, and if $\eta < 1$ it is of second order.

The values of dT_N/dP and η for the alloys with $x = 0.5$ and 0.8, as well as the experimental values of the parameters used to calculate them, are shown in Table I, where it can be seen that in both cases $\eta < 1$. Thus, according to the exchange-striction theory of Bean and Rodbell, the antiferromagnetic–paramagnetic transformations in the $Mn_{1-x}Cr_xSb$ alloys should be first-order phase transitions. The discrepancy between the theory and experiment may be due to the large exchange constant anisotropy, which was not taken into account in this theory.[20] The experimental data [13] on the anomalous temperature dependences of the crystal lattice parameters of CrSb near T_N are indirect evidence for the existence of such anisotropy in $Mn_{1-x}Cr_xSb$. Moreover, in the system of alloys being studied it is highly probable that there are nonlinear exchange-striction interactions, which, when taken into account, can lead to a substantial change in the parameter η.[21] Unfortunately, it does not appear possible to test this conclusion at the present time because of the lack of experimental data on the elastic properties of $Mn_{1-x}Cr_xSb$.

CONCLUSIONS

1. The $Mn_{1-x}Cr_xSb$ alloys can be assigned to the class of magnets having mixed exchange of random sites. The magnetic transformations of the ferromagnetic and antifer-

TABLE I. Values of dT_N/dp and η for the alloys $Mn_{1-x}Cr_xSb$ and the experimental values of the physical parameters used to calculate them

x	T_N, K	V_0, Å^3	$\Delta V/V$, 10^{-3}	$\varkappa\ 10^{-12}$ cm^2/dyne	σ/σ_0	dT_N/dP, deg/kbar	η
0,5	420	83,5	4,5	2,2	0,93	−1,5	0,02
0,8	610	82,0	15,0	2,2	0,90	−15,0	0,17

romagnetic phases in this system occur independently of each other and have a different character.

2. The appearance of first order antiferromagnetic–paramagnetic transitions observed in the $Mn_{1-x}Cr_xSb$ alloys cannot be explained on the basis of the exchange-striction theory of Bean and Rodbell in spite of the large compressibilities of these alloys and, according to theoretical estimates, the very large shifts of T_N with pressure. The question of using modified models of this theory still remains open, since the experimental data required to test them does not yet exist.

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[1)]The sintering temperature within this range was chosen depending on the chemical composition of the alloy. For $x = 0$ it was 1050 K, and for $x = 0.8$ it was 1150 K.

[2)]The presence of free antimony in the alloy can have no effect on the magnetic properties of the basic phase of $Mn_{1-x}Cr_xSb$, since the antimony is diamagnetic.

[3)]It should be noted that the independence of the ferromagnetic and antiferromagnetic transitions in binary alloys with competing exchanges has been observed previously[15,16] in high-pressure neutron diffraction studies of chromium tellurides, which structurally and magnetically are similar to the MnSb alloys.

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