Amorophous magnetism in iron-nickel-manganese alloys

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We establish for the first time the magnetic diagram of Fe-Ni-Mn alloys with a region of amorphous magnets characterized by "frozen" regions of short-range ferro- and antiferromagnetic order and interacting with one another through the region of disoriented spin. The new magnetic state is named "mixomagnetism."

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A large class of amorphous magnets has been discovered recently, and to determine their magnetic state new concepts, "spin glass"[1] and "mictomagnetism"[2] have been introduced. In spin glass, each individual spin is in its own random field H_i, but unlike a simple paramagnet it has, as $T \to 0$, a larger rigidity of the spin system relative to an external magnetic field. The spin-glass state is observed in dilute alloys such as Cu-Mn[3] and Au-Fe[4] and its

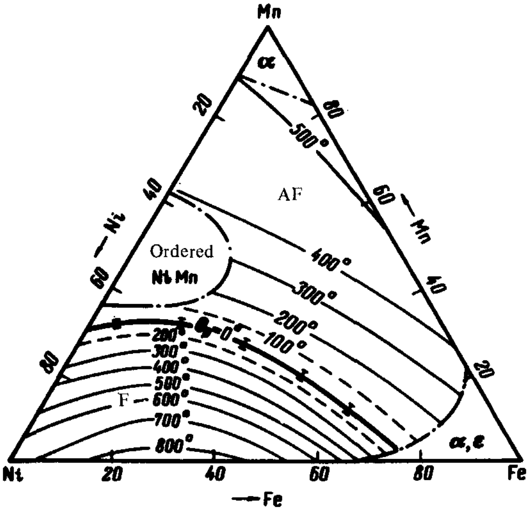

FIG. 1. Projection of the diagram of the magnetic state of Fe-Ni-Mn alloys.

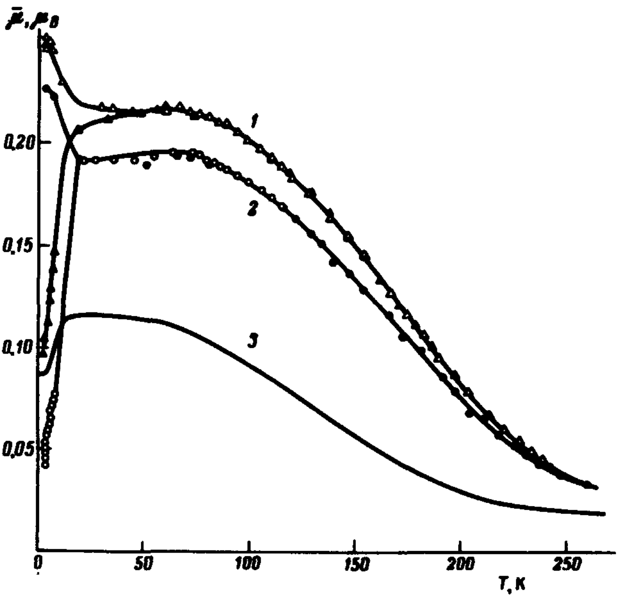

FIG. 2. Magnetization curves plotted in a 5.7 kOe field, and cooling curves to 4.2 °K without a field (light circles) and in a field of 15.7 kOe (dark circles): 1—45 Fe 35Ni 20 Mn, 2—55Fe 30Ni 15Mn, 3—66Fe 24Ni 10Mn.[8]

cause is the oscillatory long-range character of the exchange interaction, described by the RKKY mechanism. The term "mictomagnetism" was coined by Beck[2] to define another class of amorphous magnets having in the ground magnetic state "frozen" ferromagnetic clusters that are randomly dispersed in the spin glass.

In the investigation of the magnetic-state diagram of iron-nickel-manganese alloys we have observed a region of compositions which can also be classified as amorphous magnets. Their principal state, however, cannot be described in the framework of spin glass or mictomagnetism.

To construct the diagram of the magnetic state of ternary iron-nickel-manganese alloys, a large set of compositions (about 100) was used, with a formula $(Fe_cBi_{1-c-m})\,Mn_m$, which made it possible to go over gradually, via fixed additions of manganese (3,5,6.5,9.0,10.0,15,20.0 at.%) from the Fe-Ni system to Ni-Mn and Fe-Mn. All the investigated samples had an fcc structure in the initial quenched state. The principal measurements of the Curie point were made with the aid of the Mössbauer effect by observing the vanishing of the paramagnetic absorption line as the temperature was scanned, and the Néel points were measured by neutron diffraction and determined from the temperature dependence of the antiferromagnetic reflection (110).

Figure 1 shows a projection of the investigated diagram, containing a large region of ferromagnetic alloys in the left-hand corner, and antiferromagnetic ones in the upper and right-hand corners. Between them lies a transition region marked by the dashed line on the ferro- and antiferromagnet side, within

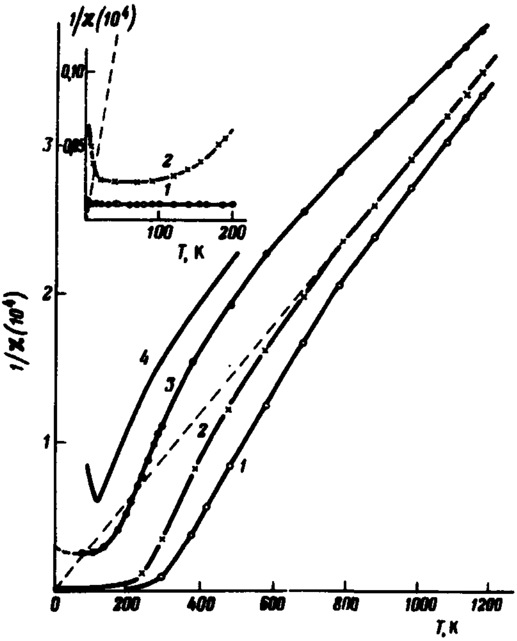

FIG. 3. Temperature dependence of the reciprocal susceptibility for alloys of the transition region: 1—50Fe 35Ni 15Mn ($\theta_p > 0$); 2—55Fe 30Ni 15Mn ($\theta_p = 0$), 3—60Fe 25Ni 15Mn ($\theta_p < 0$), 4—65Fe 21Ni 14Mn.[8]

which we were unable to determine in any way an alloy Curie point lower than 200 °K or a Néel point lower than ~100 °K. For these alloys, the temperature magnetization curves and the amplitudes of the paramagnetic γ resonance line become strongly smeared in the region of the second-order phase transition, and the neutron-diffraction patterns show now antiferromagnetic reflection even at helium temperature within the limits of the experimental accuracy (~ 8%).

The magnetic properties of the transition region were investigated particularly carefully with a magnetic balance from the temperature of liquid helium to 1200 °K. Anomalies at low temperatures were reliably observed on the temperature dependences of the magnetization in the low-temperature region for various magnetic fields, as shown by way of illustration in Fig. 2. The anomalies vanished when the sample was cooled to helium temperature in an external magnetic field. Moreover, the minimum gave way to a maximum, and the hysteresis loop shifted by approximately 0.5—1.5 kOe. These singularities of the magnetic properties are typical of alloys with exchange anisotropy[5] due to the coexistence of regions of short-range ferro- and antiferromagnetic ordering.

In a large temperature range, the alloys of the transition region have also a magnetic susceptibility that deviates from the Curie-Weiss law. Typical curves of the reciprocal susceptibility, shown by way of example in Fig. 3, have a clearly pronounced s-shape. The presence of a gently-sloping section at low temperature indicated at first glance that these alloys are spin glasses. However, the condition for the latter[6] is $(\chi^{-1})_{sg} > (\chi^{-1})_p$ at $T < T_c$ and $(\chi^{-1})_{sg} = (\chi^{-1})_p$ at $T \geq T_c$, and the paramagnetic Curie point is equal to zero ($\theta_p = 0$). In our case, $(\chi^{-1}) < (\chi^{-1})_p$ in a considerable temperature interval and this situation is observed not only for alloys with $\theta_p = 0$, but also for compositions with $\theta_p < 0$. Therefore the principal magnetic state of the alloys of the transition region differs from the spin-glass state.

There are no grounds for regarding them as mictomagnets. According to Beck's definition,[2] in mictomagnets there exist only short-range ferromagnetic-order regions. Therefore this condition could be satisfied by transition-region alloys with $\theta_p > 0$ (curve 1, Fig. 3), but judging from the temperature dependences of the magnetization they have also certain regions in which short-range antiferromagnetic order predominates.

Consequently, the magnetic ground state of Fe-Ni-Mn alloys of the transition region constitutes a new type of amorphous magnets and is named here "mixomagnetism" (from the word mixed). It is characterized by the presence of frozen regions in which short-range ferro- and antiferromagnetic order predominates. These regions interact with one another via the zone of disoriented spins.

Mixomagnetism is typical of all transition-region alloys, including those with $\theta_p = 0$, which are marked on the phase diagram by a thick line, but we call special attention to alloys with $\theta_p < 0$, where the temperature plot of the reciprocal susceptibility crosses twice the linear plot of χ^{-1} of a simple paramagnet with $\theta_p = 0$ (curve 3, Fig. 3).

The main cause of the complex magnetic state of Fe-Ni-Mn alloys in the transition region is the presence in them of a mixed exchange interaction between the atoms. This was established in[7], where it was shown by using inelastic neutron scattering by spin waves that two of the six interactions (iron-iron and manganese-manganese) are negative. It is the presence of a mixed exchange interaction which determines in fact the predominance of the ferro- or antiferromagnetic ordering in a particular fluctuation that is present in perfectly disordered alloys as a result of the statistical distribution of the atoms.

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