and introduced the dimensional constant a, which was omitted above.

To obtain the polarization on scattering through angle ϑ it is necessary to integrate $Pd^2\sigma/d\Omega dE'$ over the energy transfer and divide by $\sigma(\vartheta)$. The integration over E' is equivalent to integration over q over the region $q \geqslant p\vartheta$; this leads simply to the replacement $q \to p\vartheta$ in (A.4) and gives the expression (29) of the main text.

1) We recall that by the discontinuity of a function across the cut we mean the quantity $\Delta_x f(x) = [f(x+i\delta) - f(x-i\delta)]/2i$.

2) In Ref. 8 the spin dependence of the odd vertices was determined without taking this fact into account.

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An alternative explanation of the anomalies of the physical properties of Invar alloys

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The residual magnetic moment and unidirectional exchange anisotropy of a chromium-rich iron–chromium alloy and an iron–nickel Invar alloy were investigated as a function of temperature. In both cases the magnetic moment and the unidirectional anisotropy were retained in the temperature range between the Curie and Néel points. These experimental results were used to draw conclusions on the nature of the physical anomalies of Invar alloys. The proposed model was found to be in agreement with all the currently available experimental data.

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Several models have been suggested to explain the anomalies of the physical properties of Invar alloys. They include the latent antiferromagnetism model of Kondorskiĭ,[1-3] the model of two γ states of Weiss,[4] the models based on the alloy heterogeneity (Schlosser[5,6]) and allowing for the ordering in alloys (Kachi and Asano[7-9]), the model of weak band ferromagnetism of Wohlfarth,[10,11] and others. All these models explain more or less satisfactorily the anomalies of the dependence of the magnetic moment and Curie temperature of the alloys (FeNi, FePt, FePd) on their compositions, anomalous values of the high-field susceptibility, etc. However, none of these models explains all the physical properties of Invar alloys, for example, the temperature dependence of the linear expansion coefficient (see Fig. 2b below).[12] Some of them are even in conflict with the experimental observations.

In the models postulating antiferromagnetism of Invar alloys[3] there still remains the question how to explain the influence of antiferromagnetism on the physical properties of Invar alloys at temperatures above the Néel point T_N of the antiferromagnetic component (this temperature is ~50° K for the Fe–Ni alloys).

We investigated chromium-rich Fe–Cr alloys from which samples with a low expansion coefficient, known as "nonmagnetic Invars," were prepared. The investigated alloys with 78–93% Cr exhibited unidirectional exchange anisotropy.[13] One of the investigated alloys

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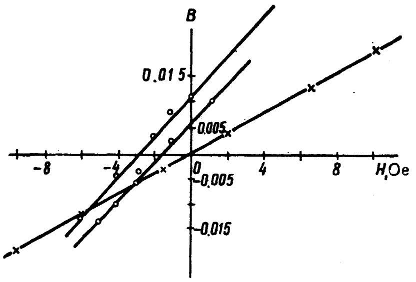

FIG. 1. Part of a hysteresis loop of the Fe_8Cr_{92} alloy cooled to helium temperatures in the absence and presence of a field of 400 Oe (Ref. 14).

containing 92% Cr and 8% Fe was quite interesting. It did not exhibit a residual magnetic moment when cooled to helium temperatures in the absence of a magnetic field (Fig. 1). However, when the same cooling took place in a magnetic field, this alloy acquired ferromagnetic properties: a residual magnetic moment and a hysteresis loop, which was displaced relative to the coordinate origin opposite to the direction of the field applied during cooling.[14] The displacement of the hysteresis loop was evidence of the unidirectional exchange anisotropy of the alloy and, consequently, of the coexistence of the ferromagnetic and antiferromagnetic components. Increase of the temperature to 20° K destroyed 80–90% of the magnetic moment (Fig. 2a) and halved the displacement of the hysteresis loop. At still higher temperatures the residual moment remained almost constant and it disappeared completely only when the Néel point T_N of the antiferromagnetic component (25° K) was reached. The displacement of the hysteresis loop then increased somewhat, then decreased slowly and disappeared at T_N of the antiferromagnetic component (250° K).

The behavior of the magnetic properties of this alloy can be understood on the basis of the following model of Invar alloys. Both ferromagnetic and antiferromagnetic components exist in such alloys. In the ferromagnetic Invar alloys the antiferromagnetic component is present in the form of clusters in the ferromagnetic matrix; this applies to iron-base alloys (FeNi, FePd, etc.). The Curie temperature T_C of the ferromagnetic component of these alloys is considerably greater than T_N of the antiferromagnetic component ($T_C \gg T_N$). The reverse is true of the nonferromagnetic Invars: the ferromagnetic component is present in the form of clusters in the antiferromagnetic matrix (this applies, for example, to alloys based on antiferromagnetic chromium). In this case, the Curie temperature T_C of the ferromagnetic component is much lower than T_N of the antiferromagnetic component ($T_N \gg T_C$). There is an exchange interaction between the ferromagnetic and antiferromagnetic components, which is indicated by the unidirectional exchange anisotropy of Invar alloys.[15,16] This exchange interaction has the following effect: between the Curie and Néel temperatures ($T_C < T < T_N$) the ferromagnetic component of an antiferromagnetic Invar is not in the paramagnetic state but retains a certain magnetic moment (~10% M_0) induced by the antiferromagnetic matrix.[17] The moment of the ferromagnetic component (~10% M_0) observed above T_C corresponds to the magnetization which this component would have had in an isolated state at the temperature ~$0.98T_C$.

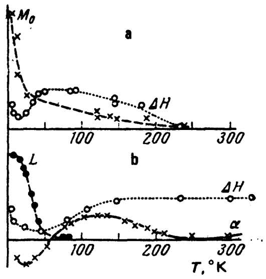

FIG. 2. a) Temperature dependences of the residual magnetic moment M_0 and of the displacement ΔH of the hysteresis loop of the Fe_8Cr_{92} alloy. b) Temperature dependences of the magnetic moment L of the sublattices of the antiferromagnetic component of an iron—nickel Invar,[19] of the displacement ΔH of the hysteresis loop, and of the linear expansion coefficient α (Ref. 12).

It follows that a magnetic state corresponding approximately to the Curie temperature is induced in the ferromagnetic component of our alloy above T_C (~20° K). In other words, the region of T_C seems to be extended over the whole temperature interval between the Curie and Néel points and, consequently, all the anomalies of the physical properties usually observed in the region of T_C are found throughout this interval.

We may expect an exactly opposite situation in the ferromagnetic Invars. In that case the antiferromagnetic component does not become paramagnetic above the Néel point (~50° K for the iron–nickel Invars). The ferromagnetic component induces, by the exchange interaction, some sublattice moment in the antiferromagnetic component and this is retained right up to T_C of the alloy (~500° K for the iron–nickel Invars).

We investigated an iron–nickel Invar alloy with 72% Fe and 28% Ni, which was subjected to a special heat treatment intended to ensure retention of 47.5% of the fcc phase right down to helium temperature. After cooling in a magnetic field this alloy exhibited a displaced hysteresis loop at 4.2° K. The temperature dependence of the loop displacement ΔH_S of this alloy was similar to the temperature dependence of ΔH_S of the 92% Cr = 8% Fe alloy (Fig. 2b). This loop displacement was retained up to 300° K. Such observations were evidence of retention of antiferromagnetism in the iron–nickel Invar above T_N (~50° K) right up to room temperature.

Our previous investigations of the magnetocaloric effect in the iron–nickel Invar alloys[19] also demonstrated the presence of the antiferromagnetic component. The two-lattice model was used to find the magnetic moment of the sublattices L and its temperature dependence (Fig. 2b).[19]

We can easily show that the magnetic contribution to the linear expansion coefficient should be proportional to the derivative of the magnetization with respect to temperature $\alpha \propto dM/dT$. It is clear from Fig. 2b that near the low-temperature minimum the temperature dependence of the linear expansion coefficient of the $Fe_{65}Ni_{35}$ alloy does indeed represent the temperature derivative of the magnetization of the sublattices of the antiferromagnetic component, i.e., the negative contribution to the linear expansion coefficient below 50° K is due to the change in the sublattice magnetization L of the antiferromagnetic component.

The situation above 50°K is as follows. The antiferromagnetic component, present in the form of clusters in the ferromagnetic matrix, loses 80–90% of the sublattice magnetization L_0 at temperatures above its Néel point T_N and the remaining 10–20% of L_0 is due to the exchange interaction with the ferromagnetic component. Since this interaction works in both directions, it follows that an almost paramagnetic cluster disorients the ferromagnetic matrix spins in a certain region around it and this region (a "cloud") increases with rising temperature. The spin disorientation in the cloud and the cloud size rise on increase in temperature and there is a corresponding fall in the magnetic moment of the alloy.[18,21] Thus, the usual reduction in the magnetization of the ferromagnetic component of Invar alloys with rising temperature is supplemented by a fall of the magnetic moment due to the spin disorientation around antiferromagnetic clusters. The reduction in the ferromagnetic moment with rising temperature which is due to the exchange interaction with the antiferromagnetic moment becomes noticeable already on approach to T_N (Ref. 18). Above T_N the moment falls rapidly and it represents 0.7 of the moment at 0°K even at temperatures $0.6T_C$ (in the case of a single-phase ferromagnet this reduction is attained at temperatures of $0.85T_C$). However, the subsequent fall of the magnetic moment of Invar alloys is less rapid than in the case of a single-phase ferromagnet.[21] This is due to the fact that the role of the exchange interaction between the components begins to decrease, because, as indicated by neutron-diffraction studies,[20,22,23] the overlap of the magnetic inhomogeneity regions begins in this range of temperatures.

The position of the second minimum of the temperature dependence of the linear expansion coefficient represents the volume of the ferromagnetic component interacting with the antiferromagnetic clusters. An increase in temperature above the Néel point results in an increase in this volume and there is a corresponding increase in the negative contribution to the linear expansion coefficient. At room temperature the iron–nickel Invars exhibit an overlap of the neighboring spin-disorientation regions[23]; this immediately reduces the effectiveness of the exchange interaction between the components because of the noncoherence of the exchange interaction in the overlap zones, so that the negative contribution to the linear expansion coefficient begins to decrease slowly. This gives rise to the wide (along the temperature axis) second minimum of the temperature dependence of the linear expansion coefficient in the region of $0.6T_C$.

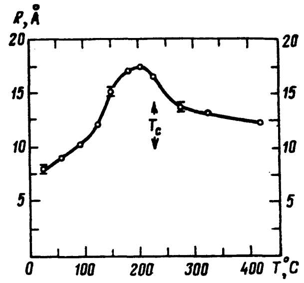

FIG. 3. Effective radius in neutron scattering by magnetic inhomogeneities.[20]

It follows that above T_N the Invar alloys retain a certain proportion of the ferromagnetic component with partly disoriented spins in a state similar to that of a ferromagnet in the region of T_C (Ref. 24), as shown in Fig. 3. This volume increases on increase in temperature[20,23] and, together with antiferromagnetic clusters, is responsible for all the anomalies of the physical properties of Invar alloys.

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