depend continuously on the temperature. Then the phase transition at $T = T_c^{(2)}$ corresponds to the vanishing of the transverse stiffness and is analogous to the phase transition in the XY model.

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[1] The group $Z(n)$ can be defined, e.g., as the set of integers $0, 1, \ldots, n-1$, the group multiplication coinciding with addition modulo n.

[2] The fields under consideration are a certain formal generalization of a gauge field. A geometrical interpretation of these fields is, however, not known. For $q=2$ the generalized gauge field coincides with the usual one with gauge symmetry $Z(2)$. We note that gauge models with any commutative symmetry can be generalized in a similar formal manner.

[3] We note that, for a different choice of the interaction energy, all the results cited below remain valid but the KW transformation leads to a change of the functional form of $U(\{\Phi_x\})$.

[4] The formula (6) is a particular case of the general relation.

$$\sum_\nu \chi_\nu(G) = \begin{cases} n, & G=I \\ 0, & G\neq I \end{cases}.$$

Here ν labels the irreducible representations of the point group G, n is its order, and $\chi_\nu(G)$ are the characters of these representations. This relation and the analogous formula for continuous groups makes it possible to use the method presented to obtain KW relations for systems with any commutative group.

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Hyperfine magnetic fields at the nuclei ^{57}Fe and ^{119}Sn in the alloy $Fe_{48}Rh_{52}$ under pressure

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The Mössbauer effect is use to measure the pressure dependences of the hyperfine magnetic fields H and of the isomeric shifts ε at the nuclei ^{57}Fe and ^{119}Sn in the alloy $Fe_{48}Rh_{52}$ with ~1 at.% Sn as an impurity. Pressure causes ε to decrease, and this corresponds to an increase (for ^{57}Fe) or a decrease (for ^{119}Sn) of the density of the s electrons at the nuclei. In the ferromagnetic (FM) state of the alloy, at 398 K, $\Delta H/H\Delta p = (-2.8\pm0.2)\times10^{-3}$ kbar^{-1} for ^{57}Fe and $(-4.8\pm0.8)\times10^{-3}$ kbar^{-1} for ^{119}Sn; in the antiferromagnetic state (AMF) at 78 K, $\Delta H/H\Delta p \approx 0$ for ^{57}Fe and $\Delta H/H\Delta p = (-6.2\pm1.0)\times10^{-3}$ kbar^{-1} for ^{119}Sn. The results are attributed to the strong dependence of the magnetization of the alloy matrix on the pressure for ^{57}Fe in the FM state and to the absence of "local" polarization of the s-like collectivized electrons and to the pressure dependence of the magnetic moments of the Fe ions in the AFM state. The causes of the different effects of pressure on the magnetic moments of the Fe ions in the FM and AFM states are discussed. The results for ^{119}Sn in the FM and AFM states agree with a previously proposed model [A. E. Balabanov, N. N. Delyagin, *et al.*, Sov. Phys. JETP **27**, 752 (1968) and elsewhere; I. N. Nikolaev and V. P. Potapov, *ibid.* **45**, 840 (1977)] of the hyperfine fields at the Sn impurity atoms in magnetic matrices. An estimate is obtained of the radial dependence of the hyperfine field at the ^{119}Sn nuclei for the AFM state, namely, $H(r)$ varies more strongly than r^{-9}.

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This is a logical continuation of a number of preceding studies[1-6] of the influence of pressure on hyperfine interactions in magnets. The purpose of these studies was to attempt to explain the mechanism whereby hyperfine magnetic fields are produced at nuclei of atoms in magnetic matrices and, in particular, determine the role of spin polarization of collectivized electrons in the onset of magnetic order. In alloys of the Fe_xRh_{1-x} system, when the composition or the temperature is changed, a transformation from the ferromagnetic (FM) into the antiferromagnetic (AFM) state is observed, the parameters of the crystal lattice change jumpwise by 0.3%, and the structure remains cubic. In this case there is a rare opportunity of tracing, in samples having the same composition, the influence of pressure (interatomic distance) on the hyperfine magnetic fields at the nuclei of the matrix (^{57}Fe) and impurity (^{119}Sn) atoms in two magnetic states, FM and AFM, which are produced by varying the temperature an which differ in the orientation of the magnetic moments of the iron atoms, and hence in the polarization of the conduction electrons. For the Fe_xRh_{1-x} alloys, detailed studies were made of the magnetic fields at the nuclei ^{57}Fe (Ref. 7) and ^{119}Sn (Ref. 8), of the distributions of the magnetic moments and of the spin density,[9] and also of the influence of pressure on the temperatures of the

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AFM → FM → PM (paramagnetic) transitions.[10] The choice of this object of investigation is therefore enticing also from the point of view that to interpret the experimental results on the effect of pressure on the hyperfine magnetic fields it is possible to resort to data obtained by several physical methods.

In the present study we investigated the dependences of the hyperfine magnetic fields and of the ismoreic shifts on the pressure at the nuclei ^{57}Fe and ^{119}Sn in the alloy $Fe_{48}Rh_{52}$ with tin impurity, in the FM and the AFM states.

EXPERIMENT

Samples of the alloy $Fe_{48}Rh_{52}$ with ~1 at.% tin impurity (the alloy composition is indicated with the impurity disregarded) were obtained by vacuum metling followed by homogenization at 1000°C for 50 hours. The ingots were ground into powders that were annealed at 900° C for 20–30 hours and then cooled slowly to room temperature. This heat treatment made the alloy fully ordered, with the impurity Sn atoms substituted for Fe atoms.[8]

The magnetic fields and the isomeric shifts were measured by the Mössbauer method with a gamma source in the form of $Ba^{119m}SnO_3$ and ^{57}Co in metallic chromium. At room temperature the ^{119}Sn spectrum was a superposition of a weakly resolved doublet line and a well-resolved sextet; the ^{57}Fe spectrum consisted of two overlapping sextets. This corresponded to a mixture of FM and AFM phases. The phases coexisted in the interval 270–340 K. The samples were made single-phase by cooling to 78 K (AFM state) or by heating to 398 K (FM state).

The pressure on the absorber samples was produced with a steel chamber whose construction was described by Panyushkin.[11] At 78 and 398 K the high-pressure chamber was placed respectively in a bath of liquid nitrogen or transformer oil. The pressure-measurement accuracy was ±0.2 kbar, and the temperature accuracy was ±0.2°. The magnetic fields were determined by measuring the distance between the outermost lines of the six-line spectra, and in the case of the ^{119}Sn in the AFM phase they were calculated from the measured widths of the doublet lines.

RESULTS AND DISCUSSION

1. Magnetic fields at ^{57}Fe nuclei

In the absence of pressure, the hyperfine fields at the ^{57}Fe nuclei in the $Fe_{48}Rh_{52}$ alloy are equal to 270 ± 0.4 and -244.2 ± 0.4 kG at 78 and 398 K, respectively; this agrees with the data of Ref. 7. In the 0–10 kbar interval we measured the values of $\Delta H = H(p) - H(0)$. The relative changes of the magnetic fields, $\Delta H/H$, are shown in Fig. 1 as functions of the pressure in the FM and AFM states of the alloy. It is seen from the figure that $\Delta H/H\Delta p = (-2.8 \pm 0.2) \cdot 10^{-3}$ kbar^{-1} for the FM state and $\Delta H/H\Delta p \approx 0$ for the AFM state. The isomeric shift at the ^{57}Fe nuclei decreases linearly with increasing pressure: $\partial\varepsilon/\partial p = (-2 \pm 1) \cdot 10^{-3}$ mm-sec^{-1} kbar^{-1}. A decrease of ε means an increase of the density of the s-like conduction electrons. Let us analyze these results.

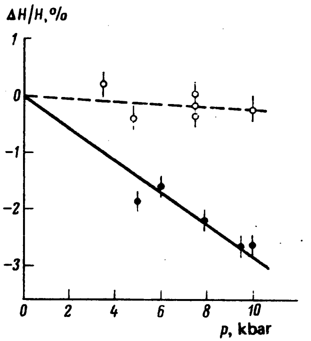

FIG. 1. Relative changes of the magnetic fields at the ^{57}Fe nuclei in the alloy $Fe_{48}Rh_{52}$ with Sn impurity vs. the pressure: light circles—AFM state ($T = 78$ K), dark circles—FM state ($T = 398$ K).

The pressure can alter the hyperfine field at the ^{57}Fe nuclei in a ferromagnetic matrix via the following effects: 1) shift of the Curie temperature (T_c), 2) change of the magnetic moments of the Fe ions, 3) spatial redistribution of the spin density in the crystal, which manifests itself by a change in the degree of polarization of the collectivized s-like electrons and of their density in the region of the ^{57}Fe nuclei. The first of these effects can be taken into account if the value of $\partial T_c/\partial p$ is known. For the alloy $Fe_{48}Rh_{52}$ we estimated the contribution made to ΔH by the $T_c(p)$ dependence, using the value $\partial T_c/\partial p = -0.75$ deg/kbar obtained for the alloy $Fe_{50}Rh_{50}$ which is close to it in composition.[12] This contribution was of the same sign, but smaller by an order of magnitude than the observed value of ΔH, so that in this case it can be neglected.

Without repeating the arguments advanced in Ref. 3 to explain the $H(p)$ relation in metallic iron, which are equally applicable to the alloy $Fe_{48}Rh_{52}$, we write down for $\Delta H/\Delta p$ an expression that takes into account the last two of the aforementioned effects [see formula (7) of Ref. 3]:

$$\frac{\Delta H}{\Delta p} = H_c \frac{\Delta \mu_{Fe}}{\mu_{Fe} \Delta p} + H_{ce} \left(\frac{\Delta \sigma_0}{\sigma_0 \Delta p} + \frac{|\Delta V|}{V \Delta p} \right). \qquad (1)$$

Here H_c and H_{ce} are the Fermi contact fields from the polarized s electrons of the ion core and the s-like conduction electrons, μ_{Fe} is the magnetic moment of the Fe ion, σ_0 is the magnetization of the matrix as $T \to 0$, and V is the sample volume. The difference between formulas (1) in this paper and (7) in Ref. 3 consists only of the fact that the factor $\Delta\sigma_0/\sigma_0$ in the first term of (7) is replaced by $\Delta\mu_{Fe}/\mu_{Fe}$, inasmuch as the magnetic moments of the Fe and Rh ions in the $Fe_{48}Rh_{52}$ alloy are different.

We use now formula (1) to explain qualitatively the $H(p)$ dependence; quantitative estimates are impossible as yet, since there are no experimental data on the values of H_c, H_{ce}, $\Delta\mu_{Fe}/\mu_{Fe}\Delta p$, $\Delta\sigma_0/\sigma_0\Delta p$. It is known, however, that for the $Fe_{50}Rh_{50}$ alloy the compressibility is $\Delta V/V\Delta p \approx -0.5 \cdot 10^{-3}$ kbar^{-1}, and according to the estimate of Ref. 10 $\Delta\sigma_0/\sigma_0\Delta p \approx -1.8\cdot 10^{-3}$ kbar^{-1}. We shall use these data to estimate H/H in the alloy $Fe_{48}Rh_{52}$. Next, if we assume the equality $\Delta\mu_{Fe}/\mu_{Fe}\Delta p \approx \Delta\sigma_0/\sigma_0\Delta p$ and recognize that $|\Delta\sigma_0|\sigma_0\Delta p \gg |\Delta V|V\Delta p$, then we obtain from formula (1) a value of $\Delta H/H\Delta p$ close in absolute value to the experimentally observed one, and having the same sign (see Fig. 1). It follows therefore that the main cause of the change of H is apparently the decrease of the magnetization of the matrix under pressure. The causes of the anomalously large change of σ_0 under pressure will be discussed below.

We consider now the AFM state. Under pressure, the field at the ^{57}Fe nuclei can change because of two reasons: 1) change of the magnetic moments of the Fe ions, and 2) changes of the "local" polarization of the s-like conduction electrons (the polarization of these electrons, averaged over the crystal, is obviously equal to zero, but the possibility in principle of polarization in the immediate vicinity of the magnetic moments of the Fe ions is not excluded). Formula (1) then takes for the AFM state the form

$$\frac{\Delta H}{\Delta p} = H_c\frac{\Delta\mu_{Fe}}{\mu_{Fe}\Delta p} + H_{ce}\frac{|\Delta V|}{V\Delta p}, \tag{2}$$

where now H_{ce} is Fermi contact field due to local polarization.

The results of the experiment (Fig. 1) show, within the limits of the attained accuracy, that neither of the foregoing reasons for changing H seem to occur, since the cancellation of the terms in (2) is of quite low probability. Consequently, in the AFM state the local polarization is very small (if it exists at all), and the magnetic moments of the Fe ions are practically independent of the pressure.

These conclusions raise the question of why the magnetic moments of the Fe ions are differently affected by pressure in the FM and the AFM states. We note first that the exchange interaction in the $Fe_{48}Rh_{52}$ alloy depends very strongly on the distances between the Fe and Rh atoms: this is evidenced by the very strong pressure dependence of the temperature of the transition from the AFM to the FM state[12] and by the presence of a first-order phase transition in the AFM ⟶ FM transformations.[10] Furthermore, in the FM state, the maxima of the spin densities of the Rh ion are located at a distance ~0.5 Å from the nucleus.[9] On the basis of this fact, the authors of Refs. 9, 13, and 14 have arrived at the conclusion that the magnetic moments of Rh are produced by collectivized d electrons, namely, the magnetic moment of the Fe sublattice splits the d subbands of Rh. Therefore an appreciable fraction of the spin density in the $Fe_{48}Rh_{52}$ alloy (practically the entire magnetic moment of the Rh ions) is concentrated in the space between the Fe and Rh ions. This explains the strong dependence of the magnetization on the pressure: in the FM state the pressure deforms the wave functions of the d-band electrons and by the same token greatly perturbs the spin density between the Fe and Rh ions. This is reflected in the magnetic moments of the Fe ions and manifests itself in a very strong $H(p)$ dependence.

Experiments on neutron diffraction revealed no magnetic moments at the Rh ions in the AFM state.[9] In addition, estimates of the lattice contribution to the total entropy jump in the AFM ⟶ FM transitions and measurements of the magnetic susceptibility in the AFM phase also lead to the conclusion that there is no localized moment at the Rh ions.[15] Therefore the decrease of the distances between the atoms in the AFM state produces practically no perturbation of the spin density in the immediate vicinity of the Fe ions, and consequently does not influence the hyperfine fields at the ^{57}Fe nuclei.

2. Magnetic fields at the ^{119}Sn nuclei

At normal pressure, the hyperfine fields and the isomeric shifts at the ^{119}Sn nuclei in the $Fe_{48}Rh_{52}$ alloy are respectively 23.9 ± 0.7 kG and 1.46 ± 0.03 mm/sec at 78 K (AFM phase), and 106.1 ± 0.4 kG and 1.31 ± 0.03 mm/sec at 398 K (FM phase) and agree with the data of Delyagin and Kornienko.[8] The isomeric shift decreases with increasing pressure: $\partial\varepsilon/\partial p = (-7 \pm 3)\cdot 10^{-3}$ kbar^{-1}, meaning a decrease in the density of the conduction s-electrons at the nuclei. Figure 2 show plots of the relative changes of the magnetic field with changing pressure; $\Delta H/H\Delta p = (-4.8 \pm 0.8)\cdot 10^{-3}$ kbar^{-1} for the FM state and $\Delta H/H\Delta p = (-6.2 \pm 1.0)\cdot 10^{-3}$ kbar^{-1} for the AFM state. We emphasize that in an antiferromagnet the field changes more strongly than in a ferromagnet.

We now discuss these results from the point of view of the model of hyperfine fields at the ^{119}Sn nuclei, a model proposed by us as a concrete variant of the "competing contributions" model.[16] According to Ref. 5, the field at the ^{119}Sn nuclei in a ferromagnetic matrix is of the form

$$H = H^{-}_{loc}(r) + H_{ep}^{-}(r) + \sum_{i\geqslant 2} H^{+}_{i ep}(r); \tag{3}$$

here $H^{-}_{loc}(r)$ is the negative contribution from the polarization of the local charge ΔZ that screeens the impurity Sn ion, $H^{-}_{ep}(r)$ is the negative contribution of the conduction electrons due to the first (and possibly second) coordination sphere of the Sn atom, $\sum_{i\geqslant 2} H^{+}_{i\,ep}(r)$ is the positive contribution from the polarization of the conduction electron due to the third (second) and more

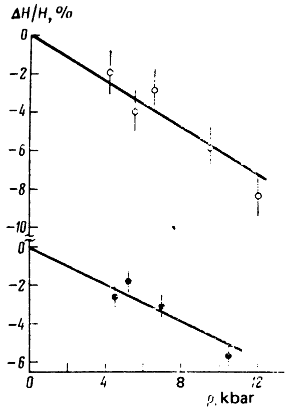

FIG. 2. Relative changes of the magnetic field at the ^{119}Sn nuclei in the alloy $Fe_{48}Rh_{52}$ with tin impurity, vs. pressure. Light circles—AFM state (T = 78 K), dark circles—FM state (T = 398 K).

remote spheres, i is the number of the coordination sphere, and r is the coordinate. The resultant field H consists of contributions $H^-(r)$ and $H^+(r)$ which are large in absolute value and of opposite sign, with $H^-(r)$ more strongly dependent on r than $H^+(r)$. From this formula it follows that: 1) the change of the field under pressure $\Delta H = H(p) - H(0)$ should always be negative regardless of the sign of H, 2) the quantity $\Delta H/H\Delta p$ should be smaller the larger the modulus of H (at comparatively equal compressibilities of the Sn in the matrices). As seen from Fig. 2, the first consequence holds true. As to the second, a comparison of $\Delta H/H\Delta p$ with H for a large number of investigated substances (see the table in Ref. 5) seems at first glance to indicate that for the alloy $Fe_{48}Rh_{52}$ the observed value of $\Delta H/H\Delta p$ is too high. Allowance must be made here, however, for the anomalous decrease of the magnetization of the matrix under pressure. Then the effect of interest to us, which is connected with redistribution of the spin density near the Sn ions, should be smaller than the observable quantity $\Delta H/H\Delta p$ by an approximate factor $\Delta\sigma_0/\sigma_0\Delta p$ ($\Delta\sigma_0/\sigma_0\Delta p$ of the previously investigated substances is smaller by approximately one order of magnitude that of $Fe_{48}Rh_{52}$). When this circumstance is taken into account the behavior of $H(p)$ for ^{119}Sn in $Fe_{48}Rh_{52}$ agrees with the previously observed regularities and consequence 2) likewise holds true.

Let us generalize formula (3) to the case of antiferromagnetic matrix when the conduction-electron polarization averaged over the crystal is zero:

$$H = H_{loc}^-(r). \tag{4}$$

In the AFM state the local charge ΔZ is polarized mainly by the nearest coordination sphere of Sn with a nonzero magnetic moment. In the case of the ordered AFM alloy $Fe_{48}Rh_{52}$ this is the second sphere relative to Sn, and consists of Fe atoms. Since the pressure has practically no effect on the magnetic moments of the Fe ions in the AFM state, the reason why the field decreases at the ^{119}Sn nuclei is that the density of the polarized s-like electrons is decreased.

It was mentioned in Ref. 5 that comparison of the quantities $\Delta H/H\Delta p$ and $\Delta V/V\Delta p$ makes it possible to determine in principle the concrete form of the radial dependence of $H(r)$ in the case of an AFM matrix, when $H(r) \equiv H_r^-(r)$. This calls for knowledge of the compressibility of the impurity atoms, which may differ from the compressibility of the matrix. This difference was first pointed out in Refs. 17 and 18, but was not yet confirmed by direct experiments. Therefore the estimate below of the radial dependence of $H(r)$ is quite approximate. Thus, if we assume that the compressibility of the impurity Sn atoms in $Fe_{48}Rh_{52}$ is close to the compressibility of Sn in metallic tin, then we obtain $H_{loc}^-(r) \propto r^{-9}$. On the other hand if none the less somehow close to the compressibility of the matrix, then the $H_{loc}^0(r)$ dependence is much stronger than r^{-9}.

In conclusion, the authors thank N. N. Delyagin for supplying the alloy samples and for a number of valuable critical remarks made in the discussion of the results.

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