SOVIET PHYSICS JETP VOLUME 32, NUMBER 5 MAY, 1971

MAGNETIC HYPERFINE INTERACTION FOR IMPURITY Sn^{119} ATOMS IN THE FERRO- AND ANTIFERROMAGNETIC ALLOY FeRh

N. N. DELYAGIN and É. N. KORNIENKO

Nuclear Physics Institute of the Moscow State University

Submitted June 2, 1970

Zh. Eksp. Teor. Fiz. 59, 1524–1533 (November, 1970)

Magnetic hyperfine interaction for Sn^{119} impurity atoms in ferromagnetic (FM) and antiferromagnetic (AFM) FeRh alloys containing from 49.5 to 53 at. % Rh was investigated by means of the Mossbauer effect. The transition from the AFM to the FM state as the temperature is increased is accompanied by a sharp increase in the hyperfine field for Sn impurity atoms. The values (extrapolated to 0°K) are 147 ± 3 kOe in the FM phase and 21 ± 2 kOe in the AFM phase. The strong positive field in the FM phase is interpreted in terms of a model in which the difference between the radial dependences of the positive and negative contributions to the hyperfine field is taken into account. It is shown that for Sn atoms in metallic ferro- and antiferromagnetic substances a simple relation exists between the hyperfine field strengths and the character of the magnetic moment distribution over the coordination spheres. In both FM and AFM FeRh alloys the hyperfine magnetic field for Sn impurity atoms decreases with temperature much more rapidly than the hyperfine field for Fe atoms.

THE characteristics of hyperfine interaction in metallic systems occupy the attention of many authors and are investigated by various methods. In recent years, the nature of magnetic hyperfine interaction in metals and alloys has become much better understood; however, there are still many aspects of this problem that are far from being clear and continue to be discussed. In the interpretation of experimental data authors are prone to use either empirical models that have not yet obtained a sufficient theoretical foundation or theoretical ideas of somewhat doubtful adequacy for any real situation. The development of a theory of magnetic hyperfine interaction in metallic systems and the formation of a single approach to the interpretation of experimental data depend to a very large extent on new results from the investigation of systems with different magnetic characteristics.

Magnetic hyperfine interaction for nonmagnetic atoms (i.e., atoms not having an intrinsic magnetic moment) in ferro- and antiferromagnets arises as a result of a polarization of its electrons by the magnetic moments of neighboring atoms. In order to analyze the experimental data on the magnetic fields acting on the nuclei of atoms in magnetically ordered alloys, it is necessary, in particular, to have sufficient information about the radial dependence of the exchange interaction, which is responsible for these fields. In other words, one needs to know the relative contributions (in sign and magnitude) of the magnetic moments of the neighboring atoms arranged in the different coordination spheres to the hyperfine field. Some experiments pertaining to this problem and their interpretation were considered in an earlier paper.[1] It was noted that the features of the radial dependence of the exchange interaction can have a very strong effect on the hyperfine interaction for Sn atoms, since for this element the relatively small observed hyperfine fields are the algebraic sum of two large ones, almost equal in magnitude but of opposite sign. The experimental data for Sn impurity in different ferro- and antiferromagnetic substances can be explained by assuming that these two contributions to the field are characterized by different radial dependences. This means that even small changes in the distribution of the mean magnetic moments over the coordination spheres can alter the magnetic fields on the nuclei of Sn atoms very drastically. As a result, Sn displays "anomalous" values of the hyperfine magnetic fields in different matrices, sharp anomalies in the temperature dependence of the magnetic hyperfine interaction,[1,2] etc. The known values of the magnetic hyperfine fields for Sn in metallic ferromagnets varies from -329 kOe in Gd[3] to $+107$ kOe in the alloy Co_2MnSn.[4]

To investigate the radial dependence of the exchange interaction, it is convenient to use systems in which the mean magnetic moment is a known and rapidly varying function of the coordination sphere number (ordered alloys, intermetals). For this it is necessary that the magnetic structure of the alloy be rather well known and relatively simple. Unfortunately, only a very small number of such systems is known for Sn. Wider possibilities are afforded by the study of magnetic hyperfine interaction for Sn impurity atoms in different metallic ferro- and antiferromagnetic substances. Experiments in the last few years[1-3,5-7] have shown that one can obtain in this way extremely useful information both about the features of the magnetic hyperfine interaction and about the magnetic characteristics of the matrix.

One of the interesting possibilities in such experiments is associated with the transition from the ferromagnetic (FM) to the antiferromagnetic (AFM) state, which is observed in certain systems with a change in temperature. In this transition the crystallographic characteristics of the system do not usually change or change only slightly, but the values of the mean magnetic moments in the different coordination spheres change sharply. As a result, it is possible to compare the values of the magnetic fields at the nucleus of a given atom in practically identical systems, but with

Table I. Distribution of mean atomic magnetic moments ($\bar{\mu}_i$) over the coordination spheres for the two types of lattice sites in FM and AFM FeRh alloy

i	n_i	$\bar{\mu}_i$				i	n_i	$\bar{\mu}_i$			
		Rh site		Fe site				Rh site		Fe site	
		FM	AFM	FM	AFM			FM	AFM	FM	AFM
1	8	3.1	0	1.0	0	4	24	3.1	3.3	1.0	0
2	6	1.0	0	3.1	−3.3	5	8	1.0	0	3.1	−3.3
3	12	1.0	0	3.1	+3.3	6	6	1.0	0	3.1	+3.3

Note.—i is the number of the coordination sphere, n_i is the number of atoms in the i-th coordination sphere. The magnetic moment of the Rh Atom in the AFM alloy is taken to be equal to zero.

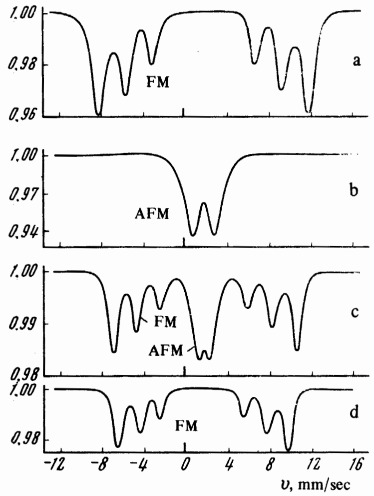

FIG. 1. Mossbauer absorption spectra for Sn^{119} impurity atoms in ferromagnetic (FM) and antiferromagnetic (AFM) FeRh alloys: a—alloy with 49.7% Rh at 77 K; b, c, d—52% alloy at 77, 290, and 357 K, respectively. The ordinate is the intensity of the γ-quantum flux in relative units; the abscissa is the velocity of the γ-quantum sources.

different distributions of the magnetic moments of the neighboring atoms over the coordination spheres.

We report here an investigation, using the Mossbauer effect on Sn^{119}, of the magnetic hyperfine interaction for Sn impurity atoms in ordered alloys of Fe and Rh. These alloys are well known examples of metallic systems in which there is a first-order phase transition with an inversion of the exchange interaction. At temperatures below the transition temperature T_t the ordered FeRh alloy is antiferromagnetic; above T_t it is ferromagnetic. The temperature T_t depends on the composition of the alloy. For the equal-atom composition $T_t \approx 340°K$; however, the data of different authors on this temperature do not agree very well, possibly because of the high sensitivity of T_t to the impurities of other elements.[8-10] As the Rh content is reduced, T_t rapidly drops, and the alloy $Fe_{51}Rh_{49}$ remains ferromagnetic at least down to 1.4°K.[10] According to magnetic measurements (see, for example, [8,11] the AFM ⟷ FM transition occurs over a temperature interval of only a few degrees, but in [12], where the neutron diffraction method was used, coexistence of FM and AFM was observed over a wide temperature range.

The ordered alloy FeRh has a BCC (CsCl) structure, which may be considered as made up of two simple cubic sublattices (Fe and Rh). The ordered structure occurs over a wide range of concentrations (greater than 20 at. % Rh); near the equi-atomic composition complete order is achieved even in quenched alloys. The kinetics of the ordering process was thoroughly investigated in [13]. The magnetic structure of the FeRh alloys was most thoroughly studied by the method of neutron diffraction by Shirane, Nathans, and Chen.[14] According to their results, the magnetic moments of the Fe and Rh atoms near the equal atom composition in the FM phase are parallel and equal respectively to 3.1 and 1.0 μ_B. In the AFM phase the Fe moments are 3.3 μ_B. The Rh moment in the AFM phase was not measured; it is usually assumed to be zero. In the AFM phase the directions of the moments on the Fe atoms alternate (magnetic structure of the G-type according to the classification presented in [15]). The distribution of the mean magnetic moments over the coordination spheres in the FM and AFM phases is presented in Table I.

The magnetic hyperfine interaction for the Fe atoms in FeRh alloys was investigated by means of the Mossbauer effect by Shirane et al.[16] and Obenshain et al.[17] The latter, in particular, found that the temperature dependence of the hyperfine magnetic field for Fe^{57} in the FM phase follows a $B(^3/_2)$ Brillouin function, and in the AFM phase the field varies with temperature as

$$H(T) = H(0)(1 - aT^n), \tag{1}$$

where $a = 7.32 \times 10^{-8}$ and $n = 2.45$.

We investigated ordered FeRh alloys in the concentration range 49.5 to 53.0% Rh, containing from 0.7 to 1.0 at. % Sn enriched to 87% isotope Sn^{119}. (The compositions of the alloys will be indicated in atomic percent Rh, calculated without the Sn taken into account; the accuracy of determination of the composition was not worse than 0.3%.) At lower Sn concentrations, measurements were not made because of the difficulties associated with the strong absorption by rhodium of the resonant γ-radiation of energy 23.9 keV. The samples were obtained by melting in vacuum and homogenization at 1000°C for 50 h. The ingots were ground to powder, which was then annealed at 900°C for 20–50 h and slowly cooled to room temperature. Measurements of the Mossbauer absorption spectra were carried out at temperatures from 4.2 to 750°C with a $BaSnO_3$ source in an electrodynamic spectrometer with an NTA-512 analyzer.

The magnitude of the hyperfine magnetic field and its temperature dependence for a single magnetic phase did not vary with alloy composition; Figure 1 shows typical absorption spectra for the 49.7 and 52% alloys, the ones

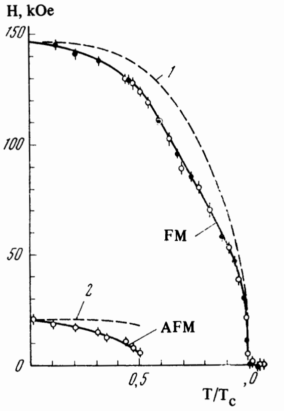

FIG. 2. Temperature dependence of the hyperfine magnetic field for Sn^{119} impurity atoms in ferromagnetic (FM) and antiferromagnetic (AFM) FeRh alloys containing 49.7% Rh (solid circles) and 52% Rh (open circles). The dashed curves are: 1—Brillouin function 147B (3/2); 2—function calculated from Eq. (1) with H(0) = 21 kOe.

we investigated most thoroughly. For the 49.7% alloy, no transition to AFM was observed. The sharp change in the hyperfine field during the AFM to FM transition is clearly seen in the absorption spectra for the 52% alloy (Fig. 1, b–d). The dependence of the hyperfine field on temperature is shown in Fig. 2.

The absorption lines in the spectra were markedly broadened, particularly for the AFM phase at low temperatures. This broadening is explained by some variation in the magnitude of the hyperfine field associated with the statistical distribution of the Sn impurity atoms and with the deviation of the composition of the investigated alloys from equi-atomic. The line broadening diminished with increasing temperature, but near the Curie temperature T_C it increased again. Supposedly, the broadening near T_C is due to relaxation effects, but we did not investigate this phenomenon in detail. In the paramagnetic region the absorption line width was 0.83 ± 0.03 mm/sec.

The spectra were analyzed using g factors for the ground and excited states of Sn^{119} equal to -2.093 and $+0.46$, respectively. The sign of the hyperfine field in the FM phase was determined by measurement of the absorption spectra in applied transverse magnetic fields of 10 to 16 kOe. Control measurements of the Mossbauer spectra for the 14.4-keV γ-radiation of Fe^{57} were also made; the results agreed with the data of [16, 17].

RESULTS

The magnitudes of the magnetic hyperfine fields for Sn^{119} impurity atoms in ordered FeRh alloys (49.5–53% Rh) at low temperatures (extrapolation to 0°K) were found to be $+147 \pm 3$ kOe in the FM phase and 21 ± 2 kOe in the AFM phase. The hyperfine field in the FM phase is the same large positive field known for Sn at the present time.

The absorption spectra obtained for Sn^{119} in the FM phase show that the Sn impurity atoms occupy only one kind of site in the FeRh lattice (only Fe or only Rh sites). In fact, if the Sn atoms were located on sites in both sublattices, we should have observed two hyperfine fields differing in magnitude and possibly in sign, since the distribution of the mean atomic magnetic moments over the coordination spheres is very different for the two types of sites (see Table I). In particular, the mean magnetic moment of the first coordination sphere in the FM phase for the Rh sites is $3.1\,\mu_B$ but only $1\,\mu_B$ for the Fe sites. In the discussion, we shall present arguments that support the contention that the Sn atoms occupy only Fe sites. This particular arrangement of Sn atoms is achieved very easily and was observed for all alloys irrespective of the annealing time.

It is significant that the Sn impurity in the amounts used did not have any great effect on the basic magnetic properties of the alloys. The Curie temperatures we measured on our alloys was found to be in good agreement with the literature data obtained on alloys without Sn impurity. For example, our 52% alloy has $T_C = 656 \pm 3$°K; the value reported in [17] is 654°K. It should be noted, however, that such a comparison is difficult because of the gross discrepancies between the data of different authors, which reaches 20 to 30°K for alloys in the concentration range of 50 to 52% Rh.

The first-order phase transition (FM ⟷ AFM) for our samples was observed in the same temperature region as for alloys not containing Sn. The high sensitivity of the hyperfine field for Sn to the magnetic properties of its surroundings permitted this transition to be registered very sharply. The temperature interval in which both phases coexisted was extremely wide. For example, for the 52% alloy, both phases were observed simultaneously at temperatures from 270 to 335°K. In accordance with the data of [12], it might be assumed that the coexistence of the phases in a broad temperature interval is a property of the FeRh alloy, irrespective of its impurity content. However, it is quite probable that the widening of the transition region in our case is connected with the effect on the temperature T_t of impurity Sn atoms that are nonuniformly distributed over the sample volume. The Sn impurity evidently does lower the transition temperature somewhat, since according to the literature, disappearance of the transition should be observed (for alloys without tin) at somewhat lower Rh concentrations. Note that the upper limit of the coexistence region for our 52% alloy was very close to $T_t = 330$°K, which is the value found in [17] for an alloy of the same composition without tin.

The temperature dependence of the hyperfine field for Sn^{119} impurity atoms in the FeRh alloys both in the FM phase and in the AFM phase was markedly sharper than the temperature dependence of the hyperfine field for Fe^{57} atoms (Fig. 2). A particularly sharp dependence was observed for the AFM phase, where raising the temperature from 4.2 to 300°K cut the hyperfine field in half.

DISCUSSION

It is usually assumed that the basic (if not the only) source of hyperfine field for a nonmagnetic atom in a ferromagnetic matrix is the interaction of this atom with polarized conduction electrons. Daniel's model,[18] as well as ours,[19] is based on this assumption. In Shirley's model,[20] along with this mechanism, the possibility is considered for some atoms that the wave functions of the outer electrons of the nonmagnetic atoms overlap with the wave functions of the magnetic 3d electrons. These models give a qualitative explanation of some of the important features of the hyperfine interaction of impurity atoms in ferromagnetic matrices, but they still do not pretend to a quantitative interpretation of the data on alloys. The radial distribution of the spin density of conduction electrons in explicit form is considered in the model of Caroli and Blandin,[21] which is used for the interpretation of the experimental data on certain alloys (see, for example, [4,22]). This model, however, excessively idealizes the real situation and contains free parameters that cannot be measured directly, and for this reason we believe that any quantitative interpretation of experimental results based on this model can hardly be good enough.

In [1] we discussed certain features of the radial dependence of the contributions to the magnetic hyperfine field which permitted an explanation of some of the experimental data on the magnetic hyperfine interaction for Sn impurity atoms in metallic ferro- and antiferromagnetics. We shall now use the same approach to qualitatively explain the results described above.

1. Magnitudes of the Hyperfine Fields for Sn Impurity Atoms in the FeRh Alloy

According to the model proposed in [19] (see also [1]), the hyperfine field H for a nonmagnetic atom in a metallic ferromagnet can be represented as the sum of two large contributions of opposite sign:

$$H = -H^- + H^+. \tag{2}$$

For Sn, H^- and H^+ are almost the same magnitude; hence the observed field H is relatively small. Both H^- and H^+ are sums of partial contributions corresponding to magnetic moments located in different coordination spheres relative to a given Sn atom, so that Eq. (2) can be written down as follows:

$$H = \sum_i (-n_i\mu_i h_i^- + n_i\mu_i h_i^+), \tag{3}$$

where i is the coordination sphere number, n_i and μ_i are the number of atoms and the atomic magnetic moment in the i-th sphere, h_i^- and h_i^+ are the negative and positive partial contributions to the hyperfine field.

It is obvious that h_i^- and h_i^+ decrease with distance (with increase in the coordination sphere number); however, the form of the functions h_i^- and h_i^+ is unknown, and Eq. (3) cannot be used directly for interpreting the data on alloys. In [1] we presented arguments according to which h_i^- and h_i^+ have different radial dependences. That is to say, h_i^+ decreases with distance more slowly than h_i^-, or in other words, the negative contribution to the field is more "local" than the positive, since the latter is ultimately determined by a larger number of coordination spheres. It is obvious, then that the magnitude of the hyperfine field ought to depend not only on the magnitudes of the magnetic moments of the matrix atoms, but also on the character of the distribution of these moments over the coordination spheres. Considering that for Sn, $H^- \approx H^+$, we should expect a predominance of the positive contribution to the hyperfine field in those cases when the atomic magnetic moment of the nearest neighbors is significantly smaller than the average atomic magnetic moment of the alloy. Other things being equal, a relative increase in the moment in the first coordination sphere, on the other hand, ought to lead to the appearance of large negative fields.

The positive hyperfine field for Sn in a matrix of Ni was attributed in [1] to the strong suppression by the impurity atom of the magnetic moments of the matrix atoms in the first coordination sphere. The large positive field (+107 kOe) observed by Williams[4] in the alloy Co_2MnSn is explained by the relatively small moment of the Co atoms (about $0.7\,\mu_B$) situated in the first sphere relative to Sn, compared to the mean moment of the alloy ($1.35\,\mu_B$). On the other hand, in antiferromagnetic Cr the mean magnetic moment is zero, whereas the moment of the first sphere is nonzero. In this connection, a large hyperfine field of 98 kOe is observed[7] for Sn impurity atoms in a Cr matrix, in spite of the small magnetic moment in the first coordination sphere. (The sign of the field in this case must be assumed negative relative to the direction of the magnetic moments of the Cr atoms in the first sphere.[1])

The large positive field that we found for Sn atoms in the FM phase of the FeRh alloy agrees well with these ideas. To explain this, it suffices to assume that the Sn atoms in FeRh are localized on sites of the Fe sublattice. In this case (see Table I), the atomic magnetic moment of the first coordination sphere ($1\,\mu_B$) is one-half as large as the mean moment of the alloy ($2.05\,\mu_B$), leading to a marked relative decrease in the negative contribution to the hyperfine field.

The correlation of the values of the hyperfine fields for Sn with the distribution of magnetic moments over the coordination spheres can be treated semiquantitatively with the aid of a simple model used in [1] for the interpretation of the temperature dependence of the magnetic hyperfine interaction. By drastically simplifying the real situation, one can say that the negative contribution to the field H^- is completely "local," i.e., it is determined by the magnetic moments of the matrix atoms in the first coordination sphere, whereas the positive contribution consists of two parts, of which the first αH^+ is "local" in the same sense as H^- and the second $(1-\alpha)H^+$ is "collective," i.e., is determined by the mean magnetic moment of the alloy. In this approximation;

$$H^- = n_1\mu_1 h_1^-,$$
$$H^+ = n_1\mu_1 h_1^+ + \bar{\mu}\bar{h}, \tag{4}$$

where $\bar{\mu}$ is the mean magnetic moment of the alloy, $\bar{h}$ is the positive contribution to the hyperfine field per $1\,\mu_B$, averaged over all spheres except the first. From Eqs. (2) and (4) we obtain

$$H = -n_1\mu_1(h_1^- - h_1^+) + \bar{\mu}\bar{h}, \tag{5}$$

whence

$$H/\mu_1 = -n_1(h_1^- - h_1^+) + \bar{h}\bar{\mu}/\mu_1. \tag{6}$$

Equation (6) shows a linear dependence of H/μ_1 on $\bar{\mu}/\mu_1$ under the condition that the parameters h_1^-, h_1^+, and $\bar{h}$ do not differ very much for different metallic systems. A comparison of the experimental data (see Table II) with Eq. (6) is shown in Fig. 3. It is seen that to a good approximation the relation between these quantities is indeed linear, which confirms our ideas about the radial dependence of the positive and negative contributions to the field. In view of the avowed approximate character of the model on which Eq. (6) was based, the scatter of the experimental points in Fig. 3 must be considered surprisingly small.

Table II. Experimental data on the hyperfine magnetic fields for Sn atoms and on the magnetic moments in several metallic ferro- and antiferromagnets

Matrix	μ_1	$\bar{\mu}$	H	H/μ_1	$\bar{\mu}/\mu_1$
Fe	2.2	2.2	—83	—38	1.0
Co (ГЦК)	1.7	1.7	—22	—13	1.0
Ni	~0.45	0.6	+19	+42	1.33
Gd	7	7	—329	—47	1.0
Co_2MnSn	0.7	1.35	+107	+153	1.93
FeRh	1.0	2.05	+147	+147	2.05
Cr	~0.5	0	—98	—196	0

Note.—μ_1 is the atomic magnetic moment in the first coordination sphere (relative to Sn), $\bar{\mu}$ is the mean atomic magnetic moment of the alloy, and H is the hyperfine magnetic field for the Sn atom in kOe.

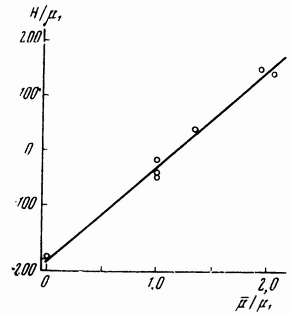

FIG. 3. Correlation of the quantities H/μ_1 and $\bar{\mu}/\mu_1$ for Sn atoms in metallic ferro- and antiferromagnetics (see Table II). H is the hyperfine field in kOe, μ_1 is the atomic magnetic moment in the first coordination sphere, and $\bar{\mu}$ is the mean atomic magnetic moment of the alloy.

It is interesting that according to Fig. 3, in metallic systems, for which $\bar{\mu}/\mu_1 \approx 1.15$, one would expect for Sn impurity atoms hyperfine fields that are close to zero, regardless of the absolute values of the magnitudes of the atomic magnetic moments. Such a situation can arise, for example, in a matrix with a uniform distribution of moments over the coordination spheres, if the perturbation introduced by the Sn atom leads to a small decrease in the moments in the first coordination sphere.

In the AFM FeRh alloy, the mean magnetic moment of the first coordination sphere of the Sn impurity atom is equal to zero (see Table I); hence the hyperfine field is determined by the moments of Fe atoms located in more distant spheres (in the second and third, mainly). The signs of the moments in these spheres alternate, which obviously leads to an effective diminution of the contributions to the field from neighboring spheres. As a consequence, the observed hyperfine field is small.

2. Temperature Dependence of the Hyperfine Fields for Sn Impurity Atoms in FeRh Alloys

In the final analysis, the temperature dependence of the hyperfine field for Sn impurity atoms in the FeRh alloy is determined by the temperature dependence of the mean values of the magnetic moments of the Fe and Rh atoms $\langle\mu_{Fe}\rangle$ and $\langle\mu_{Rh}\rangle$, which to a first approximation additively affect the polarization of the conduction electrons. The temperature dependence of $\langle\mu_{Fe}\rangle$ should be close to that of the hyperfine field for the Fe atom, since this field in the FeRh alloy is determined mainly by the intrinsic magnetic moment of the atom. The mean moment of the Rh atom can behave otherwise because of the difference in the effective exchange fields acting on the atoms in the two sublattices. In this connection it is natural to assume that the observed large difference in the temperature dependences of the hyperfine fields for Sn and for Fe (Fig. 2) is associated with $\langle\mu_{Rh}\rangle$. Unfortunately, this assumption does not explain the strong temperature dependence of the hyperfine field for Sn in the AFM alloys. More than this, difficulties also arise in the interpretation of the temperature dependence of the field in the FM phase. In this case, the moments of the Rh atoms in the first coordination sphere should give a negative contribution to the hyperfine field for Sn (since $h_1^- > h_1^+$). And the strong temperature dependence of the observed positive hyperfine field can occur only under the condition that $\langle\mu_{Rh}\rangle$ diminishes with increasing temperature to a lesser extent than $\langle\mu_{Fe}\rangle$. However, such a behavior of $\langle\mu_{Rh}\rangle$ would be difficult to explain.

An alternative interpretation of the strong temperature dependence of the hyperfine field for Sn atoms can be based on a consideration of the effect of an impurity atom on the exchange interaction in the FeRh alloy. An atom of Sn, not having a magnetic moment of its own, is equivalent to a vacancy in the Fe sublattice, and so it is natural to expect that the exchange interactions for the atoms close to the impurity will be weakened. As a result the mean magnetic moments of the Fe and Rh atoms located close to the impurity will strongly depend on temperature compared with the moments of atoms far from the impurity (or compared to the moments of atoms in an alloy without the tin impurity). This effect of an impurity Sn atom can be particularly strong in the AFM alloy, where, evidently, there is no exchange interaction between Fe and Rh. It is quite possible that in the AFM phase the temperature dependences of $\langle\mu_{Fe}\rangle$ in the second and third spheres are different. If the contributions to the hyperfine field due to the moments of Fe atoms in these spheres then have different signs (because of oppositely oriented moments), it is natural to expect a very strong dependence of the magnetic hyperfine field for the Sn impurity atom on temperature, which is indeed observed in our experiment.

---

[1] A. E. Balabanov and N. N. Delyagin, Zh. Eksp. Teor. Fiz. 57, 1947 (1969) [Sov. Phys.-JETP 30, 1054 (1970)].

[2] T. E. Cranshaw, J. Appl. Phys. 40, 1481 (1969); G. P. Huffman, F. C. Schwerer, and G. R. Dunmyre, J. Appl. Phys. 40, 1487 (1969).

[3] V. Gotthardt, H. S. Möller, and R. L. Mössbauer, Phys. Lett. 28A, 480 (1969).

[4] J. M. Williams, J. Phys. (Proc. Phys. Soc.) 2C, 2037 (1969).

[5] A. E. Balabanov and N. N. Delyagin, Fiz. Tverd. Tela 9, 1899 (1967) [Sov. Phys.-Solid State 9, 1498 (1968)].

[6] B. Window, Phys. Lett. 24A, 659 (1967); A. P. Jain and T. E. Cranshaw, Phys. Lett. 25A, 425 (1967); I. R. Williams, G. V. H. Wilson and B. Window, Phys. Lett. 25A, 144 (1967); D. C. Price and R. Street, J. Phys. (Proc. Phys. Soc.) 1C, 1258 (1968); B. Window, J. Phys. (Proc. Phys. Soc.) 2C, 2380 (1969).

[7] R. Street and B. Window, Proc. Phys. Soc. (London) **89**, 587 (1966); R. Street, B. C. Munday, B. Window, and I. R. Williams, J. Appl. Phys. **39**, 1050 (1968).

[8] J. S. Kouvel, J. Appl. Phys. **37**, 1257 (1966).

[9] P. H. L. Walter, J. Appl. Phys. **35**, 938 (1966).

[10] P. Tu, A. J. Heeger, J. S. Kouvel, and J. B. Comly, J. Appl. Phys. **40**, 1368 (1969).

[11] E. M. Hofer and P. Cucka, J. Phys. Chem. Solids **27**, 1552 (1966).

[12] E. Kren, L. Pal, and P. Szabo, Phys. Lett. **9**, 297 (1964).

[13] J. M. Lommel and J. S. Kouvel, J. Appl. Phys. **38**, 1263 (1967).

[14] G. Shirane, R. Nathans, and C. W. Chen, Phys. Rev. **134A**, 1547 (1964).

[15] E. O. Wollan and W. C. Koehler, Phys. Rev. **100**, 545 (1955).

[16] G. Shirane, C. W. Chen, P. A. Flinn, and R. Nathans, Phys. Rev. **131**, 183 (1963).

[17] F. E. Obenshain, L. D. Roberts, D. W. Forester, and J. O. Thomson, Rev. Mod. Phys. **36**, 395 (1964).

[18] E. Daniel, Hyperfine Structure and Nuclear Radiation, ed. E. Matthias and D. A. Shirley, North Holland Pub. Co., Amsterdam, 1968, p. 450.

[19] A. E. Balabanov and N. N. Delyagin, Zh. Eksp. Teor. Fiz. **54**, 1402 (1968) [Sov. Phys.-JETP **27**, 752 (1968)].

[20] D. A. Shirley, S. S. Rosenblum, and E. Matthias, Phys. Rev. **170**, 363 (1968).

[21] B. Caroli and A. Blandin, J. Phys. Chem. Solids **27**, 503 (1966).

[22] T. Shinohara, J. Phys. Soc. Japan **27**, 1127 (1969).

Translated by L. M. Matarrese
176