The inverse situation, when the vector **l** moves along the straight line L while **m** lies in the plane P, is possible only for zero velocity of motion of the stationary-profile wave; the permissible orientations of **n** and ν are also given by the relations (4.2).

Thus for any orientation of **n** and ν, lowering of the order of the Landau-Lifshitz system of equations is possible. For this purpose it is sufficient, for example, to choose the direction

$$\mathbf{n}_L=[\mathbf{n}\nu].$$

Analysis of these exact classes of solutions reduces (by choice of an appropriate system of coordinates and by renormalization of the independent variables x and t) to the completely integrable problem of a uniaxial one-sublattice ferromagnet.

We note that separation of exact classes of solutions and lowering of the order of the Landau-Lifshitz system of equations is possible also for the case when the free energy of the magnetic material has the more general form

$$2F=A[(\mathbf{m}_1')^2+(\mathbf{m}_2')^2]+A_1\mathbf{m}_1'\mathbf{m}_2'-K[(\mathbf{m}_1\mathbf{n})^2+(\mathbf{m}_2\mathbf{n})^2]-K_1(\mathbf{m}_1\mathbf{n})(\mathbf{m}_2\mathbf{n})+2d\nu[\mathbf{m}_1\mathbf{m}_2].$$

In this case, however, the resulting system of equations with a four-dimensional phase space may prove unintegrable. (The system can obviously be integrated in the case $\mathbf{n}\|\nu$: but we know of no magnet with such an orientation of the axes of anisotropy and of Dzyaloshinskiĭ interaction.)

The authors are grateful to A. V. Mikhaĭlov for critical comments.

[1]E. K. Sklyanin, O. polnoĭ integriruemosti uravneniĭ Landau-Lifshitsa (On the complete Integrability of the Landau-Lifshitz Equations), Preprint E-3-1979, LOMI, Academy of Sciences, USSR.
[2]V. M. Eleonskiĭ, N. N. Kirova, and N. E. Kugalin, Zh. Eksp. Teor. Fiz. 79, 321 (1980) [Sov. Phys. JETP 52, 162 (1980)].
[3]M. Lakshmanan, Th. W. Ruijgrok, and C. J. Thompson, Physica 84A, 577 (1976).
[4]B. A. Dubrovin, S. P. Novikov, and A. T. Fomenko, Sovremennaya geometriya (Modern Geometry), Nauka, 1979, p. 55.

Translated by W. F. Brown, Jr.

NMR investigation of the effect of hydrostatic pressure on magnetization of the intermetallic compound YFe_2

V. A. Vasil'kovskiĭ, N. M. Kovtun, A. K. Kupriyanov, S. A. Nikitin, and V. F. Ostrovskiĭ

Donetsk Physicotechnical Institute of the Academy of Sciences of the Ukrainian SSR
(Submitted 3 July 1980)
Zh. Eksp. Teor. Fiz. **80**, 364–367 (January 1981)

It is shown by the spin echo method that the local fields at the Fe^{57} nuclei decrease on application of hydrostatic pressure, while the local fields is the nuclei of the nonmagnetic yttrium ions increase. This change in the local fields is attributed to occupation of the d band by yttrium valence electrons, resulting in a decrease in the magnetic moment of the iron atom.

PACS numbers: 76.60.Lz

INTRODUCTION

There is very little information on the effect of high hydrostatic pressure on the magnetic moment of iron in alloys. This is the result of technical difficulties: the accuracy of traditional magnetic measurement methods as well as the magnitude of the expected effect often require high pressures that cannot be achieved under laboratory conditions. Accordingly, a method is increasingly widely used which is based on comparison of magnetic characteristics of compounds having different lattice parameters. From such a comparison of the intermetallic compounds YFe_2 and $LuFe_2$, Buschow and Van Stapele[1] concluded that the magnetic moment of iron μ_{Fe} increases on compression of the lattice. In our opinion, this conclusion is somewhat premature, since the observed change in the magnitude of μ_{Fe} on going from one compound to another may be connected not only with the change in the distances between the ions, but also with the change in electronic structure. The electronic structure factor is significant if it is recognized that in alloys with iron, cobalt, and nickel, the valence electrons of rare-earth elements and yttrium, making a transition to the localized $3d$ states or occupying the d band, contribute to the magnetic moment of the $3d$ metals.[2] Within the framework of this idea, the valence electrons of yttrium and lutecium can make different contributions to μ_{Fe} of the compounds YFe_2 and $LuFe_2$. Thus, to explain the effect of the distance between ions and the electronic structure on μ_{Fe} in the indicated alloys we need experimental results obtained by hydrostatic compression of the lattice under the action of pressure.

Resonance methods and especially NMR at the Fe^{57} nuclei are suitable for such precision measurements.

 0038-5646/81/010185-03$02.40

Comparison of the local fields at the Fe^{57} nuclei with μ_{Fe} in the compounds YFe_2, $LuFe_2$, and $ZrFe_2$, which have different lattice parameters, is evidence of the constancy of the parameter $\mu_{Fe}^{-1}H^{Fe}$. Consequently, the change in the field H^{Fe} under the action of hydrostatic compression should illustrate the nature of the change in the magnetic moment of the iron. Furthermore, comparison of the data on the effect of high pressure on the NMR of Fe^{57} and Y^{89}, as will be shown below, makes it possible to also explain the mechanism whereby magnetic fields are induced at the nuclei of the nonmagnetic yttrium ions.

In this work we study the effect of high hydrostatic pressure on the local fields at the Fe^{57} and Y^{89} nuclei in the compound YFe_2. Examination of the experimental results allows us to obtain information on the mechanism of development of the magnetic moment of the iron atoms in compounds of the type Y_xFe_y, and also on the mechanism of induction of local fields at the nuclei of the yttrium ions.

EXPERIMENTAL PART

Intermetallic compounds YFe_2 have a cubic structure of the Laves phases (type C-15)[3]. The positions of the yttrium atoms make up a structure similar to the structure of diamond. The iron atoms form a continuous framework of tetrahedra with vertices in contact, with point symmetry $3\bar{m}$. Magnetically, the indicated compound is a ferromagnet whose magnetism is due to the iron sublattice.[4] A sample prepared by a technique described earlier[5] was used for the investigation. The phase composition was monitored by x-ray diffraction.

To produce high hydrostatic pressure (up to 7 kbar at 4.2 °K) we used a chamber made of BrB2 beryllium bronze. The pressure-transmitting medium was a mixture of dehydrated transformer oil and kerosene. The pressure produced in the chamber was measured with a manganin transducer (calibrated to 15 kbar at the All-Union Scientific Research Institute of Physicotechnical and Radiotechnical Measurements) and an MO-62 d.c. bridge. The error in the resistance measurement was not more than ±0.01 ohm, which corresponds to pressure error not more than 100 bar. The experimentally obtained temperature dependence of the electrical resistance of the pressure transducer was used to measure the pressure in the chamber at low temperatures. Here we assumed that the baric coefficient does not depend on temperature.

The NMR spectra were recorded using a spin-echo spectrometer at a temperature of 4.2 °K. The lengths of the first and second pulses were 10 μs, separated by 60 μs; the repetition frequency of each run was 4 Hz. The resonance frequency was measured accurate to 20 kHz.

For the YFe_2 compound, two NMR lines of width 0.2 and 0.4 MHz were obtained at frequencies 45.9 ± 0.02 and 28.8 ± 0.02 MHz, respectively. Measurements in an external magnetic field (up to 8 kOe) showed that the high-frequency signal is shifted downward in frequency, and the rate of the shift corresponds to the gyromagnetic ratio for the Y^{89} nucleus. The low-frequency signal is smothered by the noise on application of an external field, but comparison with results of a previous paper[6] allows us to assume that it is due to the Fe^{57} nuclei.

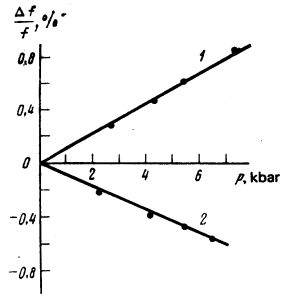

FIG. 1. Change $\Delta f/f$ of the NMR frequencies of (1) Y^{89} and (2) Fe^{57} in YFe_2 under the action of hydrostatic pressure at 4.2 °K.

Under the action of hydrostatic pressure p, the resonance frequency of the NMR signal of Y^{89} increases, while the NMR frequency of Fe^{57} decreases. The rate of change of frequency is $\partial f/\partial p = 50.5$ kHz · kbar^{-1} in the first case and $\partial f/\partial p = 24.5$ kHz · kbar^{-1} in the second. The experimental results are given in Fig. 1.

DISCUSSION OF EXPERIMENTAL RESULTS

We noted above that a change in the field H^{Fe} on compression of the lattice should illustrate the change in the magnetic moment of iron. Therefore the decrease in the field H^{Fe} in YFe_2 that we observed experimentally under the action of pressure is evidence of such a decrease of μ_{Fe}. The increase of μ_{Fe} on going from YFe_2 to $LuFe_2$ must be attributed not to a decrease in the lattice parameter (as in Ref. 1), but rather to the difference in valence electrons of yttrium and lutecium. The 5*d* and 6*s* electrons of lutecium are farther removed in energy from the 3*d* electrons of iron than are the 4*d* and 5*s* valence electrons of yttrium. Therefore, the contribution of the valence electrons to μ_{Fe} will be higher in YFe_2 than $LuFe_2$. This implies that the moment of the iron decreases with an increase in the contribution of the valence electrons.

The ideas presented above may be used to explain the change of μ_{Fe} in the compounds Y_xFe_y. In the intermetallic compounds Y_xFe_y, the moment of the iron atoms decreases with increase in the mole fraction of yttrium ions.[2] The change of μ_{Fe} in these compounds is easily explained by the increase in the effect of the valence electrons with increasing density of the trivalent yttrium ions.

In pure iron metal, $\mu_{Fe} = 2.2\ \mu_B$. According to our measurements of the absolute saturation, the values of μ_{Fe} in YFe_2, YFe_3, and Y_6Fe_{23} are equal to 1.45 μ_B, 1.7 μ_B, and 1.9 μ_B respectively. Comparing the magnitudes of μ_{Fe} in Y_xFe_y compounds of different stoichiometry, we obtained the dependence of μ_{Fe} on the number n of yttrium valence electrons ($n = 3x/y$) per iron atom:

$$\mu_{Fe} \approx \mu_0 - Kn\mu_B \qquad (1)$$

Here $\mu_0 = 2.2\ \mu_B$ is the magnetic moment of the iron

atoms in the pure metal, while the parameter K, equal to 0.5, characterizes the degree of polarization of the valence electrons. Obviously, the moment of iron in Y_xFe_y compounds is linearly dependent on the number of yttrium valence electrons per iron atom.

The idea itself that the valence electrons of yttrium (or lutecium) affect the magnitude of μ_{Fe} in alloys is not new. However, up to the present time it remained unclear whether the mechanism of the contribution of these electrons to the magnetic moment of the iron is the occupation of the localized $3d$ states of the iron atoms or occupation of the $3d$ states in the d band by the indicated electrons. The answer to this question, as will be shown below, must be provided by the results of experimental investigations of the effect of high hydrostatic pressure on the NMR frequencies of Fe^{57} and Y^{89}.

As follows from the presented experimental results (see Fig. 1), the NMR frequency of Fe^{57} (or H^{Fe}) decreases with pressure, while the NMR frequency of Y^{89} increases. This fact is difficult to understand within the scope of current notion that the local field at the yttrium nuclei is proportional μ_{Fe}. To explain this anomaly, we used the empirical formula (1). The change in μ_{Fe} under the action of pressure may be written as

$$\frac{\partial \ln \mu_{Fe}}{\partial p} \approx \frac{\mu_0}{\mu_{Fe}} \frac{\partial \ln \mu_0}{\partial p} - n \frac{K\mu_B}{\mu_{Fe}} \frac{\partial \ln K}{\partial p}. \quad (2)$$

From this we have for the change in the polarization of the valence electrons under pressure

$$\frac{\partial \ln K}{\partial p} \approx \frac{\mu_0}{Kn\mu_B} \frac{\partial \ln \mu_0}{\partial p} - \frac{\mu_{Fe}}{Kn\mu_B} \frac{\partial \ln \mu_{Fe}}{\partial p}. \quad (3)$$

Substituting into this expression the value of $\partial \ln \mu_0 / \partial p$ for metallic iron (assuming that $\partial \ln \mu_0 / \partial p \approx \partial \ln H^{Fe} / \partial p = -0.16 \cdot 10^{-3}$ kbar^{-1}) from the paper of Benedek and Armstrong,[7] and $\partial \ln \mu_{Fe} / \partial p = (-0.85 \pm 0.1) \cdot 10^{-3}$ kbar^{-1} from our experimental data for YFe_2, and taking it into account that for a given compound YFe_2 the number n is equal to 1.5, we obtain $\partial \ln K / \partial p = 1.24 \cdot 10^{-3}$ kbar^{-1}.

This value of $\partial \ln K / \partial p$ is close to the experimental value $\partial \ln H^Y / \partial p = (1.1 \pm 0.1) \cdot 10^{-3}$ kbar^{-1}. Therefore it is reasonable to assume that the change in the field at the Y^{89} nuclei under the action of pressure is due not to a change in the direct overlap of the wave functions of the yttrium ions with the wave functions of the $3d$ electrons, but rather to a change in the effect of the polarized valence electrons of yttrium. This change in H^Y with pressure cannot be connected with the transition of valence electrons of yttrium to localized $3d$ states of the iron atom, since in this case the dependence of H^Y on pressure would duplicate that for the moment μ_{Fe}. Consequently, the decrease in the magnetic moment of iron with increase in the mole fraction of yttrium in the compounds Y_xFe_y is due to occupation of a d band by the valence electrons of yttrium.

Thus, it follows from the above that: 1) the magnetic moment of iron in the compounds Y_xFe_y may be represented as the difference between two contributions, $\mu_{Fe} = \mu_0 - \mu_1$; the first contribution μ_0 corresponds to the electronic configuration of the iron atoms in the pure metal, while the second contribution μ_1 is connected with the polarized conduction band formed by the valence electrons of yttrium; 2) under the action of pressure, the magnetic moment μ_{Fe} in YFe_2 decreases, owing for the most part to the increase in the contribution μ_1; 3) the local fields at the Y^{89} nuclei are due to polarized, collectivized electrons of yttrium.

[1]K. H. J. Buschow and R. P. Van Stapele, J. Phys. (Paris), Collow. C1, C-672 (1971).
[2]K. H. J. Bushcow, Phys. Status Solidi A 7, 199 (1971).
[3]P. L. Krip'yakevich, M. A. Teslyuk, and B. M. Frankevich, Kristallografiya 10, 422 (1965) [Sov. Phys. Crystallography 10, 344 (1965)].
[4]E. Burzo, Zs. Angew. Phys. 32, (2), 127 (1971).
[5]V. A. Vasil'kovskiĭ, M. N. Kovton, A. K. Kupriyanov, S. A. Nikitin, and V. F. Ostrovskiĭ, Zh. Éksp. Teor. Fiz. 65, 693 (1973) [Sov. Phys. JETP 38, 342 (1973)].
[6]S. A. Nikitin, V. A. Vasil'kovskiĭ, N. M. Kovtun, A. K. Kupriyanov, and V. F. Ostrovskii, Zh. Éksp. Teor. Fiz. 68, 577 (1975) [Sov. Phys. JETP 41, 285 (1975)].
[7]G. B. Benedek and J. Armstrong, J. Appl. Phys. 32, 106S (1961).

Translated by Cathy Flick