fied with the hydrodynamic instability considered theoretically in [3].

We are grateful to A. V. Loginov and V. L. Sizonenko for discussing the work and to V. T. Pilipenko for help with the measurements.

[1] V. L. Sizonenko and K. N. Stepanov, Nuclear Fusion 7, 131 (1967).
[2] M. V. Babykin, P. P. Gavrik, E. K. Zavoiskii, L. I. Rudakov, V. A. Skoryupin, and G. V. Sholik, Zh. Eksp. Teor. Fiz. 46, 511 (1964) [Sov. Phys.-JETP 19, 349 (1964)].
[3] K. N. Stepanov, Zh. Tekh. Fiz. 34, 2146 (1964) [Sov. Phys.-Tech. Phys. 9, 1653 (1965)].
[4] V. L. Sizonenko, K. N. Stepanov, and J. Teichmann, Comptes Rendus due Colloque International sur l'Interaction des Champs H. F. Associes a un Champ Magnetique Statique avec Plasma, Saclay, 15-18 January 1968; V. L. Sizonenko and K. N. Stepanov, Zh. Eksp. Teor. Fiz. 56, No. 1 (1969) [Sov. Phys.-JETP 29, No. 1 (1969)].
[5] V. I. Aref'ev, I. A. Kovan, and L. I. Rudakov, ZhETF Pis. Red. 7, 286 (1968) [JETP Lett. 7, 223 (1968)].
[6] L. V. Dubovoi and V. P. Fedyakov, Zh. Eksp. Teor. Fiz. 53, 789 (1967) [Sov. Phys.-JETP 26, 485 (1968)].
[7] M. P. Vasil'ev, L. I. Grigor'eva, A. V. Longinov, B. I. Smerdov, and V. V. Chechkin, ibid. 54, 1646 (1968) [27 (1968)].
[8] V. V. Chechkin, M. P. Vasil'ev, L. I. Grigor'eva, and B. I. Smerdov, Nuclear Fusion 4, 145 (1964).
[9] V. V. Chechkin, M. P. Vasil'ev, L. I. Grigor'eva, and B. I. Smerdov, In: Vysokochastotnye svoistva plazmy (High-frequency Properties of Plasma), AN USSR, 1965, p. 15.

STABILIZATION OF HYPERFINE STRUCTURE OF THE MOSSBAUER LINE IN PARAMAGNETS IN A WEAK EXTERNAL MAGNETIC FIELD

A. M. Afanas'ev and Yu. M. Kagan
Submitted 7 October 1968
ZhETF Pis. Red. 8, No. 11, 620-624 (5 December 1968)

It is known that a distinct magnetic hyperfine structure (hfs) of the Mossbauer line should be produced in a paramagnet, in the absence of an external field, if the relaxation time of the electron spin of the Mossbauer atoms is sufficiently large [1,2]. Under certain conditions, however, such a structure may turn out to be quite sensitive not only to the relaxation time, but also to very weak static magnetic fields. Naturally, under real conditions this should lead to a smearing of a part or perhaps even the entire hfs, owing to random magnetic fields produced by the ions of the surroundings [3]. It turns out, and it will be demonstrated below, that it is possible to obtain again a clear-cut hfs from such an unresolved structure by applying to the paramagnet a small external magnetic field (we emphasize that we are dealing with fields weak enough for the direct interaction of the field with the nucleus to be negligibly small), i.e., we are faced with a unique effect of hfs stabilization.

To describe the hyperfine structure of the ion in the presence of an external magnetic field H and in the absence of quadrupole interaction, we can use the spin Hamiltonian in the form

$$\hat{\mathcal{H}} = A_{ik} I_i S_k + g_{ik} \mu_0 S_i H_k . \qquad (1)$$

Here $\vec{I}$ - spin of the nucleus and μ_0 - Bohr magneton. For a free ion, $\vec{S}$ is the total angular momentum of the electron shell and A_{ik} and g_{ik} are proportional to δ_{ik} (here g is the usual Lande factor). In the case of a crystal, when the energy of the Stark splitting

of the ground term of the ion in the crystal field is large compared with the energy of the hyperfine interaction, we have for each individual Stark level a Hamiltonian in the form (1), where S is the effective spin, the magnitude of which is determined by the multiplicity of the degeneracy of the corresponding level (see, e.g., [4]).

Let us consider first, for simplicity, the case when $A_{ik} = A\delta_{ik}$ and $g_{ik} = g\delta_{ik}$. Let further

$$H \ll A/g\mu_0. \tag{2}$$

The energy levels will then be determined by the value of the total angular momentum $\vec{F} = \vec{I} + \vec{S}$ with projection of this momentum M_F on the direction $\vec{H}(I + S \geq F \geq |I - S|)$:

$$E_i(F^i, M_F^i) = \frac{F^i(F^i+1) - S(S+1) - I^i(I^i+1)}{2} A^i + L_F^i g\mu_0 M_F^i H,$$
$$L_F^i = \frac{F^i(F^i+1) + S(S+1) - I^i(I^i+1)}{2F^i(F^i+1)}. \tag{3}$$

Here $i = 0$ or 1, depending on whether we are considering the ground state of the nucleus or and excited state.

It follows directly from (3) that there are now many lines of the transition $E_1 - E_0$ for a given radiation multipolarity, and that very weak fields $H \gtrsim \Gamma_0/g\mu_0$ (Γ_0 - natural width of the Mossbauer line) cause splittings and shifts of the lines, noticeably altering the spectrum. This indeed causes the strong smearing of the spectrum when weak fields of random magnitudes act on it in random fashion. (For Fe^{57} nuclei, the spectrum becomes smeared in fields on the order of several Oe.)

Such a sensitivity of the spectrum to small H is explained physically by the fact that the levels between which the transition takes place are mixed electron-nuclear levels, and the magnetic field shifts these levels by an amount on the order of the interaction of this field with the magnetic moment of the electron shell, and not with the magnetic moment of the nucleus (see (3)).

If now

$$H \gg A/g\mu_0, \tag{4}$$

then the coupling between $\vec{I}$ and $\vec{S}$ is broken (a unique Paschen-Back effect), and the energy levels will be determined by the values of the spin projections I_z and S_z on the direction of the magnetic field:

$$E^i(I_z^i, S_z) = A^i I_z^i S_z + g\mu_0 S_z H. \tag{5}$$

Since the projection S_z is conserved in the nuclear transition, it is easy to see that now the position of the hfs lines does not depend on H at all, i.e., the structure turns out to be insensitive to external fields and is consequently stable.

On going over to a real crystal, the anisotropy of the tensors A_{ik} and g_{ik} introduces a large number of fundamental singularities, although the entire qualitative picture remains the same. Let the tensors A_{ik} and g_{ik} be diagonalized in one and the same coordinate system. Then a quite realistic situation is one in which $g_x = g_y = 0$, $g_z \neq 0$, and $A_x = A_y = 0$ and $A_z \neq 0$. It is easy to see that at this level the energies take the form (5), and the hfs of the Mossbauer line is stable and independent of the magnetic field. At an arbitrary ratio of the tensor components, condition (2) leads to a system of mixed electron-nuclear levels, i.e., to an hfs that is smeared by the weak magnetic fields in the crystal, while condition (4) leads to a stable hfs. However, in this case the magnitude of the stabilizing field can change strongly, depending on its direction in the single crystal. If we take into account the fact that in the case of the so-called weak crystalline field g_i and A_i are proportional to each other, then, for example in the case of axial symmetry, the corresponding ratio H_z/H_x will, roughly speaking, be proportional to $(A_x/A_z)^2$. We note also that when

$$A_x = A_y \gg A_z, \qquad A_z \gg A_x, A_y \tag{6}$$

we can obtain a clear-cut hyperfine structure also in a polycrystalline sample, in spite of the sensitivity of the hfs to the direction of the stabilizing field.

We shall illustrate all these statements using as a characteristic example the ion Fe^{3+} situated in an axially symmetrical crystal field.

The main term of the ion $^6S_{5/2}$ splits in this case into three Kramers doublets

$$\begin{aligned} S_z &= \pm 5/2 \quad (A_x = A_y = 0, \ A_z = 5A), \\ S_z &= \pm 3/2 \quad (A_x = A_y = 0, \ A_z = 3A), \\ S_z &= \pm 1/2 \quad (A_x = A_y = 3A, \ A_z = A). \end{aligned} \tag{7}$$

As follows from the foregoing, the doublets $S_z = \pm 5/2, \pm 3/2$ should give clear-cut hfs spectra. The spectrum from the doublet $S_z = \pm 1/2$, in the absence of an external field, should also be strongly smeared. This is precisely the picture observed in the experiment of [2]. When an external field is superimposed, the hfs spectra of the doublets $S_z = \pm 5/2$ and $\pm 3/2$ remain unchanged, and clear-cut lines should appear in the spectrum of the doublet $S_z = \pm 1/2$. As shown by calculations, in this case, to obtain a stable picture of the spectrum from the doublet $S_z = \pm 1/2$, it is sufficient to apply a field $H_x \sim 100$ Oe. On the other hand, if the field is directed along the OZ axis, then the fields required are approximately one order of magnitude larger. Figure 1 shows spectra from the doublet $S_z = \pm 1/2$ in a field $\vec{H} = \vec{H}_0 + \vec{H}'$, where $H_0 = 100$ and 150 Oe, and $\vec{H}'$ is a field with random directions, with $H' = 10$ Oe, for the cases $\vec{H}_0 \perp OZ$ (a) and $\vec{H}_0 \parallel OZ$ (b). As seen from this figure, in case (a) the spectrum has a clear-cut set of six lines, which change little on going from 100 to 150 Oe. In the case (b) the spectrum is strongly smeared out for both values of H_0.

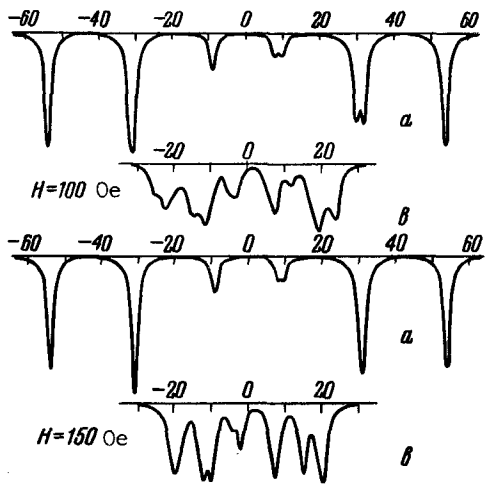

Fig. 1

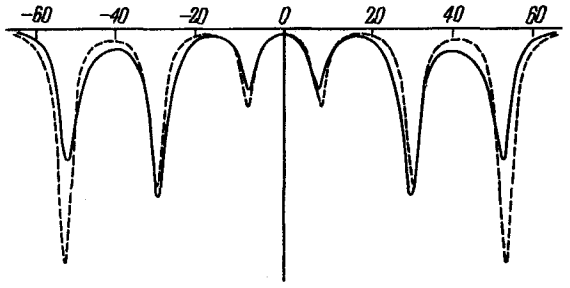

Fig. 2

It is interesting that in accordance with the considerations advanced above, the field H ~ 100 Oe turns out to be stabilizing also in the case of a polycrystal. The corresponding spectrum is shown in Fig. 2 (H_0 = 200 Oe and H' = 0). The same figure shows (dashed) the spectrum from the doublet $S_z = \pm 3/2$. By virtue of (7), the position of the lines of this doublet coincides with the position of the lines of the doublet $S_z = \pm 1/2$ in the stabilizing field perpendicular to OZ. The position of the lines in a polycrystal is very close to this case.

Gorobchenko et al. [5] performed an experiment aimed at observing the stabilization effect. On superimposing an external magnetic field (60 and 120 Oe) on a polycrystalline sample of corundum with admixture of trivalent iron ions with a Mossbauer nucleus Fe^{57}, they observed in the hfs spectrum new clear-cut lines, which were missing in a zero external field. The position of these lines corresponds to the position of the lines of the spectrum in Fig. 2.

The presence of a stabilization effect greatly broadens the class of substances in which it is possible to investigate the hfs of the Mossbauer line. These include substances with arbitrary ratio of the tensor components A_i for the majority of the Stark levels. This applies primarily to substances both with very low symmetry of the crystal field surrounding the Mossbauer ion, and with very high symmetry (e.g., cubic). A clear-cut hfs can be observed in these substances only when a stabilizing magnetic field is applied.

Application of an external field makes, as a rule, all the hfs lines sharper, thus greatly facilitating a study of the processes of spin-lattice and spin-spin relaxation.

Finally, the stabilized hfs is very sensitive to small changes of the crystal field surrounding the ion, and it is possible consequently to obtain very detailed information on the latter. This pertains primarily to experiments with single-crystal samples.

The authors are grateful to V. D. Gorobchenko for help with the numerical calculations needed to plot the figures.

[1] A. M. Afanas'ev and Yu. M. Kagan, Zh. Eksp. Teor. Fiz. 45, 1660 (1963) [Sov. Phys.-JETP 18, 1139 (1964)].
[2] G. K. Wertheim and M. P. Remeika, Phys. Lett. 10, 14 (1964).
[3] H. H. Wickman, M. P. Klein, and D. A. Shirly, Phys. Rev. 152, 345 (1965).

[4] W. Low, ed. Paramagnetic Resonance, Interscience, 1962.
[5] V. D. Gorobchenko, I. I. Lukashevich, V. V. Sklyarevskii, K. F. Tsitskishvili, and N. I. Filippov, ZhETF Pis. Red. 8, 625 (1968) [JETP Lett. 8, 386 (1968)].

OBSERVATION OF THE EFFECT OF STABILIZATION OF THE HYPERFINE STRUCTURE OF TRIVALENT Fe^{57} IN CORUNDUM BY A WEAK EXTERNAL MAGNETIC FIELD

V. D. Gorobchenko, I. I. Lukashevich, V. V. Sklyarevskii, K. F. Tsitskishvili, and N. I. Filippov
Submitted 23 September 1968
ZhETF Pis. Red. 8, No. 11, 625-629 (5 December 1968)

The Mossbauer effect is used more and more frequently for investigations of the hyperfine structure (hfs) of nuclear levels in paramagnetic substances with sufficiently large electron-spin relaxation times. The possibility of successfully using the Mossbauer effect for this purpose was first established by A. M. Afanas'ev and Yu. M. Kagan [1]. An investigation of the hfs in paramagnets makes it possible in principle to study the behavior of spin-lattice relaxation as a function of the temperature, to draw conclusions concerning the character of the spin-spin relaxation, and also to obtain useful information on the crystal surroundings and valence state of a paramagnetic ion. The complexity of the hfs in paramagnets frequently makes it very difficult to extract the necessary information from the experimentally measured spectra.

There exists, however, a class of interesting phenomena, predicted by A. M. Afanas'ev and Yu. M. Kagan [2], which greatly facilitate the solution of the problems raised above, and in addition, are of great independent interest for research. We have in mind primarily the effect of stabilization of the hfs in paramagnets by means of an external magnetic field.

As shown in [2], the hfs is sensitive not only to the relaxation time of the electron spin of the paramagnetic ion, but also in many cases to very weak external magnetic fields acting on this ion. The reason for such a sensitivity is that in a weak field the states between which nuclear transitions take place in the paramagnetic ion are not purely nuclear, but mixed nuclear-electronic states, and therefore the transition changes not only the state of the nucleus, but also the state of the electron shell. If the ion is in a magnetic field H, this causes the levels between which the transition takes place to shift in turn by an amount $\sim\mu_B H$, where μ_B is the Bohr magneton. (We note that for Fe^{57} nuclei this shift is on the order of 1.34 natural widths at H = 1 Oe.) Therefore, small magnetic fields (for Fe^{57} - on the order of several Oe) suffice to change noticeably the hfs, and in the case of randomly distributed fields they can smear out the hfs completely.

On the other hand, if the external magnetic field is not too weak, so that the magnitude of its interaction with the spin of the shell is much larger than the constant of the hyperfine interaction (we note that in this case we are dealing with fields only on the order of several hundred Oe), then the Mossbauer transitions again become purely nuclear. This is caused by the fact that now the states of the ion, between which the transition takes place, are products of purely nuclear states by purely electronic states, and the corresponding selection rules for the nuclear transitions do not in themselves provide for a change in the