A. V. Zalesskiĭ. *Domain walls in magnetic materials according to NMR spectroscopy.* A distinctive feature of NMR in a ferromagnet is that the intensity of NMR absorption is dominated in many cases by nuclei in domain walls, since the gain η_W is larger for these nuclei than for nuclei in the domains. The difficulties involved in interpreting in-wall NMR spectra are commonly mentioned, but a study of these spectra might yield valuable information on the properties of the walls at a microscopic level since the nuclei are in a sense microscopic probes which can penetrate into the interior of a wall.

The theoretical papers by Turov *et al.*[1] have substantially changed our understanding of the in-wall NMR spectra. In the present paper we report an experimental study of domain walls by an NMR method in certain magnetically ordered crystals. Some of these results have been published previously.[2]

The most interesting objects for study turned out to be crystals of rare earth orthoferrites with the general formula $RFeO_3$ (R is a rare earth ion). In these orthorhombic weak ferromagnets the in-wall NMR signals can be obtained in their "pure form." Furthermore, the domain walls in orthoferrites can with-stand quite strong fields (up to 10 kOe or higher) perpendicular to the *c* easy axis without undergoing any significant structural change. It thus becomes possible to study the spectra in external fields. The spectra of ^{57}Fe nuclei which we observed consist of two peaks at closely spaced frequencies ν_{max} and ν_{min}. A theory explaining these spectra has been derived by Zvezdin.[3] The reason for the presence of two lines is that, as the antiferromagnetism vector **G** in a wall rotates, two frequency branches arise because of a lowering of the symmetry (in comparison with that in the domains). The resonant peaks at frequencies ν_{max} and ν_{min} correspond to a maximum spectral density which itself corresponds to the condition $d\nu_i(\theta)/d\theta = 0$, where $\nu_i(\theta)$ is the angular dependence of the NMR frequency for one of the branches, and θ is the angle through which **G** rotates with respect to the orthorhombic axis *a* inside a wall. A remarkable feature of the spectra is the possibility of determining the plane of rotation of **G** from the nature of the shift of the frequencies ν_{max} and ν_{min} in fields H_x (parallel to the *a* axis) and H_y (parallel to the *b* axis). Two types of walls may occur in orthoferrites: 1) a wall involving a rotation of **G** and of the ferromagnetism vector **F** as a common unit in the *ac* plane (this is an analog of ordinary Bloch walls) and 2) a wall involving a rotation of **G** in the *ab* plane, with **F** retaining its orientation along the *c* axis but changing in magnitude, crossing zero and changing sign at the center of the wall. The possibility in principle that such walls exist—they have no analog in ordinary ferromagnets—was analyzed for the case of orthoferrites in Refs. 4 and 5. The nature of the changes in the frequencies ν_{max} and ν_{min} for the walls of types *ac* and *ab* is shown in Figs. 1a and 1b, respectively. The experimental results show that at high temperatures walls of type *ac* exist in orthoferrites. On the other hand, in the orthoferrite $DyFeO_3$, in which a Morin transition occurs at low temperatures ($T_M = 40$ K) in the *ab* plane, walls of the *ab* type have been observed in the interval $40 < T < 150$ K (frequency shifts of the type in Fig. 1b).[6] At $T > 150$ K, a rotation in the

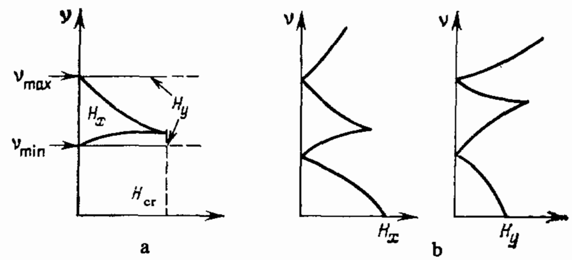

FIG. 1. Changes in the frequencies ν_{max} and ν_{min} in external fields. a—For domain walls of type *ac*; b—type *ab*.

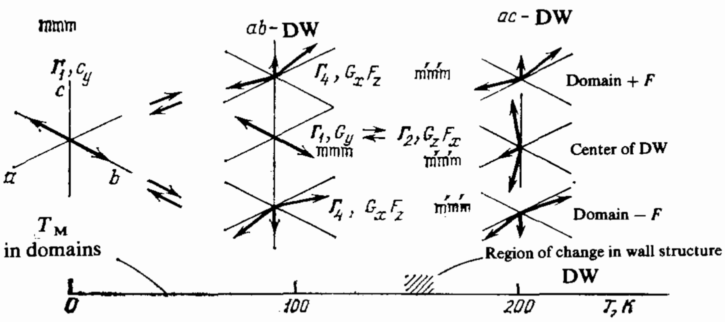

FIG. 2. Schematic diagram of the temperature-induced change in the structure of domain walls in $DyFeO_3$ (the Morin point is inside the wall).

a,c plane begins to correspond to a minimum of the wall energy, and the wall structure changes from type *ab* to type *ac*. This transition occurs in the temperature range 150–160 K. The change in structure is shown schematically in Fig. 2, where spin configurations for domains and for the center of walls are shown in a common notation. It can be seen from Fig. 2 that a reorientation transition accompanied by a change in the point group of the magnetic symmetry, $mmm(\Gamma_1,G_y)\rightarrow m'm'm(\Gamma_2,G_zF_x)$, with a rotation of **G** in the *b,c* plane and with the appearance of F_x, occurs at the center of the wall in the course of the structural change. This is a sort of Morin transition, but it occurs locally at the center of a wall rather than in the interior of the domains (the magnetic structure in the domains does not change). The walls, which have a G_y antiferromagnetic structure at the center at $T<150$ K, serve as nucleating regions of the antiferromagnetic phase, which arises throughout the crystal at $T<T_M$.

We have been considering the case in which it is possible to extract information about the internal structure of walls from NMR spectra. What other information can we find from in-wall NMR?

The magnitude of the splitting $\Delta\nu=\nu_{max}-\nu_{min}$ in orthoferrites may serve as a measure of the anisotropy of the local hyperfine fields at the ^{57}Fe nuclei. As the atomic number of the *R* ion decreases, i.e., as the orthorhombic distortions decrease in the series of orthoferrites, $\Delta\nu$ decreases.[7]

Experiments by the spin-echo method have revealed a difference in the conditions for the formation of the NMR peaks in spectra found by steady-state and pulsed methods. The spin echo in the $YFeO_3$ crystal is formed by nuclei which lie in a layer of a wall near the domain.[8]

Measurements of the temperature dependence of the NMR frequencies yield information on the in-wall spin (Winter magnons).

The intensity and shape of the NMR line for in-wall nuclei are affected by factors associated with the real structure of the crystal (impurities and defects), since η_W depends on such structure-sensitive characteristics of the wall as damping, elasticity, mobility, and resonant frequency. The effect of the defect concentration can be seen particularly vividly in hematite crystals.[9] Quenching and annealing have strong effects on the dynamic properties of "free" and "rigid" walls and thereby change the shape of the line of the "steady-state" NMR spectrum. In the case of $YFeO_3$, the presence of the impurity Fe^{4+} ion causes a narrowing of a wall at $T<15$ K, sharply intensifying the NMR absorption.[10]

In an analysis of the in-wall spectra it is important to know the localization of the nuclei responsible for the resonant peaks. In multiple-sublattice hexagonal ferrites, the nuclei of each of the sublattices establish a separate line shape, which may consist of a single line at the edge of a wall, a single line at the center of a wall, or two lines simultaneously.[11] These results support the applicability of the theory of Turov *et al.*[1] not only to simple ferromagnets but also to complex multiple-sublattice ferrimagnets.

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Translated by Dave Parsons