Experimental evidence for suppression of elastic scattering of nuclear resonant gamma rays in a perfect crystal

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Suppression of resonance elastic scattering of gamma rays by nuclei with propagation of radiation in a perfect crystal outside the Bragg angle is observed for the first time.

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As shown in Refs. 1 and 2, the parameters of nuclear gamma resonance, characteristic of an isolated nucleus, can be greatly changed as a result of scattering of γ rays by systems of identical nuclei. A γ ray, after entering a system of nuclei resonantly tuned to it, is captured in it. As a result, there arises a collective excitation of the state in which each nucleus is excited with a known probability amplitude. The system of nuclei in a certain sense behaves in interacting with the quantum as a single ensemble, having its own effective resonant parameters (see, for example, Ref. 3). The nature of the resonance response of this ensemble to a large extent depends on whether or not the nuclear system is regular. For example, a γ ray captured by a regular system of nuclei (in an ideal frozen crystal), must be emitted only in the direction of the initial radiation (we are examining the case of rays incident on the crystal outside Bragg's angle). That is, there must be no elastic resonance scattering of γ rays. This result is equivalent to the disappearance of the elastic width of a nuclear level as a result of absorption of γ rays in a perfect crystal, predicted in Ref. 2.

Evidently, suppression of elastic scattering of γ rays can be observed in crystals with a high degree of perfection by reducing to a minimum anything causing localization of nuclear excitation in the crystal. Crystals with the required quality were grown at the Physical Institute of Czechoslovakian Academy of Sciences. These were crystals of iron borate $Fe^{57}BO_3$, enriched with a resonant isotope up to 85%. One of the reasons for localization of excitation in the crystal is the rotation of the spin in the ground state of a nucleus during the scattering process. Under conditions of magnetic hyperfine splitting, to which the ground and excited levels of the Fe^{57} nuclei in these crystals are subjected, there is the possibility of excluding this channel. A diagram of nuclear transitions between levels of the ground and first excited states of the nucleus being examined are presented in the upper part of Fig. 1. There is a fundamental difference between resonances 1 and 6 and the other resonances. This difference is attributed to the fact that the excitation of the nuclear transitions $\frac{1}{2} \rightarrow \frac{3}{2}$ and $-\frac{1}{2} \rightarrow -\frac{3}{2}$, due to the selection rule for $M1$ transitions, can be accompanied by decay only into the initial states with respect to the spin projection, whereas the selection rules allow a return to any sublevel of the ground state from each of the $\pm\frac{1}{2}$ sublevels of the excited state. In the latter case, during the scattering process, the nuclear spin can rotate and a γ ray with a different energy can be

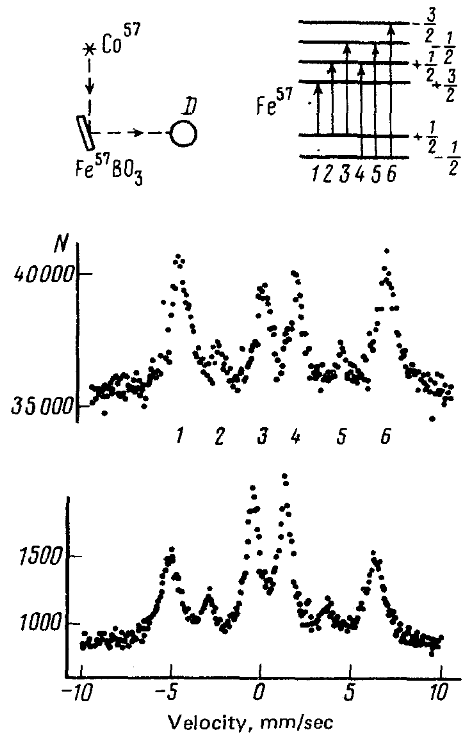

FIG. 1.

emitted.[4] Thus, resonances 1 and 6 present an unusual opportunity for studying the scattering of rays in the absence of the inelastic incoherent channel, related to the rotation of the nuclear spin in the ground state. In addition, the presence of the two types of transitions examined in a single Mössbauer spectrum allows comparing directly elastic and inelastic scattering of γ rays according to the intensity of the corresponding resonance lines.

The experimental arrangement is shown in Fig. 1. The crystals were oriented relative to the incident beam so as to avoid Bragg scattering. The crystallographic plane (111), the easy magnetization plane, reached the surface of the crystal. A source of 14.4-keV Mössbauer radiation, Co^{57}, in a chromium matrix with a total activity of 100 mCi was used. The divergence angle of the rays incident on the crystal was 0–5°. The 90° geometry allowed lowering the Rayleigh electron scattering background. An external magnetic field was applied to the crystal perpendicular to the scattering plane. It transformed the crystal into a single domain state, in which the effective magnetic fields on the nuclei lay in the scattering plane ($FeBO_3$ is a skewed antiferromagnet). For fixed orientation of the magnetic fields relative to the incident beams, only four of the six possible nuclear transitions could be effectively excited, namely, 1, 6, 3, and 4, for which the change in the magnetic quantum number is $\Delta m = \pm 1$. The nuclear resonance cross sections for these transitions have the same polarization dependence. In the given geometry, they approached their maximum values. Both orthogonal polarization components of the incident beam participated identically in the excitation of the transitions.

The two Mössbauer spectra presented in Fig. 1 differ in that in one case (the upper spectrum) the detector recorded secondary 6.3-keV radiation, accompanying the decay of the excited nuclei, while in the other (the lower spectrum) the detector recorded the resonant scattering of 14.4-keV radiation. The upper spectrum actually reflects the pattern of resonance absorption of γ rays in a crystal in the given geometry. It shows, in particular, that transitions 1 and 6 are most intense. Indeed, as is well known, the corresponding resonant cross section is three times greater than the cross section for resonances 3 and 4. The actual ratio of the intensities of the external and internal lines was found to be less than 3, which is attributable to saturation due to absorption of radiation in a thick specimen.

We shall now turn to the lower spectrum. First we note that as a result of transition to scattering, an unusual inversion occurred in the relation of the internal and external line intensities. The most intense lines are now lines 3 and 4. These are exactly the resonances, whose excitation led to the discovery of the scattering processes resulting in the rotation of the nuclear spin $\pm 1/2 \rightarrow \mp 1/2 \rightarrow \mp 1/2$. We recall that such processes are forbidden for resonances 1 and 6.

The predominance of internal lines 3 and 4, to which inelastic scattering contributes, over the external lines 1 and 6, under the conditions such that the resonant excitation cross sections of the corresponding transitions are related inversely, proves the suppression of elastic scattering of γ rays in a system of nuclei in a perfect crystal.

In the spectrum measured, residual scattering of 14.4-keV γ rays is still observed upon excitation of resonances 1 and 6. Let us consider in greater detail the possible reasons for this scattering. First of all, it stems from spin incoherence. At room temperature, both nuclear sublevels in the ground state have virtually equal populations, so that only one half of the Fe^{57} nuclei interact with γ rays with definite resonant energy. Isotopic incoherence also makes its own contribution: the nonresonant isotope makes up 15% of the iron nuclei. To some extent, incoherent scattering stems from inelastic processes resulting from thermal vibrations of the crystal lattice and vibrations in the spin system of the crystal.

As far as resonances 3 and 4 are concerned, in addition to the reasons listed above, as already mentioned above, another inelastic process related to rotation of the nuclear spin is in effect; as can be seen, for non-Bragg scattering of γ rays, this process dominates over other processes.

1. Yu. Kagan and A. M. Afanas'ev, Zh. Eksp. Teor. Fiz. **50**, 271 (1966) [Sov. Phys. JETP **23**, 178 (1966)].
2. A. M. Afanas'ev and Yu. Kagan, Zh. Eksp. Teor. Fiz. **52**, 191 (1967) [Sov. Phys. JETP **25**, 124 (1967)].
3. U. Van Börck, G. V. Smirnov, R. L. Mössbauer, H. J. Maoros, and N. A. Semioschkina, J. Phys. C: Solid St. Phys. **13**, 4511 (1980).
4. A. N. Artem'ev, G. V. Smirnov, and E. P. Stepanov, Zh. Eksp. Teor. Fiz. **54**, 1028 (1968) [Sov. Phys. JETP **27**, 547 (1968)].

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