Suppression of a nuclear reaction in $Fe^{57}BO_3$ crystal

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(Submitted 24 August 1979)
Zh. Eksp. Teor. Fiz. 78, 1196–1208 (March 1980)

Research on iron borate crystals, which offer extensive possibilities of observing 100% suppression under purely nuclear diffraction conditions, was performed for the first time ever. The possibility of artificially disturbing the suppression effect by rotating the magnetic field applied to the crystal is demonstrated experimentally. To estimate the scale of the residual nuclear gamma-quantum absorption in the crystal, a method is used with a standard resonant absorber that demonstrated the sensitivity of the Laue-diffraction Mössbauer spectra to restoration of the resonant absorption of the gamma beam. The observed volcano-shaped profile of the spectrum is well described by the Kagan-Afanas'ev theory of dynamic resonant scattering.

PACS numbers: 76.80. + y

The effect of suppression of a nuclear reaction (SE) in resonant interaction of Mössbauer radiation with perfect crystals, which was predicted theoretically,[1] was observed and investigated in a number of experiments, a brief survey of which is presented in Ref. 2. These experiments have revealed various manifestations of the SE in crystals of varying crystal symmetry, and the universal character of the phenomenon was demonstrated.

The suppression effect is most clearly manifest under conditions when the interaction of the γ quantum with the crystal is determined primarily by processes of resonant absorption and scattering in the nuclear system of the crystal. To ensure such conditions, it is necessary first to produce a crystal maximally enriched with Mössbauer isotope nuclei, and to make possible the suppression of the scattering of the γ quanta by electrons. One of the effective method of separating the role of nuclear coherent scattering is based on the use of the polarization properties of nuclear resonant scattering of the quanta,[3] first realized with an antiferromagnetic hematite crystal.[4] In the same crystal, the SE was first observed for purely nuclear diffraction of γ quanta.[5]

We report here observation of the SE in the antiferromagnetic iron borate crystal $Fe^{57}BO_3$. By virtue of the different positions of the iron nuclei in the unit cell of the hematite and iron-borate crystals, the latter are superior for the investigation of the SE in that it is possible to realize in them complete vanishing of the nuclear excitation amplitude, and to observe a 100% SE, something impossible with hematite crystals. To estimate the scale of the SE we have used here, for the first time ever, the method of standard resonant absorber. The sensitivity of the nuclear Laue diffraction spectra to the restoration of the resonant absorption of the γ beam was demonstrated. The possibility of artificially upsetting the SE by changing the configuration of the wave field in the crystal is experimentally demonstrated. The analytic part of the article deals with some singularities of the interaction between gamma radiation and a crystal under conditions of pure nuclear diffraction.

$Fe^{57}BO_3$ CRYSTALS

The $FeBO_3$ crystal is a magnetic dielectric. It has a rhombohedral unit cell with space group $D_{3d}^6(R\bar{3}c)$. The unit cell contains two molecules of the material. The iron ions lie on the [111] threefold axis and occupy positions at the start and center of the rhombohedron diagonal. At room temperature, iron borate is a canted antiferromagnet. The two magnetic sublattices have equal magnetic moments, practically oppositely oriented perpendicular to the [111] axis. The magnetic properties and structure of the iron borate made it possible, just as in the case of the hematite crystal,[4] to separate the γ-quantum diffraction by only the nuclear lattice of the crystal, using reflections with odd sum of Miller indices.

To observe the SE we must be able to produce in the crystal a γ-quantum state describable by a superposition of two coherent wave. For this paired superposition state, the amplitude for the production of the excited nucleus is made up of the excitation amplitudes in the incident and diffracted waves. The SE sets in when total cancellation of the added amplitudes takes place. The phase ratio of these waves needed for complete cancellation is reached only when the structural factors in the scattering amplitude are exactly equal to unity. The structure of the hematite crystal does not make it possible to satisfy this condition, since the iron nuclei, which lie on a threefold axis (major diagonal of the rhombohedron) has a displacement parameter $u = 0.355$. In the best case it is possible to come close to unity only in reflections with a Miller-index sum equal to 7. Since the iron nuclei in the $FeBO_3$ crystal are located exactly at the starting point and midpoint of the major diagonal of the unit cell, the structural factors there are equal to unity for iron nuclei in any diffraction direction. For this reason it is possible in principle to observe the SE in an iron borate crystal for any nuclear reflection.

The solution-melt crystallization method was used to grow the $Fe^{57}BO_3$ crystals. A modification of the technological process was developed to permit the use of a small initial amount of isotopically enriched material. The initial components (in wt.%) were melted in a plat-

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inum crucible at 850 °C: $50B_2O_3$, 28.6PbO, 13.4PbF_2 of OSCh (extreme purity) grade, and $8Fe_2O_3$ enriched with Fe^{57} to 85%. The capped crucible was placed in a resistance furnace, heated to 1150 °C, and kept at this temperature for 8 hours. The subsequent changes in temperature were at a rate of 200 deg/hr. The temperature was lowered to 800 °C and held there for one hour, raised from 800 to 900 °C, again lowered to 800 °C, held there for an hour, followed by a final rise to 880 °C. It was cooled from this point to 750 °C at a rate of 2 deg/hr. The furnace was turned off at 750 °C. The crystals were separated from the melt in a 20% aqueous solution of nitric acid and were well-formed hexagonal plates up to 4 mm in diameter and 0.1 mm thick. The (111) plane emerged to the surface.

The preliminary selection of the sample for the investigation was by topographic photography of the crystals. The chosen single-crystal plate was half a heagon 3 mm high, 1.5 mm wide, and 40 m thick. The topograms of even the better samples showed some stresses to be present in the crystals. The rocking curves of the selected sample, measured with MoK_α radiation in the antidispersion combination of reflections $SiO_2(20\bar{2}2)_{Bragg}$-$FeBO_2(112)_{Laue}$ had widths from 10″ to 12″ on the illuminated area 3×0.2 mm of the second crystal. When allowance is made for the remaining dispersion, the broadening of the curves compared with that calculated for perfect crystals was 3″–5″. These results corroborate the topographic data that some strain, albeit small, is present in the crystal.

EXPERIMENTAL SETUP. STANDARD RESONANT ABSORBER

The measurements were made with a Mössbauer diffractometer.[6] Figure 1 shows schematically part of the setup used in the experiment. We investigated the diffraction of the Mössbauer quanta by an $Fe^{57}BO_3$ crystal in transmission of the rays through the crystal (Laue geometry). Information in the intensity of the interaction between the γ quanta and the nuclei in the crystals upon passage of quanta in the paired state through the crystal is contained to equal degree in both the direct and in the inclined Laue-diffracted beams.[6] When a widely divergent incident beam is used, however, measurements in the deflected beam are more effective, since they make it possible to track only the quanta in a narrow angle interval in which it is precisely that pair states are produced. The direct-beam background,

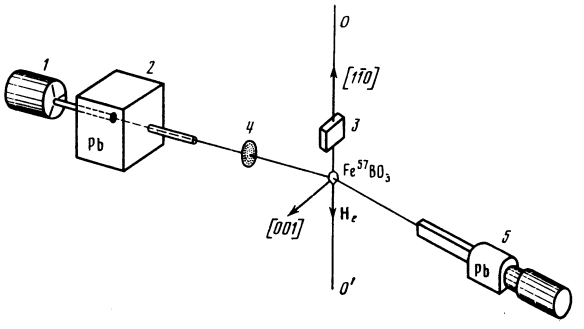

FIG. 1. Experimental setup.

which exceeds appreciably the useful count under these conditions, is automatically excluded.

The γ-ray source had at the start of the measurements an activity of 180 mCi of Co^{57} in a Co matrix. The active-spot diameter was 40 mm and the effective thickness 10 μm. The source line width was 1.5 times the natural width of the nuclear level, and the recoilless radiation factor was 0.76. The source was installed in a cavity in the protective lead block 2, and the beam was extracted through a channel bounded by a copper collimator tube. A two-circle GUR-4 goniometer with vertical axis OO' was placed 50 cm away from the source. The goniometer head was used to place the $Fe^{57}BO_3$ crystal on the goniometer axis in such a way that the axis was in the central section of the crystal and parallel to the $[1\bar{1}0]$ crystallographic direction. The end of the crystal was secured with beeswax on the end of a copper wire of 0.5 mm diameter. The quantum beam incident on the crystal had an 8 mm diameter, covered the entire crystal, but did not touch any of the other parts. This was important for the lowering of the incoherent-scattering background.

The detector unit was the same as used in Ref. 6. The detector head, which contained a scintillation crystal, was surrounded by a lead shield to limit the background. A long lead collimator with transverse dimensions 3 ×10 mm for the entry of the Laue-diffracted beam was placed ahead of the entry into the detector. Owing to the low magnetic anisotropy (~1 Oe) of the iron borate in the (111) plane, it was sufficient to apply to the crystal a magnetic field of several Oe to produce uniform magnetization in the plane of the plate. The field was produced by a piece of a permanent ceramic magnet (3). It could be rotated about the center of the crystal, with one of its poles facing the crystal. The weak ferromagnetic moment of the crystal followed the direction of the applied field.

An essential element of the experimental setup was the standard absorber 4. The idea of using this absorber is to imitate the residual resonant absorption of the quanta in the crystal. If the periodicity of the crystal lattice is violated somewhere, but the paired state produced by the undisturbed part of the crystal is not upset, then local nuclear resonant absorption should occur in the disturbed region. In fact, the presence of defects in the crystal is accompanied by a certain displacement of the Fe^{57} nuclei from the positions in the ideal lattice. The nuclei removed from the points where the combined amplitude of formation of an excited nucleus is strictly equal to zero begin to absorb quanta, inasmuch as the excitation amplitudes in the incident and diffracted waves are no longer cancelled out in their new positions. A comparison of the resonant absorption of the γ quanta by the crystal's own defects with the known additional absorption would make it possible to estimate quantitatively the scale of the residual resonant absorption in the crystal. Judging from its purpose, it is seen that the purpose of the additional absorber is calibration. The residual absorption should be calibrated in successive measurements of the Laue-diffraction spectra without the standard absorber and with the absorber

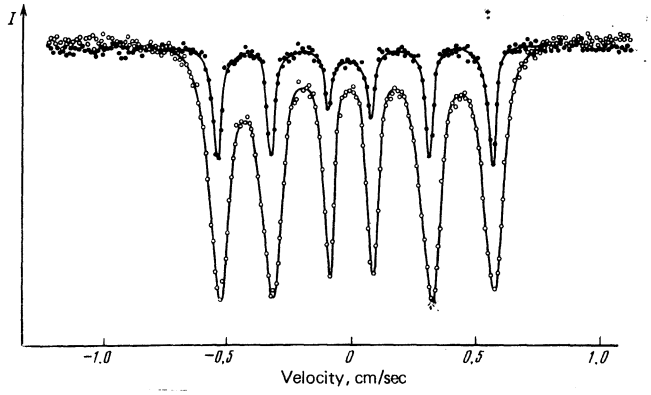

FIG. 2. Mössbauer absorption spectra in investigated crystal (○) and in standard absorber (●).

placed in the quantum beam.

To enable the standard resonant absorber to imitate the resonant absorption in the crystal, it was made of the same material as the crystal. One of the grown $Fe^{57}BO_3$ crystals was finely ground and the powder compacted to form a disk of uniform thickness 0.8 μm.

The Mössbauer absorption spectra of the γ quanta in the standard absorber and in an investigated $Fe^{57}BO_3$ crystal 40 μm thick are compared in Fig. 2. To suppress the hard gamma components in the measurement of these spectra, we used a pure beam of 14.4 keV energy, obtained by first reflecting the beam from a graphite crystal. As seen from Fig. 2, the iron-borate crystal was a strong resonant absorber. The absorption for the outermost transitions reached saturation. This follows from the fact that the depths of the corresponding resonance dips are equal. The scale of the absorption under saturation condition is now determined by the line width. Compared with the crystal, the standard was obviously a thin absorber. If we use the exponential law $I=I_0\exp\{-\frac{1}{2}\mu_r t\}$ (μ_r—is the usual resonant-absorption factor), which is valid for thin absorber, we find that the absorption factor for the outer ($\pm\frac{1}{2}\rightarrow\pm\frac{3}{2}$) resonances is equal to 0.9.

MEASUREMENTS AND RESULTS

From among the possible nuclear reflection, we chose the (001) reflection for the formation of the paired state of the γ quantam in the $Fe^{57}BO_3$ crystal. This reflection is closest to a symmetrical diffraction geometry. Figure 3a shows the geometry of the vectors in the scattering scheme. The angle between the chosen reflecting planes and the crystal surface was $\varphi=74.4$, and the Bragg angle was $\theta=6.5°$. The asymmetry parameter $\beta=\cos\sphericalangle(\mathbf{k}_0\mathbf{n})/\cos\sphericalangle(\mathbf{k}_1\mathbf{n})$ was thus 1.06. The measurements were made for two directions of the external magnetic field $\mathbf{H}_e$—vertical and horizontal. First a few words on the measurements for the case illustrated in Fig. 3a. At this crystal magnetization, the moments of the sublattices were in the scattering plane, and the effective magnetic fields at the nuclei $\mathbf{H}_1$ and $\mathbf{H}_2$ rotated together with these moments.

The first experiment was aimed at observing the passage of the γ quanta through the crystal under conditions when they interact resonantly with the nuclei. To produce the paired state of the quantum it was necessary to adjust the system for the nuclear reflection (001). A direct search for this reflection was extremely difficult because of the large thickness of the crystal in terms of the nuclear factor (see Fig. 2). The crystal angular position at which nuclear diffraction should take place was therefore localized by using the nearest electronic reflections in the absence of nuclear absorption of the quanta. The neighboring resolved reflections having a common axis with (001) were $(11\bar{2})$ and (002). To prevent absorption of the quanta by the nuclei when tuned to electronic reflections, the source line was diverted with aid of a vibrator far away from the resonance region. The obtained electronic reflections shown in Fig. 4a correspond to the outermost maxima. The angle distance between them agreed well with the calculated value, thus attesting to sufficiently accurate adjustment of the crystal. After these measurements the crystal was rotated into the angle region ($\theta_{cryst}=0$ in Fig. 4a), where, according to the calculations, nuclear reflection should occur; the source line was aligned with the nu-

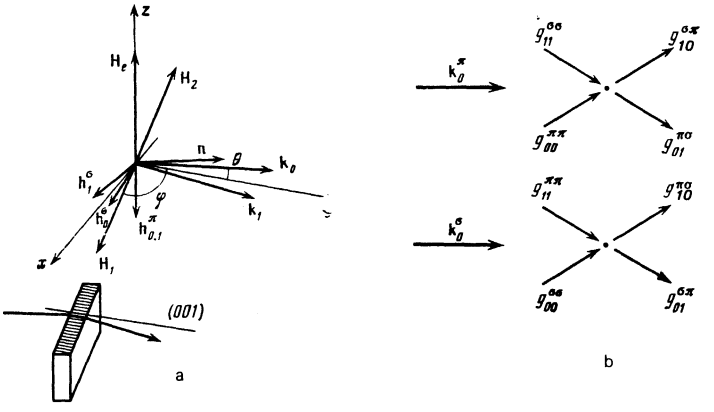

FIG. 3. a) Geometry of vectors in the scattering scheme: $\mathbf{n}$ is the inward normal to the crystal surface, $\mathbf{k}_0$ and $\mathbf{k}_1$ are the wave vectors of the incident and scattered waves, $\mathbf{h}^\sigma_{0,1}$ and $\mathbf{h}^\pi_{0,1}$ are the polarization vectors, $\mathbf{H}_e$ is the intensity of the external magnetic field, $\mathbf{H}_1$ and $\mathbf{H}_2$ are the intensities of the magnetic fields at the iron nuclei, φ is the angle between the entrance surface of the crystal and the reflecting plane, and θ is the Bragg angle. b) Schematic representation of the process of the onset of the superposition states excited in the crystal by π and σ polarized components of the incident gamma beam.

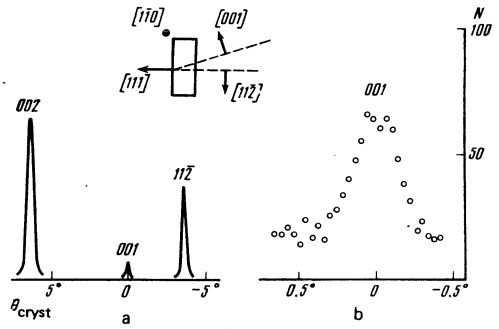

FIG. 4. a) Scheme of the search for the (001) nuclear Laue reflection, and the measured angular diffraction spectra of the nuclear and reference electronic reflection. b) (001) nuclear peak in enlarged scale.

clear resonance $+\frac{1}{2} \rightarrow +\frac{3}{2}$, and a search for the nuclear peak was made. The measurement result is the central maximum on Fig. 4a; the same maximum, but on an enlarged scale, is shown in Fig. 4b. Its appearance indicates that in the angle region where pure nuclear diffraction produced a superposition paired state of γ quanta we succeeded in observing the passage of radiation through the crystal, even though at resonance, under ordinary condition, the crystal was practically a blackbody absorber. The useful counting rate at the peak was 0.05 quanta/sec. The observed passage of the resonant quanta could be only the result of suppression of the nuclear reaction.

After tuning to resonance, the angle position was fixed and the Laue-diffraction frequency spectra were measured. In these measurements the line source passed with constant velocity (the vibrator operated in this case in a constant-acceleration mode) through the entire spectrum of the hyperfine splitting of the nuclear energy levels. The results are shown in Fig. 5a. The positions of the resonances are indicated by the dashed lines. It is seen that under the Laue-diffraction conditions the quanta passed through the crystal only in the case of resonances with $\Delta m = \pm 1$. By virtue of the polarization properties of the transitions with $\Delta m = 0$, their excitation is accompanied by mutual extinction of the waves scattered by the nuclei, exactly as in electron Rayleigh scattering for this reflection. No paired state is therefore produced, and transitions with $\Delta m - 0$ operate only in absorption: the resonances have intensity dips. The profiles of the measured maxima recall volcanoes. The maxima have considerable width, reaching 22 natural nuclear level widths (Γ_n) for the outermost resonances. Gently sloping craters are observed on the crests.

The resultant picture is quite complicated and we shall return to its analysis later. The principal conclusion, however, can be drawn even now: we have directly observed in our measurements the passage of γ quanta at resonance under conditions of strong absorption. We recall that in the experiment with the hematite[5] relatively deep dips appeared on the crests of the maxima. One of the reasons was incomplete compensation of the amplitudes of the excitation in the paired state of the γ quantum. In iron borate crystal, on the other hand, the only

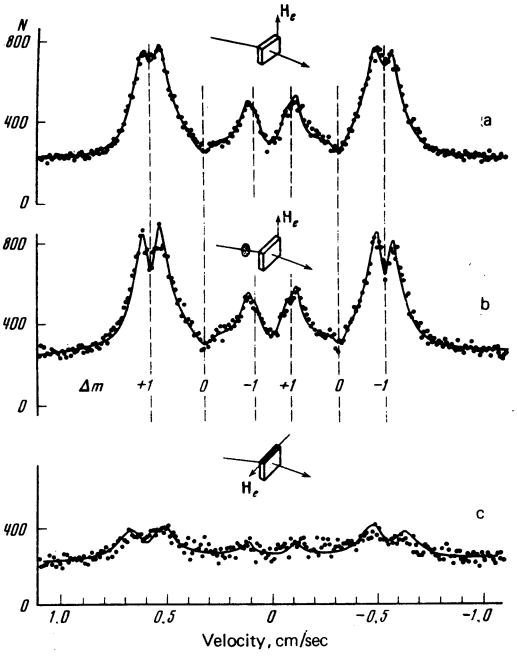

FIG. 5. Mössbauer spectra of (001) Laue diffraction: a—external magnetic field perpendicular to scattering plane, b—the same with standard absorber in gamma beam, c—external magnetic field in the scattering plane. Points—experiment, solid lines—calculation in accord with the Kagan-Afanas'ev dynamic theory.

cause of the residual nuclear absorption could be imperfections in the crystal. To calibrate the resonant absorption remaining in the crystal, measurements were made of the same spectrum with the standard absorber added. The result is shown in Fig. 5b. Distinct rather deep dips due to resonance absorption in the standard appear at the resonance positions on the crests of the maxima. A unique inversion took place—the standard, which was thinner by a factor of 50 than the investigated crystal (see Fig. 2), exhibited a much greater absorptivity than that remaining in the crystal. We verify thus the strong action of the suppression effect under the conditions in question.

We discuss now the measurements for the second direction of the external magnetic field. The latter was rotated in the sample plane through 90°, after which the effective fields H_1 and H_2 at the nuclei turned out to be aligned along the z axis (see Fig. 3). The Laue-diffraction frequency spectrum measured under these conditions is shown in Fig. 5c. An indirect comparison with the results of the preceding measurements shows that the SE was considerably disturbed after the rotation of the field, and as a result the resonant absorption of the γ quanta in the crystal was restored. We proceed now to an analysis of the results.

DISCUSSION OF RESULTS. SINGULARITIES OF PURE NUCLEAR LAUE DIFFRACTION

1. First, using the deductions of the Kagan-Afanas'ev (KA) dynamic theory,[1] we shall answer the following question: What causes the formation of the gamma quantum paired state in a crystal to be so different for the two field directions that a radical restoration of the nu-

clear absorption takes place in one of the cases? To this end, we determine first the coefficients of the dynamic equations in each of the considered cases. A detailed expression for the coefficients is given for magnetic dipole interaction in Ref. 2. It is easy to show that in the situation shown in Fig. 3 the following relations hold between the coefficients: for the electronic part of the coefficients

$$\chi_{00}=\chi_{11}=\chi, \quad \chi_{01}=\chi_{10}=0$$

for both the π and the σ polarized components of the incident beam; for the nuclear part of the coefficients and an entering π wave

$$g_{00}^{\pi\pi}=\frac{1}{v+i},$$
$$g_{01}^{\pi\sigma}=-g_{10}^{\sigma\pi}=\frac{i\cos(\varphi-\theta)}{v+i}, \tag{1a}$$
$$g_{11}^{\sigma\sigma}=\frac{\cos^2(\varphi-\theta)}{v+i},$$

and for an input σ wave

$$g_{00}^{\sigma\sigma}=\frac{\cos^2(\varphi+\theta)}{v+i},$$
$$g_{01}^{\sigma\pi}=-g_{10}^{\pi\sigma}=\frac{i\cos(\varphi+\theta)}{v+i}, \tag{1b}$$
$$g_{11}^{\pi\pi}=\frac{1}{v+i},$$

where v shows the deviation from resonance in units of the half width $\Gamma_n/2$ of the nuclear level. The foregoing coefficients are normalized to $|g_{00}^{\pi\pi}(\nu=0)|$. Vanishing of χ_{01} and χ_{10} means that electronic diffraction is forbidden.

In this case we encounter an unusual and rather interesting situation, wherein the superposition paired state is made up of orthogonally polarized π and σ waves. The input π wave excites in the $\mathbf{k}_1$ direction a σ wave which in turn, rescattered in the $\mathbf{k}_0$ direction, produces a π wave. Analogously for an input σ wave, i.e., in scattering by a unit cell of the crystal, the polarization state of the primary wave is radically changed. The connection between the polarizations in the corresponding superpositions is shown in Fig. 3b. Each input polarization excites in the crystal a wave field of its own, without any coherent coupling with another. The superposition excited by the σ wave mades a small contribution to the total field, inasmuch as in the considered case (Fig. 3) the interaction of the primary σ wave with the nuclei is greatly weakened, $\cos^2(\varphi+\theta)=0.025$. Also weakened is the amplitude of σ-wave scattering into a π wave, $\cos(\varphi+\theta)=0.16$. At the same time, the primary π wave is fully absorbed by the nuclei and is rescattered intensively enough into the secondary σ wave: $\cos(\varphi-\theta)=0.38$. Thus, under the chosen conditions the advantage of the coherent superposition excited at the input to the crystal by the π polarized component of the γ beam was subject to no doubt. The KA dynamic theory shows that the SE is realized for that paired state in which the parameter $\Delta=g_{00}g_{11}-g_{01}g_{10}$ vanishes. For the nuclear coefficients (1) corresponding to the field orientation in Fig. 3a this relation is satisfied exactly.

We present now the nuclear coefficients in the case of a field $\mathbf{H}_0$ turned 90° around $\mathbf{n}$. Under these conditions transitions with $\Delta m=\pm1$ can be excited only by the σ polarized component:

$$g_{00}^{\sigma\sigma}=\frac{1}{v+i}, \quad g_{11}^{\sigma\sigma}=\frac{1}{v+i},$$
$$g_{10}^{\sigma\sigma}=-g_{01}^{\sigma\sigma}=i\frac{\sin 2\theta}{v+i}. \tag{2}$$

After the rotation of the magnetic field, the paired state consists of only σ polarized waves. In this state, the nuclear excitation amplitude is no longer equal to zero: the parameter $\Delta(\nu=0)=\cos^2 2\theta$. Thus, by changing the configuration of the wave field in the crystal by rotating the magnetic moment of the crystal it becomes possible to upset artificially the conditions of the suppression effect.

2. We dwell now in greater detail on the structure of the maxima in Fig. 5a. For pure nuclear scattering of the quanta at an angle satisfying exactly the Bragg condition for the intensity of a Laue-diffracted beam we have (see Ref. 1):

$$I_{LR}=\frac{I_0}{4}\left\{1+\exp\left(\frac{-2T}{v^2+1}\right)-2\exp\left(\frac{-T}{v^2+1}\right)\cos\left(\frac{Tv}{v^2+1}\right)\right\}, \tag{3}$$

where I_0 is the intensity of the incident beam, and T is the usual resonant absorption factor in the crystal in the primary-beam direction. A typical value for the observation of the SE is $T\gg10$.

Near resonance ($v=0$), where the crystal has effectively a large thickness, so that the second and third terms in the braces can be neglected, the intensity is constant. Obviously, the thicker the crystal the wider the band in which the intensity of the transmitted beam becomes independent of the γ-quantum energy. Under these conditions the γ quanta pass through the crystal in the paired state for which the SE is realized. At distances from resonance where $T/(v^2+1)\sim1$, the next two terms of (3) come into play. The second term represents the γ quanta in a strongly absorbed state (their absorption is double the usual one), and the third represents the interference of two paired states. Figure 6 shows by way of example the behavior of each of the terms in (3) and their sums at $T=100$. Up to $v=8$ the

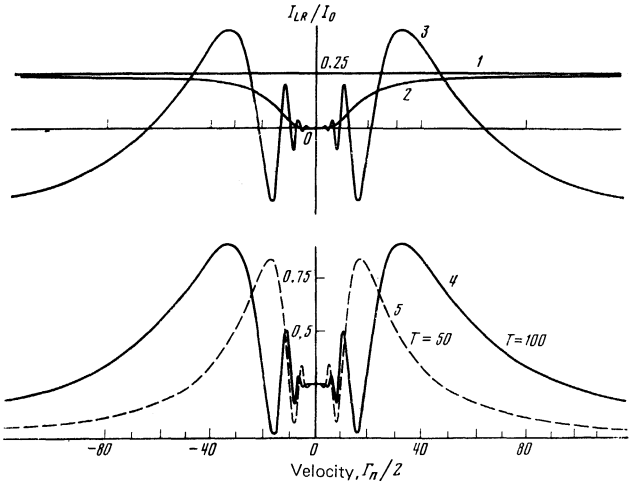

FIG. 6. Structure of maximum in the Mössbauer spectrum of pure Laue diffraction. Calculation by formula (3): curves 1, 2, and 3 correspond to the terms in the formula, curve 4—sum, curve 5 is shown for comparison.

quanta pass through the crystal only by virtue of the SE. Beyond this limit the contributions from the second and third term make themselves more and more felt. The second term approaches the limit quite rapidly whereas the third, owing to the slowly varying argument of the cosine, still oscillates. It is this last term which determines principally the variation of the function I_{LR} in the region of small thicknesses. The interference of the paired states leads at the start of the last period to a substantial rise of the intensity, followed by slow decrease, at large distances from resonance.

The physical cause of formation of a volcano-shaped profile of the maxima in the Laue-diffraction spectrum is, in final analysis, the collective action of the crystal nuclei in the γ-quantum scattering process. The coherent mechanism near the Bragg angle leads to enhancement of the elastic scattering channel in the system of nuclei. Therefore even at large distances from resonance, where the amplitude of the scattering by an individual nucleus is already small, the collective scattering manages to produce superposition paired states in the system of the crystal nuclei, and it is the interference between them that is observed. We recall that at these distances from resonance the crystal are already significantly transparent to the resonant radiation. The size of the interference region and the associated broadening of the maxima are obviously determined by the thickness of the crystal. In the lower part of Fig. 6, the summary picture is compared for two different T ($T=50$ is close to the thickness of the investigated crystal). We have considered so far only one angle interval of the function I_{LR}. A similar picture is preserved also in a certain angle interval, but with increasing deviation from the Bragg position, the collective action of the nuclear system, which leads to the increase of the intensity far from resonance, becomes weaker and the role of the near-resonance quanta increases as a result. Since we used in the experiment a broad incident beam, the measured quantity was in fact the intensity integrated over the angles. The computer-calculated integrated intensity is shown by the solid line in Fig. 5a. It is seen that integration has smoothed out the oscillations considerably and decreased the depths of the craters compared with the calculations at $\theta=\theta_B$. At the same time, the total width of the maxima remained large. On the whole, the theoretical and experimental spectra are in good agreement.

3. We concentrate now on the analysis of the spectrum in the vicinity of the resonances, where the crystal transmits the quanta only because of the SE. We consider the possible causes of the lowering of the resonant intensity. To this end we find first the factors of the residual absorption factors in a defect-free crystal.

Just as the imaginary part of the refractive index is responsible in optics for the absorption of light in a medium, the imaginary part of the complex increments $\varepsilon_0^{(1)}$ to the wave vector of the γ quantum in vacuum determines, in the KA dynamic theory, the absorption of a quantum in a paired state in the crystal. It follows from Ref. 1 that under the condition when the γ quantum interacts with nuclei and electrons in a crystal the minimum value of this quantity is

$$(\operatorname{Im}\varepsilon_0^{(1)})_{min}=\tfrac{1}{4}\{\operatorname{Im}(\tilde g_{00}+\beta\tilde g_{11})-[[\operatorname{Im}(\tilde g_{00}+\beta\tilde g_{11})]^2 -2\beta[2(\operatorname{Im}\tilde g_{00})(\operatorname{Im}\tilde g_{11})-|\tilde g_{01}\tilde g_{10}|+\operatorname{Re}(\tilde g_{01}\tilde g_{10})]]^{1/2}\}. \quad (4)$$

Substitution of (1) in (4) together with simple transformations yield

$$(\operatorname{Im}\varepsilon_0^{(1)})_{min}=\frac{1}{4}\left\{(1+\beta)\operatorname{Im}\chi+\frac{1+\beta c^2}{v^2+1} -\left[\left[(1-\beta)\operatorname{Im}\chi+\frac{1+\beta c^2}{1+v^2}\right]^2-4(1-\beta)\frac{\beta c^2}{v^2+1}\operatorname{Im}\chi\right]^{1/2}\right\}, \quad (5)$$

where c is the abbreviation for the cosines in (1).

By virtue of the smallness of the electron absorption relative to the nuclear resonant absorption ($\operatorname{Im}\chi=0.008$), the second term under the square root is much smaller than the first, so that we can confine ourselves with good approximation to the first two terms of the series expansion of the square root. We obtain ultimately

$$(\operatorname{Im}\varepsilon_0^{(1)})_{min}\approx\frac{1}{2}\left[\beta+\frac{(1-\beta)\beta c^2}{1+\beta c^2+(1-\beta)(v^2+1)\operatorname{Im}\chi}\right]\operatorname{Im}\chi. \quad (6)$$

It is seen first of all that the normal electronic absorption due to the photoeffect is preserved for the paired state of the γ quantum in the crystal under conditions of pure nuclear diffraction. At the same time, the nuclear absorption is completely suppressed. The result reflects clearly the difference between the SE and the Borrmann effect. The point is that in our case neither the electric nor the magnetic wave fields have nodes at the locations of the iron atoms, and both wave fields are elliptically polarized. Since the photoabsorption depends only on the electric field intensity, its action is preserved under these conditions—the Borrmann effect is not observed. As to the SE, by virtue of the vector relations between the nuclear magnetic moment and the wave magnetic field at the nucleus, the amplitude of the nuclear excitation is rigorously equal to zero in this case. The second terms in the brackets in (6) appears when the diffraction geometry is not symmetrical. It is of interest to note that this term, which stems from electron absorption, turns out to depend, albeit weakly, on the γ-quantum energy. This result reflects the fact that the wave field is formed in the crystal on account of the energy-dependent nuclear scattering of the quanta.

We turn now to the residual absorption in a real crystal. At low defect concentration (as in a sufficiently perfect crystal), the crystal-lattice periodicity violations due to these effects can be regarded as perturbations from the viewpoint of their action on the paired state. It can be assumed that the defects do not distort the structure of the wave field that is established in scattering by perfect regions of the crystal, and only cause local absorption of the field. Allowance for the displacements of the nuclei on which the absorption is established can be effected by introducing the Debye-Waller static factor into the amplitude of the nuclear resonant scattering. It is easy to show that in this case an additional term appears in expression (6)

$$\frac{\beta L}{[(v^2+1)(1+\beta c^2)+(1-\beta)(v^2+1)^2\operatorname{Im}\chi]}. \quad (7)$$

It has already a strong resonance dependence and constitutes resonant residual absorption. The argument of the exponential in the static Debye-Waller factor L is

proportional to $\langle s^2 \rangle$—the mean squared atom displacement due to the presence of defects in the crystal. The presence of the residual factor (7) should lead to the appearance of resonant dips against the background of intensity maxima. The absorption of a paired state by a defect can be called a local Mössbauer effect.

No account was taken in the calculated spectrum of Fig. 5a of the presence of defects in the crystals. It is seen that the experimental points in that figure fit the theoretical line well. The absence, within the measurement accuracy limits, of residual resonant absorption due to disturbances of the crystal lattice is evidence of the high perfection of the employed crystal. The solid line in Fig. 5b was calculated for $e^{-L} = 0.9$. The static Debye-Waller factor should have this value in order to obtain the picture produced with the aid of the standard.

CONCLUSION

Thus, the iron borate crystals provide the most favorable conditions for the investigation of the suppression of a nuclear reaction in pure nuclear diffraction of Mössbauer γ quanta. In these crystals, if the conditions of the total SE are maintained, it is possible to vary widely the polarization structure of the superposition state of the γ quantum in the crystal. In addition, artificial controllable violation of the SE by varying the magnetization of the crystal is easily realized.

The sensitivity of the Laue-diffraction spectra to resonant residual absorption can be used to study the static and dynamic violations of the periodicity of the crystal lattice.

The authors thank Yu. Kagan and A. M. Afanas'ev for helpful discussions of the result, V. V. Sklyarevskiĭ for constant interest and support, and N. A. Semioshkina for great help with the experiments.

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Translated by J. G. Adashko

Magnetic anisotropy of PdFe alloy near the Curie point T_c

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(Submitted 27 August 1979)
Zh. Eksp. Teor. Fiz. **78**, 1209–1222 (March 1980)

Magnetoelastic effects that occur under the action of a uniaxial load and data on the depolarization and intensity of a neutron beam passing through the specimen are used to determine the range of existence of a quasidomain structure ($\tau = (T_c - T)/T_c \approx 10^{-2}$). It is shown that the texture parameter is related to the magnetic-anisotropy and magnetostriction constants. From its temperature dependence, the dependence of the anisotropy constant on τ follows in the form of the power series. Possible reasons for such a dependence are discussed.

PACS numbers: 75.30.Gw, 75.80. + q, 75.60.Ch, 75.50.Cc

1. INTRODUCTION

By analysis of data on depolarization of neutrons in nickel,[1] Maleev and one of the authors[2] arrived at the conclusion that the observed large depolarization at a phase transition near the Curie point T_c could not be explained by critical fluctuations alone, since in the immediate vicinity of T_c there is a scattering of neutrons with spin reversal that is excessive in comparison with the critical. It is contained within a narrow cone of angles, determined by the aperture of the detector, and leads to large depolarization of the transmitted beam. This excessive small-angle scattering, apparently caused by unusual quasidomains, means that the transition to the ferromagnetic state is actually a transition of the first kind that is nearly of the second.

It is known that the chief role in the formation of domains is played by competition between the anisotropy, exchange, and demagnetization energies. In cubic ferromagnets, with lowering of the temperature near T_c the anisotropy energy ($E_K \sim M_s^4$) increases faster than the magnetostatic ($E_{ms} \sim M_s^2$), and therefore one must actually

 0038-5646/80/030609-08$02.40