[4]T. Sugawara, J. Phys. Soc. Jap. **20**, 2252 (1967).
[5]P. G. Arnold and J. Popplewell, J. Phys. F **3**, 1985 (1973).
[6]S. A. Nikitin, S. S. Slobodchikov, and O. D. Chistyakov, Zh. Eksp. Teor. Fiz. **70**, 104 (1976) [Sov. Phys. JETP **43**, 54 (1976)].
[7]I. Tokcshi, Sci. Inst. Hiroshima Univ. Ser. A 376107 (1973).
[8]A. Mishima, H. Tujii, and T. Okamoto, J. Phys. Soc. Jpn. **38**, 837 (1975).
[9]I. E. Dzyaloshinskiĭ, Zh. Eksp. Teor. Fiz. **47**, 336 (1964) [Sov. Phys. JETP **20**, 223 (1965)].
[10]N. V. Volkenstein, V. P. Dyakina, and V. E. Startsev, Phys Status Solidi **57**, 9 (1973).
[11]S. C. Keeton and T. L. Loucks, Phys. Rev. **168**, 672 (1968).
[12]D. W. Boys and S. Legvold, Phys. Rev. **174**, 174 (1968).
[13]A. R. Mackintoch, Phys. Lett. **4**, 140 (1963).
[14]G. K. White, Experimental Techniques in Low Temperature Physics, Oxford, 1958 (Russ. transl. Fizmatgiz, 1961, p. 331).
[15]N. V. Volkenshteĭn and V. P. Dyakina, Zh. Eksp. Teor. Fiz. **59**, 1160 (1970) [Sov. Phys. JETP **32**, 633 (1971)].
[16]P. G. De Gennes, J. Phys. (Paris) **23**, 510 (1962).
[17]A. J. Dekker, J. Appl. Phys. **36**, 906 (1965).
[18]T. Kasuja, Magnetism 11B, New York, Academic Press,, 1966, p. 215.
[19]S. Weinstein, R. S. Craig, and W. E. Wallace, J. Chem. Phys. **39**, 1449 (1963).
[20]H. Nagasawa and T. Sugawara, J. Phys. Soc. Jpn. **23**, 711 (1967).
[21]M. Darby and K. N. Taylor, Physics of Rare Earth Solids, Halsted, 1972 (Russ. transl. Mir, 1974, p. 170).
[22]J. M. Ziman, Electrons and Phonons, Oxford, 1960.
[23]K. P. Belov, R. Z. Levitin, S. A. Nikitin, and L. I. Solntseva, Zh. Eksp. Teor. Fiz. **54**, 384 (1968) [Sov. Phys. JETP **27**, 207 (1968)].

Translated by J. G. Adashko

Observation of the suppression of a nuclear reaction in a direct beam of γ quanta

G. V. Smirnov, N. A. Semioshkina, V. V. Sklyarevskiĭ, S. Kadechkova, and B. Shestak

I. V. Kurchatov Institute of Atomic Energy
(Submitted May 19, 1976)
Zh. Eksp. Teor. Fiz. **71**, 2214–2229 (December 1976)

The suppression of a nuclear reaction upon resonant interaction of γ quanta with a regular system of nuclei was observed in a direct beam of γ quanta passing through a perfect crystal. γ quanta of the Mössbauer transition in Fe^{57} nuclei and iron crystals enriched up to 85% by resonant Fe^{57} nuclei were utilized in the experiment. A consequence of the suppression of the reaction was a sharp increase in the transmittance of the crystal for resonant γ quanta in an angular range of 30″ in the neighborhood of the Bragg angle.

PACS numbers: 76.80.+y

INTRODUCTION

Previously unknown collective nuclear phenomena were predicted[1–3] on the basis of conservation of coherence during resonant nuclear scattering of Mössbauer γ quanta. Among the more striking effects in which an aggregate of nuclei behave as a single ensemble, one can single out the suppression of nuclear reactions (SNR) or the Kagan–Afanas'ev effect. In the example of this and other effects, Kagan and Afanas'ev showed that the nuclear parameters of the ensemble, such as the position of the resonant level, the lifetime of the excited state, the relationship between the partial widths of the nuclear levels, and so forth, may differ significantly from the corresponding parameters of the individual nucleus entering into the composition of the ensemble.

SNR should appear upon the interaction of resonant γ quanta with the nuclei in perfect crystals. Under these conditions the γ quanta are captured in a regular system of identical nuclei. The excitation which appears in such a system upon capture of an individual γ quantum cannot be associated with one or the other specific nucleus. In accordance with the quantum mechanical principle of superposition of states, it must pertain with a definite probability to each nucleus in the system and thus envelops the entire system as a whole. A collective excited state of the nuclear system appears.[2]

In virtue of the conservation of coherence during the lifetime of the collective state, the emission of a γ quantum upon decay of the collective state only takes place in certain directions. These directions are specified by the symmetry of the regular system of nuclei. In this connection it is essential that the probability for the emission of a quantum increases significantly in comparison with the probability for elastic decay of an isolated nucleus, whereas the probability for transfer of the excitation energy to a conversion electron (inelastic reaction channel) remains the same as before.

Upon fulfillment of the Bragg conditions for an incident γ quantum, elastic decay in an excited nuclear system can take place in two directions, as a consequence of which an abrupt rearrangement of the γ quantum state takes place on entrance into the crystal. A pair state appears which corresponds to the wave field representing a coherent superposition of two plane waves. Below, in connection with the propagation of this field in a crystal, the amplitude for the production of an excited nucleus will be comprised of two amplitudes. In a number of cases the resulting sum may turn out to be equal to zero, which will correspond to a discontinuation of the interaction between the quantum and the nuclei.

A strong predominance of the inelastic reaction channel is characteristic for the majority of Mössbauer transitions—the coefficient of internal conversion is much greater than unity. And although the elastic channel is a "weak" process of low probability in the case of a single nucleus, under the conditions considered above, when there is coherent amplification of elastic decay, this process may significantly alter the nature of the course of a nuclear reaction. Due to amplification of the elastic decay process, the pair state which does not interact with nuclei is formed earlier than it enters by virtue of the inelastic reaction channel, leading to destruction of the quantum. An anomalous transparency of crystals containing resonant nuclei should be observed as a consequence of suppression of the inelastic reaction channel.

SNR was investigated experimentally in crystals of tin by utilizing Mössbauer radiation of Sn^{119},[5,6,8] and in crystals of iron and α-FE_2O_3 hermatite by utilizing Mössbauer radiation of Fe^{57}.[4,7,9,10] The first experiments were performed on crystals containing small (natural for the isotopes Fe^{57} and Sn^{119}) concentrations of resonant nuclei. In these crystals the pair superposition state of the γ quantum was primarily formed due to Rayleigh electron scattering. SNR was first observed during investigation of the Mössbauer spectra of the Bragg reflection of γ quanta. At the resonant energy these spectra had a minimum caused by nuclear resonant absorption of the γ quanta. SNR revealed itself in that the depth of the minimum associated with scattering by a perfect crystal turned out to be substantially smaller than that associated with scattering on a mosaic crystal.[4,5]

SNR manifests itself more strikingly under the conditions for the passage of γ radiation through a perfect crystal. The first experiment of this kind was performed on a crystal of tin.[6] An integrated reduction of the nuclear absorption by approximately 1.5 times was observed in this experiment. In a different experiment[7] involving a crystal of iron under conditions of substantially improved angular resolution, it was observed that the nuclear transparency of the crystal increases sharply within an angular interval of 20" (the region associated with formation of the quantum's pair state) near the Bragg angle; in this connection the absorption of quanta by nuclei was reduced by 8.6 times.

Important progress in experimental investigations of SNR is related to the change to crystals which are saturated by resonant nuclei. Nuclear resonant scattering entered first and foremost into the formation of the quantum's pair state in these crystals—that is, collective nuclear phenomena played a decisive role in them.

The small light-force characteristic for the experiments under consideration in the sources utilized (10^{-7} to 10^{-8}) and the low intensity of the radiation sources[1)] themselves predetermine a big experimental complication associated with investigations of coherent phenomena. The difficulties increase substantially with the change to enriched crystals due to the enormous value of the resonant absorption cross section—it is almost two orders of magnitude larger than the cross section for the photoeffect. Therefore, first it would be convenient to achieve simpler versions of the experiments. As one of the first steps, a search was made for an integrated effect pertaining to the entire angular range in which the pair state of the γ quantum is formed. A wide incident beam was used, surely intersecting the entire range of interest to us. Under these conditions the investigation of the passage of quanta through a crystal can be done most effectively not for a direct beam, but for a beam which is deflected from the direct beam by twice the Bragg angle—the Laue diffracted beam. On the one hand this beam was equivalent to a direct beam with regard to the conditions for passage of quanta through the crystal and, on the other hand, it contained only quanta corresponding to the pair state in the crystal, i.e., it was free from background.

In the article involving a crystal of tin,[8] which contained 88% resonant nuclei, the energy dependence of the intensity of the Laue beam is compared with the usual Mössbauer spectrum for the absorption of γ quanta in this same crystal. Since the normal factor $\mu_r t$ for resonant nuclear absorption of quanta in the crystal is equal to 640, the absorption spectrum in the neighborhood of the resonance had the shape of a broad dip with a flat bottom. In contrast with this the spectrum for the Laue beam turned out to be more than two times narrower, which conclusively demonstrated the presence of SNR. Moreover, the spectrum possessed considerable asymmetry with respect to the resonance, which is also related to SNR and is due to interference between the nuclear and electron scattering associated with the formation of the pair state of a γ quantum in the crystal.

Thanks to the presence of hyperfine splitting of the nuclear levels, it was possible in the experiment on a crystal of hematite[9] (85% resonant nuclei) to essentially isolate the role of one of the polarizations in the interaction with nuclei. At the same time the conditions of the experiment were selected such that *a priori* SNR could exist only for γ quanta of this polarization. Analysis of the results of the measurements showed that for these quanta the dependence of the intensity of transmission through the crystal has a marked asymmetry in the neighborhood of the resonance, where the absorption factor was close to 200. It could be due only to the fact that the angular range, in which the pair state of a quantum in a crystal is formed, is abruptly altered due to the coherent addition of the nuclear resonant and electron scattering amplitudes, i.e., the presence of asymmetry appeared as evidence of the anomalous transmission of quanta through the crystal.

Finally, in the last experiment performed on a crystal of hematite, the Bragg direction for the incident quanta was chosen such that, as a consequence of the symmetry of the crystalline structure, the scattering by electrons

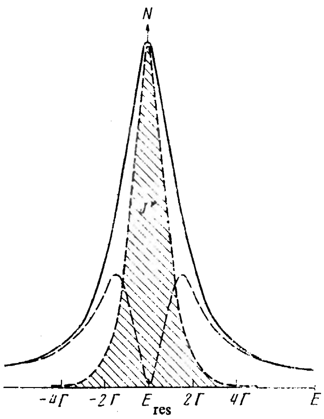

FIG. 1. Energy distribution of the γ quanta: solid line—in the radiation flux emitted by the source; dashed line—in the flux passing through the resonant filter; the shaded portion indicates the distribution of the quanta absorbed by the filter; Γ denotes the natural linewidth.

would be completely extinguished whereas the scattering by nuclei was preserved.[10]

Thus, a pair state was produced for the first time solely as a consequence of nuclear resonant interaction of the quanta. The obtained dependence of the Laue-beam intensity on the energy of the quanta had the form of broad maxima in the resonant energy region. In this experiment it was directly seen that an appreciable fraction of the quanta pass through the crystal at resonance and close to resonance, i.e., where the crystal is a very strong absorber. The relatively small dips in the background of the intensity maxima were related to residual absorption by nuclei on the scale of a few percent of the initial.

Although manifestations of SNR are found in all of the described experiments, until recently no experiment had been achieved in which the transmission of quanta through a strongly absorbing resonant medium by trans-illumination, i.e., in a direct beam, had been observed. Meanwhile, such a direct demonstration of the SNR effect has great theoretical and practical value. Furthermore, it should be noted that all of the recoilless quanta emitted by the source were utilized in the experiments considered in the investigation of SNR. However, it is well known that these quanta are distributed over an energy scale and therefore have different cross sections for absorption in the crystal. If the effective thickness of the crystal is large for a certain fraction of the quanta, it is medium or small for another fraction. Thus, a collection of different situations always occurred and the total effect was investigated. In this connection the role of the strongly absorbing component, which is the most interesting component in such experiments, could not be determined.

The goal of the present article was to achieve a direct experiment, but only for the strongly absorbing component of the γ beam.

EXPERIMENTAL TECHNIQUE

1. Nuclear-resonant filter

The problem of isolating the strongly absorbing component of the γ beam from the total flux of quanta was solved with the aid of a nuclear-resonant filter. A foil (2.9 μ thick) of polycrystalline iron, enriched up to 20% with the resonant isotope Fe^{57}, served as this filter. The energy distributions of the recoilless γ quanta are shown in Fig. 1: the energy distribution in the flux emitted by the Mössbauer source is denoted by the solid line and the distribution in the flux passing through the iron foil under nuclear resonance conditions is given by the dashed line. The latter curve was calculated with allowance for the fact that the nuclear absorption factor for quanta at exact resonance was equal to $\mu t = 4.5$ for the case under consideration. The shaded central position of the distribution refers to the quanta absorbed in the filter. It is obvious that the quanta belonging to this band are knocked out of the beam primarily because the cross section for absorption is maximal at the resonance and falls off rapidly on moving away from resonance. At the same time, for the chosen thickness of the filter the quanta existing under the wings of the distribution (~50% of the total number of recoilless quanta) pass through the filter without absorption.

The procedure of "cutting off" the wings and thereby isolating the effect associated with the strongly absorbing component of the distribution follows from the cited illustration. It is obvious that one should make two kinds of measurements: without the filter and with the filter, and then subtract the results pertaining to the first and second measurements.

2. Fe^{57} crystal. Growth and test for perfection

The central objective of the experiment was a crystal of Fe^{57} which should constitute a regular array of resonant nuclei. The problem was to be able to grow a crystal containing a small concentration of structural defects from a small amount of material (10 grams of iron containing 85% Fe^{57}) and to be able to prepare foils of thickness 20 to 50 μ without the introduction of dislocations during the fabrication process. The method of recrystalization with preliminary critical deformation of the polycrystalline sample was employed for growing the crystal.

An alloy of Fe + 1% Si was prepared in the first stage, and from it a rod was forged in the shape of a cylinder with a diameter of 4 mm. In order to obtain granules of small sizes, 0.2 to 0.5 mm, the rod was subjected to multiple rapid heating and cooling in the vicinity of the $\alpha-\gamma$ transition for the Fe + 1% Si alloy. After a critical three-percent deformation of the rod by stretching, its annealing at a temperature of 700 °C was carried out in a furnace having a temperature gradient of 200 °C/cm.[11] During the annealing process the rod was displaced in an axial direction with a velocity of 3 mm/hour. Ultimately several large crystals grew in the bulk of the rod. Thin sheets of 2 mm thickness, on the surface of which the (110) plane of the crystal emerged, were cut out of these granules by a method of electroerosion. Samples containing the smallest number of defects were chosen with the aid of x-ray topographic plotting of the surface of the sheet by the Berg–Barret method. The preparation of the foil was accomplished by a method for chemical polishing of planar samples[12] in a solution containing 5 ml of HF (50%), 80 ml of H_2O_2 (30%), and 15 ml of

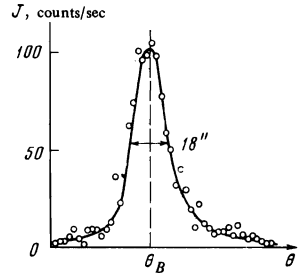

FIG. 2. Curve of the Laue reflection of MoK_{α_1} x-rays from the (1$\bar{1}$0) plane of a crystal of Fe^{57}.

H_2O.[13] During the process the accuracy of the thickness was monitored with the aid of an optical microscope. The final thickness amounted to 30 μ; it was determined from the absorption of Ag K_{α_1} x-rays.

The shape of the sample turned out to be incorrect; the transverse dimensions lay in the range from 3 to 4 mm. In connection with fastening the sample to a holder for subsequent investigations, measures were taken in order to reduce the elastic stresses in it to a minimum. For this purpose a small piece of thin cotton fabric was placed on a plane glass sheet of thickness 100 μ, and was then impregnated with a drop of thick silicone oil. The sample was placed on this soft backing. After wetting of the sample by the oil, the cohesion turned out to be sufficient to maintain it in the same vertical position during the course of all measurements.

The degree of the crystal's perfection played a decisive role in the feasibility of performing the experiment. Therefore, special attention was paid to verification of the degree of the crystal's perfection. It was determined by various methods.

First, a topographical scanning was made by the Lang method, showing that the crystal contains several blocks of area 2 to 4 mm^2. The average density of dislocations inside the blocks amounted to 10^3 to 10^4 cm^{-2}. Rocking curves for several segments inside the blocks were then measured on a two-crystal x-ray spectrometer (quartz–iron, Bragg–Laue geometry, (10$\bar{1}$0) and (1$\bar{1}$0) reflections). Characteristic Mo K_{α_1} radiation was used. The beam had a cross section 0.1×1 mm. The best segment of the crystal was thus selected. A typical rocking curve is shown in Fig. 2. Its width at half maximum is 18″.

Final verification of the chosen segment was made under operating conditions by using 14.4 keV γ rays on a two-crystal spectrometer (germanium–iron, Bragg–Laue geometry, (220) and (1$\bar{1}$0) reflections). The integrated intensity of the Laue reflection was measured for Rayleigh electron scattering of the γ rays. The ratio of the measured intensity to that calculated under the assumption of an ideal iron crystal turned out to be equal to 0.91 ± 0.05. The result indicates a rather high degree of perfection in the determined segment of the crystal.

3. Participation of different polarizations in SNR. The domain structure of Fe^{57} crystal.

The condition for the vanishing of the amplitude for the production of an excited nucleus for the pair state of a γ quantum in a crystal depends, in particular, on the multipole order of the nuclear transition and is therefore related to the polarization of the incident quanta. Theory indicates that in the case of magnetic dipole transitions, which occur in Fe^{57} nuclei (Mössbauer transitions), total suppression of the nuclear reaction can be achieved only for quanta of π-polarization. The magnetic field vector in the corresponding wave oscillates perpendicular to the scattering plane. Residual absorption by nuclei always exists for quanta of σ-polarization, the degree of which depends on the scattering angle. It is quite clear that π-polarized quanta are of most interest in investigations of SNR.

When hyperfine splitting of the nuclear levels is produced it is possible to interpret selectively the beam components of different polarization and, in particular, to distinguish the role of one of the polarizations in the interaction with nuclei. This can be done because when individual nuclear transitions are excited the interaction cross section depends strongly on the orientation of the field at the nucleus (in the considered case of a magnetic field) relative to the planes of polarization. It is obvious that knowledge of the domain structure of the crystal would be necessary to identify the interactions of quanta of various polarizations with the nuclei in our crystal. The structure was determined from the properties of the azimuthal dependence of the diffraction intensities for Mössbauer beams.[14] The Mössbauer spectra measured for two different azimuthal positions of the crystal associated with the same Bragg reflection (110) are compared in Fig. 3. The upper spectrum was measured under conditions when the crystallographic axis [011] was perpendicular to the scattering plane, and the lower spectrum—when the same axis lay in the scattering plane. On going from the first position to the second, as is obvious from the figure, the lines corresponding to transitions with change of the magnetic quantum number $\Delta m=0$ almost completely disappeared. This indicates that in the crystal the magnetizations of the various regions are primarily oriented along the

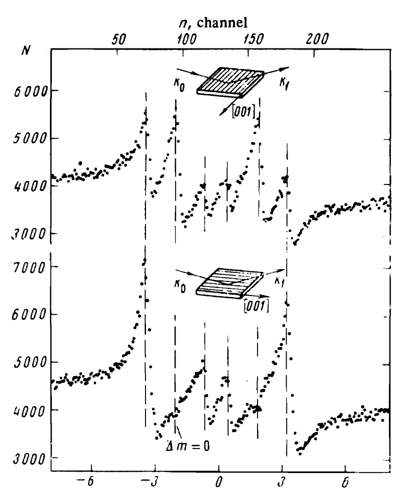

FIG. 3. Mössbauer spectra for the Bragg reflection of 14.4-keV radiation from the (110) plane of an Fe^{57} crystal for two different azimuthal positions of the crystal.

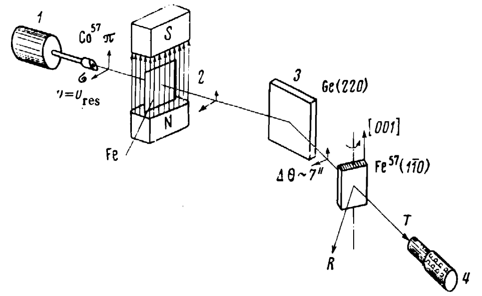

FIG. 4. Diagram of the experimental setup.

[001] direction. In fact, the polarization factor in the amplitude for nuclear scattering of γ quanta for $\Delta m = 0$ transitions is given by $P = (\mathbf{h}_0 \cdot \mathbf{n})(\mathbf{h}_1 \cdot \mathbf{n})$, where $\mathbf{h}_0$, $\mathbf{h}_1$, and $\mathbf{n}$ are unit vectors in the directions of the magnetic field intensities in the incident and scattered waves and the direction of the field at the nucleus, respectively. If $\mathbf{n}$ were parallel to the [001] axis, the polarization factor would have the value $P^{\pi} = 1, P^{\sigma} = 0$ in the first case and $P^{\pi} = 0, P^{\sigma} = 3.5 \times 10^{-2}$ in the second case, in agreement with the observed picture. The obtained information about the magnetization of the crystal is of an integrated nature since the entire surface of the crystal was irradiated in the described measurements.

The observed regularity in the domain structure of the crystal allowed us to obtain experimental conditions such that only the π-polarized quanta from the beam of γ quanta incident on the crystal interacted with the nuclei. In order to achieve this it was sufficient to tune to excitation of the nuclear transition $-\frac{1}{2} \to -\frac{1}{2}$ with zero change of the magnetic quantum number.

By virtue of the arguments cited in this section, it would be necessary to assign a second function—that of a polarizer—to the resonant filter that isolates the strongly absorbing component from the beam, so as to make this component also π-polarized. For this purpose the foil serving as the filter was magnetized to saturation in the vertical field of a constant magnet. We can henceforth call this filter a "shaper-polarizer," this name taking its total effect into account.

4. The experimental setup

The basic part of the experimental setup is shown schematically in Fig. 4. It contains the following elements: an electromagnetic vibrator (1), a source of γ quanta, the "shaper-polarizer" (2), a collimator (3), the object of investigation—a Fe^{57} crystal, and a scintillation detector (4).

The 14.4-keV resonant quanta of Fe^{57} were emitted during the decay of Co^{57} nuclei dissolved in a chromium matrix. The activity of the source was equal to 500 mCi. The active spot had the shape of a circle of diameter 4 mm. The linewidth of the source at half maximum amounted to three times the natural width of the nuclear level. The recoilless radiation factor f_s was measured with a black absorber and turned out to be equal to 0.54. In these measurements the 14.4-keV beam was separated from the remaining beams by means of (001) Bragg reflection from the surface of a pyrolytic graphite crystal.

The source was inclined 25° to the direction of the utilized rays so that the average width of the beam of rays which were parallel to this direction was equal to 1.2 mm in a horizontal plane. Tuning to a specific nuclear transition in the Fe^{57} nuclei could be accomplished with the aid of the electromagnetic vibrator operating in the regime of constant velocities.

After their passage through the "shaper-polarizer," the γ rays were incident on a germanium crystal. Separation and collimation of the 14.4-keV γ quanta was carried out by (220) Bragg reflection from this crystal. The divergence of the beam past the Ge amounted to seven angular seconds.[2)] Such a small angular divergence was necessary in order that all of the quanta could subsequently participate in SNR. The beam of quanta reflected from the Ge was incident on a monocrystal of Fe^{57} in which the effect of suppression was investigated. The crystal was cut out and oriented such that the $(1\bar{1}0)$ planes were perpendicular to the incoming and outgoing surfaces of the crystal, and the [001] axis was directed along the vertical. Alignment of the crystal was accomplished with the aid of an x-ray spectrometer.

A scintillation counter based on an FÉU-35A photomultiplier served as the detector. The detection unit was made suitable for operation under conditions corresponding to a very low level of useful counting. In order to lower the background, the photomultiplier was matched with respect to the level of intrinsic noise; low-noise amplifiers were used; the NaI(Tl) scintillation crystals were given the minimum (but adequate for the effective detection of coherently scattered beams) dimensions—$10 \times 5 \times 0.1$ mm; the scintillation material was selected for its resolving power (in the neighborhood of 14.4 keV the resolution of the detector amounted to 25%). All of the enumerated measures enabled us to obtain a background level of ~0.01 count/sec under operating conditions.

The intensity was recorded as a function of the different variables (scattering angles, energies of the quanta, and so forth) with the aid of an NTA-512B multichannel analyzer. Special measures with regard to stabilization of the power supply for the electronic equipment in the system for the detection of quanta and in the system for control of the vibrator allowed us to carry out long-term measurements (on the order of several hundred hours).

MEASUREMENT OF THE INTENSITY OF γ QUANTA PASSING THROUGH THE CRYSTAL UNDER THE CONDITIONS FOR SNR

The suppression of nuclear reactions was investigated on the basis of measurements in a beam of γ quanta passing through the iron crystal. The pair superposition state of a γ quantum can be formed in a crystal in a comparatively narrow angular interval in the neighborhood of the Bragg angle. The magnitude of this interval was determined by the amplitude of the resonant interaction of the quanta with nuclei, and in the case under con-

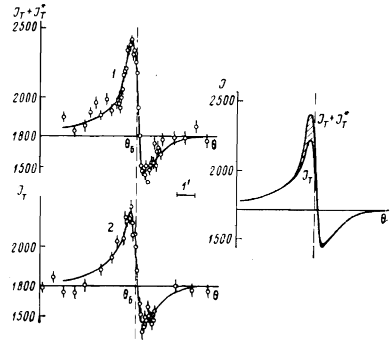

FIG. 5. The angular dependences for transmission of γ quanta by an Fe^{57} crystal in the vicinity of $\theta = \theta_B$ for $(1\bar{1}0)$ planes when the energy of the γ quanta is equal to the energy of the nuclear transition $-\frac{1}{2} \to -\frac{1}{2}$: curve 1—in the absence of the polarizer-shaper, 2—in the presence of the polarizer-shaper.

sideration it was on the order of ten angular seconds.

In the basic measurements a highly collimated (7") γ beam was directed onto the crystal near the Bragg angle—12°21' with respect to the $(1\bar{1}0)$ crystallographic planes. The detector was set up in the trajectory of the direct beam. The intensity of the γ quanta passing through the crystal was measured as a function of the angle of incidence of the photons on the crystal. Using the commonly accepted terminology, we shall call this function the rocking curve.

In these measurements the crystal was rotated with a small angular velocity corresponding to a period of 19.4 years. This slow motion was necessitated by the very low intensity of the γ source. A multichannel analyzer, operating in the regime of time scanning with measurement duration of 1000 sec in a single channel, constituted the information storage. During the time of measurement of a one point, the crystal was rotated through an angle of 2.15". The total range of measurements in the neighborhood of the Bragg angle amounted to 4'. Passage through this interval was repeated many times in order to accumulate the necessary statistics. The crystal was returned to its initial position at the beginning of each passage, and the accuracy of setting the initial position was no worse than 5". Measurements were made at the points $\theta_B \pm 1°$ in order to determine intensity levels far from the Bragg angle.

The resonant interaction of the γ quanta with the nuclei in the crystal was switched on periodically at a frequency of 2 Hz for a time of 200 sec (the resonant value of the velocity of the γ source, corresponding to the nuclear transition $-\frac{1}{2} \to -\frac{1}{2}$, was determined in preliminary calibration measurements). The time intervals during which nuclear γ resonance occurred were separated, and pulses of the appropriate duration were applied to the input of the analyzer, opening it only in these periods. The net time of detection of the quanta amounted to 40% of the total time.

Rocking curves of two types were measured: with the "shaper-polarizer" and without it. In order to normalize the curves to the same flux of incident γ quanta, the measurement time with the "shaper" was increased by 14% in comparison with the measurement time without the "shaper" in order to compensate for photoelectric absorption of quanta in an iron foil of 2.9 μ thickness. In addition, since the measurements as a whole continued during the course of several months, it was necessary to obviate the effects due to decay of the source. To this end short series were run—over a few days—involving measurements with the "shaper" and without it, and these series were alternated.

The obtained rocking curves are shown in Fig. 5. The solid lines are drawn through the experimental points.

DISCUSSION OF THE RESULTS

Let us represent the beam incident on the crystal in the form of two components: J_0 and J_0^*. Let J_0^* contain only π-polarized quanta with energies near the resonance, that is, those quanta which have been isolated by the "shaper-polarizer." We shall call this component nuclearly active. Then J_0 contains first, π-polarized quanta with energies under the wings of the Lorentzian distribution; second, π-polarized quanta emitted by the source with recoil, and third, σ-polarized quanta. The upper curve 1 in Fig. 5 is measured in the absence of the "shaper-polarizer," when both of the components under consideration were incident on the crystal. The lower curve 2 was measured with the polarizer, which cut off the path of the nuclearly-active γ quanta.

The contribution of the component J_0^* was determined by the following factors: by the factor 0.54 associated with the recoilless radiation from the source, by the fraction 0.48 of π-polarized quanta in the beam reflected from the germanium crystal, and finally by the fraction 0.4 of quanta which are resonantly absorbed in the "shaper" from the energy distribution of the recoilless π-polarized quanta. Thus, 10.4% of the incident beam was contained in the nuclearly active component. Therefore, the general form of the rocking curves was primarily determined by the component J_0. Its behavior was due primarily to the scattering and absorption by the electrons and, since the crystal was of intermediate thickness relative to electron absorption (the absorption factor $\mu_e t = 1.67$), the dispersion shape of the rocking curves[15] which is characteristic for this case was obtained.

Both curves were effectively measured during the course of the same time period and, as is evident from the figure, appeared independently of the presence of the polarizer at the same level of intensity far away from the Bragg angle. Such a result becomes clear if one considers the dependence of the transmission of Mössbauer beams on the thickness of the resonant absorber (Fig. 6). Outside of the Bragg angle the crystal behaves as an ordinary absorber having an absorption factor $\mu_p t = 65$ at resonance. As is seen from the figure, in this region the dependence on the absorber's thickness is still so weak that the addition of an additional absorber with absorption factor $\mu t = 4.5$, which the polarizer is, essentially does not alter the intensity of the passing quanta.

The matching of curves 1 and 2 with respect to the in-

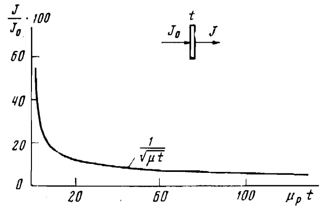

FIG. 6. Dependence of the transmission of Mössbauer radiation through a resonant absorber on the thickness of the absorber.

tensity level at the edges—see the right side of Fig. 5—indicates that a discrepancy exists between them only in the vicinity of the Bragg angle. Furthermore, the fact that an absorber which is 14.5 times thinner with respect to nuclear absorption than the crystal can noticeably change the intensity indicates that the absorption capability of the crystal has been sharply reduced at the Bragg position (see Fig. 6): μt has been reduced to a range of effective values of the order of unity, where the intensity changes sharply with thickness.

By subtracting curve 2 from curve 1, we obtain the plot of the transmission of the nuclearly active component through the crystal—Fig. 7, curve J_T^*. It has the shape of a sharp peak of width 36". The dashed lines indicate the error limits. Far away from the Bragg position, the crystal can be regarded as a black absorber: the probability that a nuclearly-active quantum will pass through the crystal is smaller than exp(−10). The sharp increase in the crystal's transmission for nuclearly active quanta, which is obtained in a narrow angular range, is convincing evidence that the mechanism for the absorption of γ quanta is strongly suppressed.

As mentioned in the Introduction, the wave field corresponding to a pair state of the γ quantum in the crystal generates two beams at the exit from the crystal—the direct beam and a beam which is deflected from the direct beam by twice the Bragg angle. Measurements similar to the described ones were made of the rocking curves in the deflected beam in order to obtain the total intensity of the γ quanta anomalously passing through the crystal. The curve pertaining to the nuclearly-active component J_R^* is shown in Fig. 7.

In agreement with the predictions of the theory, if the Bragg condition is exactly fulfilled for the incident quanta, only half of the beam can pass through the crystal without absorption. For the second half, a pair state is realized in which quanta are absorbed by the nuclei at double the usual rate. Thus, half of the quanta are destroyed immediately on entrance into the crystal. To assess the scale of the suppression effect, it is expedient to normalize the intensity of the passing γ quanta to that part of the incident beam which can penetrate anomalously. Upon total suppression of the absorption processes, $K=(J_T^*+J_R^*)/(0.5J_0^*)$ should be equal to unity. We shall call the quantity K the transmission coefficient. Let us indicate two factors which inevitably decrease K under actual conditions.

1. The divergence of a real beam, leading to a deviation from the Bragg condition.

2. The residual absorption by electrons, due to the thermal vibrations of the atoms.

The maximum value of the transmission coefficient for the nuclearly-active component, which was obtained from the measurements, lay within the limits 0.56 ± 0.18. The experimental values $J_{T\max}^*=260$ and $J_{R\max}^*=140$ were taken for the calculation of K, and the value for the photon flux incident on the crystal was taken to be $J_0+J_0^*=13\,800$. All quantities refer to a total measurement time of 3.2×10^4 sec at one angular point. As was indicated above, the contribution of the nuclearly active component J_0^* to the total flux amounted to 10.4%. If one assumes that a simple exponential law is valid for the entire group of nuclearly active quanta, then on the basis of the value of K one can obtain effective values for the residual absorption factor: from $\mu t=0.58-0.28$ and up to $\mu t=0.58+0.38$. The residual nuclear absorption and the residual electron absorption obviously also contribute to this quantity.

Let us turn our attention to questions concerning a comparison of the experimental results with the theoretical predictions. Certain formulas from[16], which are cited in the form (KA-No.), will be utilized below. All of the calculations were carried out under the assumption that the iron crystal is ideal.

In the case under consideration the solution of the dynamic diffraction problem gives expression (KA-37) for the intensity of the electric field at a depth t inside the crystal. In our specific case the complex amplitudes $\tilde g_{\alpha\beta}$ (KA-50) for the scattering of a γ quantum by a unit cell of the crystal have the following values:

$$\begin{aligned}\tilde g_{00}{}^\pi=\tilde g_{11}{}^\pi&=-0.36+0.024i-\frac{v-i}{v^2+1},\\ \tilde g_{01}{}^\pi=\tilde g_{10}{}^\pi&=-0.313+0.021i-\frac{v-i}{v^2+1},\end{aligned}\qquad(1)$$

the first two terms represent the interaction with electrons, the last term gives the nuclear part of the amplitude (v indicates the deviation from resonance in units of the half-width $\Gamma/2$ of the nuclear level);

For σ-polarized quanta

$$\tilde g_{00}{}^\sigma=\tilde g_{11}{}^\sigma=-0.36+0.024i.\ \tilde g_{01}{}^\sigma=\tilde g_{10}{}^\sigma=-0.347-0.023i,\qquad(2)$$

the σ- polarized component only interacts with electrons.

The cited quantities $\tilde g_{\alpha\beta}$ are expressed in units of the resonant value (KA-31) of the nuclear amplitude:

$$|g_{00}|=300\cdot10^{-7},$$

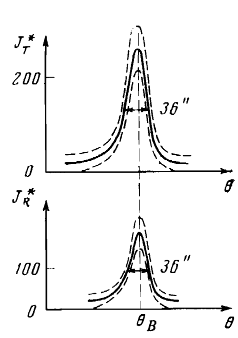

FIG. 7. Angular dependences of the transmission of the nuclearly-active component of the incident γ beam through an Fe^{57} crystal in the neighborhood of the Bragg angle.

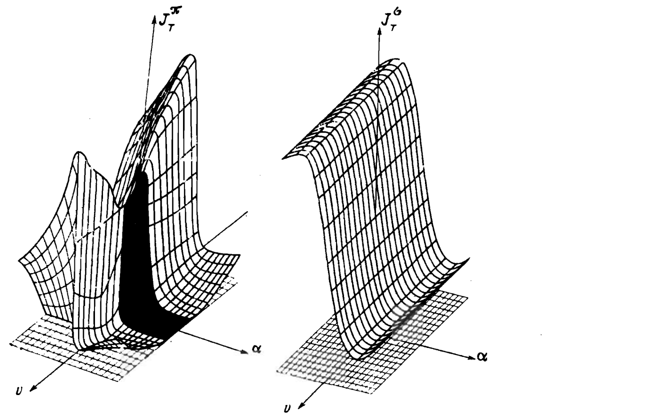

FIG. 8. Theoretical surfaces for the transmission of the π- and σ-polarized components of a γ beam through a crystal of Fe^{57} in the vicinity of the Bragg angle and near the resonance energy.

in the calculation of the latter the expression for the polarization factor in the case of magnetic splitting of the nuclear levels is used, and the broadening of the resonance lines in the crystal due to silicon impurities[17] has been taken into consideration.

In the case under consideration the quantities (KA-38) have the form

$$\varepsilon_0^{(1,2)}={}^1/_2\tilde{g}_{00}-{}^1/_4\alpha\mp{}^1/_4(\alpha^2+4\tilde{g}_{01}{}^2)^{1/2},$$

α characterizes the deviation from the Bragg angle; $\alpha=1$ corresponds to an angular interval of $7.14''$.

At the exit from the crystal, the intensity of γ photon flux in the direct beam is given by

$$J_T(\alpha,v)=|\mathbf{E}(\alpha,v)|^2,$$

where $\mathbf{E}$ denotes the total electric field intensity for the components propagating in the direction of the direct beam. Using the corresponding part of Eq. (KA-37), we obtain

$$J_T(\alpha,v)=\frac{1}{4}I_0\left\{\left|\frac{2\varepsilon_0^{(2)}-\tilde{g}_{00}}{\varepsilon_0^{(2)}-\varepsilon_0^{(1)}}\right|^2\exp\{-2\varkappa\,\mathrm{Im}\,\varepsilon_0^{(1)}t'\}\right.$$

$$\left.+\left|\frac{2\varepsilon_0^{(1)}-\tilde{g}_{00}}{\varepsilon_0^{(2)}-\varepsilon_0^{(1)}}\right|^2\exp\{-2\varkappa\,\mathrm{Im}\,\varepsilon_0^{(2)}t'\}\right\},$$

where t' denotes the thickness of the crystal in the direction of the direct beam. A small term reflecting the interference between the weakly absorbing and strongly absorbing components of the field has not been taken into consideration in the cited expression for the intensity. Total suppression of the absorption corresponds to a vanishing of the imaginary part of ε_0. The first term in the sum gives the intensity of the component of the wave field which is weakly absorbed in the crystal: exactly at the Bragg position $\alpha=0$ and for the resonance energy $v=0$ we have $\mathrm{Im}\varepsilon^{(1)}=0.0015$; the second term refers to the strongly absorbed component: for the same values of α and v we have $\mathrm{Im}\varepsilon_0^{(2)}=1.02$. For comparison one can cite the values of these quantities under conditions for the ordinary passage of γ quanta through a crystal, i.e., far from the Bragg angle: at the resonance $\mathrm{Im}\varepsilon_0^{(1)}=\mathrm{Im}\varepsilon_0^{(2)}=0.51$ and away from resonance $\mathrm{Im}\varepsilon_0^{(1)}=\mathrm{Im}\varepsilon_0^{(2)}=0.012$; in the last case one photoelectric absorption occurs.

It is important to note that for $\alpha=0$ and $v=0$ the residual absorption is only due to the photoelectric effect, whereas the nuclear absorption is completely suppressed. In fact, $\mathrm{Im}\varepsilon_0^{(1)}=(1/2)\mathrm{Im}(\tilde{g}_{00}-\tilde{g}_{01})$ and the difference inside the brackets is determined by the difference between the electronic parts of the amplitudes (1).

Physically such a situation is related to partial violation of coherence in the scattering of γ quanta by electrons, which is due to thermal vibrations of the atoms in the crystal. It is typical for the Bormann effect. Complete independence of the effect of the thermal vibrations in the crystal is a unique property of the suppression effect. In virtue of the extreme narrowness of the nuclear resonance, vibrations in the crystal do not lead to destruction of the coherence in nuclear scattering of quanta, and therefore the effect is completely undisrupted (more details are given in[1]).

The surfaces J_T^π and J_T^σ calculated for a crystal of Fe^{57} are shown in Fig. 8 to relative scale. They illustrate transmission of the π- and σ-polarized components of the γ beam through a crystal. The surfaces differ markedly in the vicinity of the resonant velocity and they merge in peripheral regions. The behavior of γ quanta belonging to the component J_0 of the incident beam is described by the surface J_T^σ and that part of the surface J_T^π which refers to the edge regions with respect to the v axis. As is evident from the figure, the cross sections of the indicated surfaces for $v=\mathrm{const}$ have a striking dispersion shape. The behavior of the nuclearly-active component J_0^* is described by the part of the surface J_T^π which is darkened in Fig. 8. The measured dependences of the intensity should be similar in shape to the cross sections for the surfaces of transmission, since an appreciable fraction of the γ quanta in the beam incident on the crystal were concentrated around definite values of energy and angle, which was also observed in the experiment.

The difference between the experimental rocking curves 1 and 2 (Fig. 5) corresponded to the cross section of the surface J_T^π in a narrow energy interval in the neighborhood of $v=0$.

Peak values of the intensities of the nuclearly-active quanta passing through the crystal in the direct and reflected beams J_T^* and J_R^* were utilized for comparison with theory. The corresponding intensities predicted by the theory were obtained by numerical calculation of the integrals

$$\int_\alpha\int_v J_T{}^\pi(\alpha,v)R'(\alpha,v)\,d\alpha\,dv,$$

$$\int_\alpha\int_v J_R{}^\pi(\alpha,v)R'(\alpha,v)\,d\alpha\,dv;$$

$J_R^\pi(\alpha,v)$ is the surface, describing the transmission of π-polarized γ quanta which enter the deflected beam after

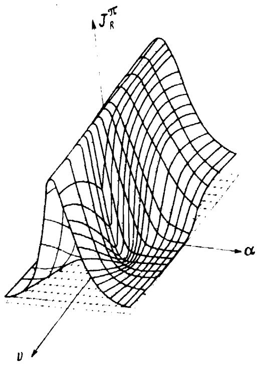

FIG. 9. Theoretical surface for Laue reflection of the π-polarized component of the beam in the vicinity of the Bragg angle and near the resonance energy.

TABLE I.

Quantity	Experiment	Theory
J_T^*/J_0^*	0.17±0.06	0.125
J_R^*/J_0^*	0.11±0.03	0.107
$K=(J_T^*+J_R^*)/0,5J_0^*$	0.56±0.18	0.464
$(\mu t)_{\text{residual}}$	$0.58^{-0.28}_{+0.38}$	0.77

the crystal; it was also calculated on the basis of Eq. (KA-37) and is shown in Fig. 9; $R^*(\alpha, v)$ is the distribution function of the nuclearly-active quanta in the plane (α, v). The cross section of this function with respect to α has the form shown in Fig. 1 (the shaded region); the cross section with respect to v was assumed to be approximately rectangular with a width of 7.0" (width of the Darwin stage for Bragg (220) reflection of 14.4-keV γ quanta from germanium).

The values obtained on the basis of measurements and calculations are cited in Table I.

As is clear from the table, the value for the transmission coefficient K predicted by the theory agrees with the experimental value within the limits of accuracy of the measurements of this quantity. The values for the effective residual absorption factor are obtained from the assumption that $K=\exp(-\mu t)_{\text{residual}}$.

Under the conditions for normal absorption of γ quanta, the effective thickness of the crystal for the nuclearly active component turns out to be very large—the average absorption factor for this group of quanta turns out to be equal to 41. In order to estimate the scale of the suppression, it is necessary to compare this value with the residual absorption factor. Recognizing that about one-third of the residual factor is due to electron absorption, one can assert that the nuclear absorption for a beam of quanta having a divergence of 7" was suppressed by approximately one hundred times. The mean free path of the γ quanta in the crystal obviously increased just as many times.

Thus, the possibility of a radical weakening of a nuclear reaction in matter has been demonstrated in the present work.

The authors are deeply indebted to Yu. Kagan and A. M. Afanas'ev for helpful discussions, to K. P. Aleshin, M. A. Volkov, and I. B. Filippov for a great deal of technical assistance, to V. V. Mostovom for assistance in the work, and to Ya. Bradler and M. Poltsarova for carrying out x-ray topographic investigations of the samples.

1)The intensity of traditional sources of Mössbauer radiation is limited and within the limits of 10^4 to 10^5 times smaller than the intensity of conventional sources of x-rays.

2)The rocking curve measured in the γ beam for a pair of germanium crystals in the Bragg–Bragg-(220)-reflection geometry had a halfwidth of 9.2" (dispersion is absent for Mössbauer radiation).

[1]A. M. Afanas'ev and Yu. Kagan, Zh. Eksp. Teor. Fiz. **48**, 327 (1965) [Sov. Phys. JETP **21**, 215 (1965)].

[2]A. M. Afanas'ev and Yu. Kagan, Pis'ma Zh. Eksp. Teor. Fiz. **2**, 130 (1965) [JETP Lett. **2**, 81 (1965)].

[3]Yu. Kagan and A. M. Afanas'ev, Zh. Eksp. Teor. Fiz. **50**, 271 (1966) [Sov. Phys. JETP **23**, 178 (1966)].

[4]V. V. Sklyarevskiĭ, G. V. Smirnov, A. N. Artem'ev, B. Sestak, and S. Kadeckova, Pis'ma Zh. Eksp. Teor. Fiz. **8**, 295 (1968) [JETP Lett. **8**, 181 (1968)].

[5]V. K. Voĭtovetskiĭ, I. L. Korsunskiĭ, and Yu. F. Pazhin, Pis'ma Zh. Eksp. Teor. Fiz. **8**, 563 (1968) [JETP Lett. **8**, 343 (1968)].

[6]V. K. Voĭtovetskiĭ, I. L. Korsunskiĭ, and Yu. F. Pazhin, Pis'ma Zh. Eksp. Teor. Fiz. **11**, 531 (1970) [JETP Lett. **8**, 376 (1968)].

[7]V. V. Sklyarevskiĭ, G. V. Smirnov, A. N. Artem'ev, R. M. Mirzababaev, B. Sestak, and S. Kadeckova, Pis'ma Zh. Eksp. Teor. Fiz. **11**, 531 (1970) [JETP Lett. **11**, 363 (1970)].

[8]V. K. Voitovetskiĭ, I. L. Korsunskii, A. I. Novikov, and Yu. F. Pazhin, Pis'ma Zh. Eksp. Teor. Fiz. **11**, 149 (1970) [JETP Lett. **11**, 91 (1970)].

[9]G. V. Smirnov, V. V. Sklyarevskiĭ, and A. N. Artem'ev, Pis'ma Zh. Eksp. Teor. Fiz. **11**, 579 (1970) [JETP Lett. **11**, 400 (1970)].

[10]V. V. Sklyarevskiĭ, G. V. Smirnov, A. N. Artem'ev, R. M. Mirzababaev, and E. P. Stepanov, Zh. Eksp. Teor. Fiz. **64**, 934 (1973) [Sov. Phys. JETP **37**, 474 (1973)].

[11]S. Kadeckova and B. Sestak, Kristall und Technik **2**, 191 (1967).

[12]F. W. Young and T. R. Wilson, Rev. Sci. Instrum. 32, 559 (1961).

[13]B. Sestak and S. Kadeckova, Phys. Status Solidi **16**, 89 (1966).

[14]R. M. Mirzababaev, V. V. Sklyarevskiĭ, and G. V. Smirnov, Phys. Lett. **A41**, 349 (1972).

[15]B. W. Batterman and H. Cole, Rev. Mod. Phys. **36**, 681 (1964).

[16]Yu. Kagan and A. M. Afanas'ev, in Mössbauer Spectroscopy and Its Applications, IAEA, Vienna, 1972, p. 143.

[17]M. B. Stearns, J. Appl. Phys. **36**, 913 (1965).

Translated by H. H. Nickle