Experimental study of the time evolution of the decay of Bragg modes of the collective nuclear excitations in the crystal

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The time evolution of the response of the collective nuclear states in a crystal has been studied experimentally for the first time. The collective nuclear states were excited selectively by a collimated γ-ray beam in the vicinity of the Bragg angle. When the Bragg angle was set in the exact position, the characteristic response time of the nuclear excitations decreased by a factor of ≈ 6 in comparison with the response time of a single nucleus.

Smirnov *et al.*[1] have shown experimentally that excited nuclear states produced in a crystal under conditions of resonant diffraction of γ rays decay more rapidly than those produced due to incoherent scattering. The accelerated decay of the Bragg modes of the collective nuclear excitations was predicted by Trammell[2] and Afanas'ev and Kagan[3] and theoretically studied in detail by Kagan *et al.*[4] Evidence of the presence of this effect was detected experimentally by Chechin *et al.*[5]

The experiment by Smirnov *et al.*[1] was carried out under conditions in which the nuclei were excited by a strongly divergent γ-ray beam, so that nearly all Bragg modes of the collective nuclear states, each of which had its particular temporal characteristic, were excited. Our goal in this study was to analyze, for the first time, the acceleration process itself, i.e., to obtain the temporal characteristic of the decay as a function of the angle at which a γ ray strikes the crystal near the Bragg angle. For this purpose we had to selectively excite various Bragg modes and to measure the time evolution of their decay. The principal results of this study were reported elsewhere.[6]

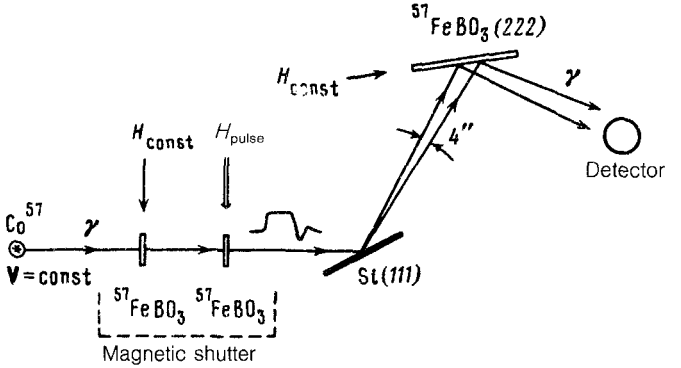

FIG. 1. Optical arrangement of the experiment in a double-crystal coherent-scattering geometry. Si(111) $\times$ $^{57}FeBO_3$(222).

The optical arrangement of the experiment is shown in Fig. 1. The Mössbauer radiation of 14.4-keV ^{57}Fe nuclei the activity of the ^{57}Co(Cr) source is 10^{10} Bq and the line width of the source is $\Gamma_s = 2.5\Gamma_n$, where Γ_n is the natural width of the 14.4-keV level is collimated to a beam divergence of 4″ by means of Bragg reflection from the (111) plane of a Si crystal. The collimated beam is aimed at a $^{57}FeBO_3$ crystal to be studied[7] (which was enriched to a 95% concentration of the isotope ^{57}Fe). The nearly perfect crystal is bent only slightly: 2″ over a 10-mm length. The x-ray topogram of the crystal is shown in Refs. 7 and 8. A $^{57}FeBO_3$ crystal is oriented with respect to the collimated γ-ray beam at angles close to the Bragg angle $\theta_B = 10.2°$, which corresponds to the nuclear Bragg reflection from the (222) plane.[1,9] The Mössbauer radiation is tuned to a resonance $\Delta m = 0$ in $^{57}FeBO_3$. The crystal is in the single-domain state when a static magnetic field is applied in the plane of the crystal and in the scattering plane. Under these conditions only the π-polarized component of γ radiation interacts with the resonance. The coherently scattered γ radiation is detected by a NaI (Tl) scintillation detector. The signal from the detector is sent to a spectrometric channel,[1,10] in which the time evolution of the diffraction of Mössbauer radiation is measured. The resolving time of the system is 6 ns.

To specify the origin of the time scale, we used as the active elements a resonant magnetic shutter with $^{57}FeBO_3$ crystals,[1,10] which opened rapidly (in a time of $\leqslant$10 ns) to pass through the γ-ray beam and then closed after 720 ns (Fig. 2a).

The time evolution of coherent nuclear scattering was measured over an angular interval of $\pm$ 10″ near θ_B. We compiled a two-dimensional set of data $I(\tau, \theta - \theta_B)$, which constitutes the intensity of resonant coherent scattering of γ rays as a function of two parameters: $\theta - \theta_B$, the relative angle of incidence of γ rays on the crystal and τ, the time delay in the emission of a γ ray from the crystal relative to the time of arrival of the leading edge of an exciting pulse.

In addition to determining the behavior of coherent scattering of γ rays, we have also measured the temporal behavior of incoherent scattering, which should characterize the decay of a single nucleus, in order to compare it with the decay of the collective excited state. For this purpose, we have measured the time evolution of the emission of conversion electrons. The small effective depth of the yield of 7.3-keV electrons (1000

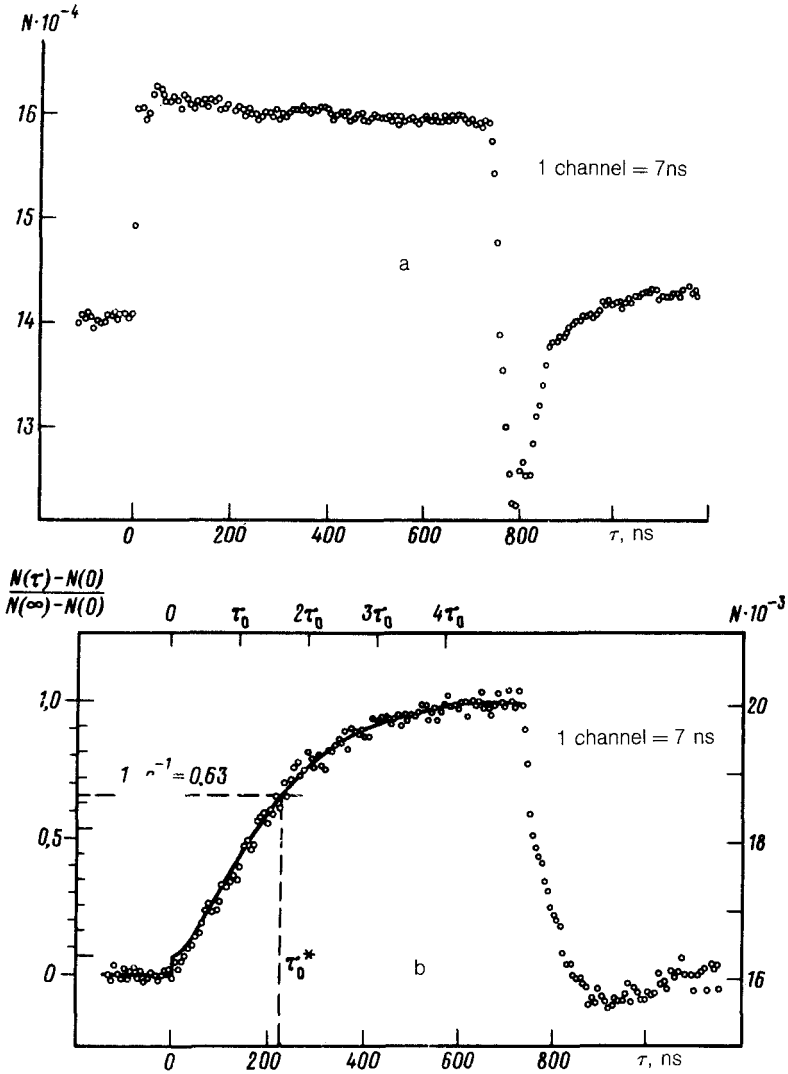

FIG. 2. (a) Intensity of Mössbauer radiation versus the time after the passage through a resonant magnetic shutter (γ-ray pulse); (b) time evolution of the escape of electrons from a polycrystalline ^{57}Fe. The $\Delta m = 0$ transition was excited. Solid line—theoretical calculation.

Å) virtually eliminates any distortion of the temporal behavior of the resonant scattering of γ rays by single nuclei. A distortion would have occurred if the electrons carried information from a very thick scattering layer ($\gg$3000 Å), in which the spectrum of incident γ rays is already markedly deformed because of resonant absorption.

To detect the electrons emerging at the surface of the target—a polycrystalline ^{57}Fe wafer—we used an avalanche gas-discharge counter.[11] The target in this counter

doubled as the anode. The time resolution of the counter was considerably better than 6 ns. For these measurements we placed the counter in the γ-ray beam beyond the resonant magnetic shutter.

Figure 2b shows the time evolution of the scattering measured from the electron yield. The solid curve in Fig. 2b represents a theoretical calculation. The time evolution of the resonant scattering was calculated by using the general response-function method proposed in Ref. 4. In the calculation we also took into account the fact that in the experiment the counter detected not only the conversion electrons but also a few photoelectrons, whose response to the excitation is nearly instantaneous. The fraction of photoelectrons amounted to 7%.

The characteristic time for the response of a nucleus, τ_0^*, to the excitation by a square pulse with a spectral width $\Gamma_s = 2.5\Gamma_n$ was $\tau_0^* = 230 \pm 10$ ns. To avoid confusion, we note that the difference of τ_0^* from a well-known value $\tau_0 = 141.1$ ns—the lifetime of the 14.4-keV level of ^{57}Fe—is completely consistent with the systematic behavior. The relation $\tau_0^* = \tau_0$ is satisfied only in the limit $\Gamma_s \to \infty$. i.e., when the nucleus is excited by the white spectrum.

Let us now consider the results of the principal measurements. From a two-dimensional set of experimental data $I(\tau,\theta - \theta_B)$ it is possible to extract both the angular and temporal scattering characteristics through integration over various temporal and angular intervals. Figure 3a shows the angular dependence of the intensity of resonant coherent scattering of γ rays by a $^{57}FeBO_3$ crystal. The plot was obtained by summing $I(\tau,\theta - \theta_B)$ over the temporal interval 200 ns$\leqslant\tau$700 ns. The half-width of the angular curve, $9.5'' \pm 0.5''$, is in good agreement with the calculations based on the theory of Refs. 4 and 12 (the solid line). To illustrate the temporal behavior of coherent scattering due to the excitation of individual groups of Bragg modes, we chose three angular intervals: the first angular interval 7″ wide is far from the Bragg angle (symmetrically to its right and left), the second interval 4″ wide is situated on the slopes of the angular curve, and the third interval 3″ wide is situated in the immediate vicinity of the Bragg angle. Figure 3b shows the corresponding time evolution of the coherent scattering singled out by the angular interval. The solid lines in Fig. 3b represent a numerical calculation based on the theory of Ref. 4. In calculating the temporal behavior we averaged the angles θ at which a γ ray strikes the crystal, and took into account the beam divergence (4″) and the curvature of the crystal (2″).

Figure 3c is a plot of the coherent response time of the nuclear system in the crystal, τ_{ex}^*, as a function of the relative angle of incidence of the γ rays on the crystal. This function is the characteristic of the acceleration process. It is evident from Fig. 3c that even far from the Bragg angle—a distance of 11″—when the intensity of coherent scattering has already decreased appreciably, the characteristic response time of a nuclear system, which is 170 ± 30 ns, is shorter than the response time of a single nucleus ($\tau_0^* = 230 \pm 10$ ns), although it approximates this time. Upon approach to the Bragg position, the characteristic response time decreases sharply and reaches a value of 40 ± 10 ns in the immediate vicinity of the Bragg angle. Despite the fact that the experiment had a limited effective angular resolution ($4'' + 2''$), the response time of the nuclear system was approximately one-sixth that of a single nucleus. Given this

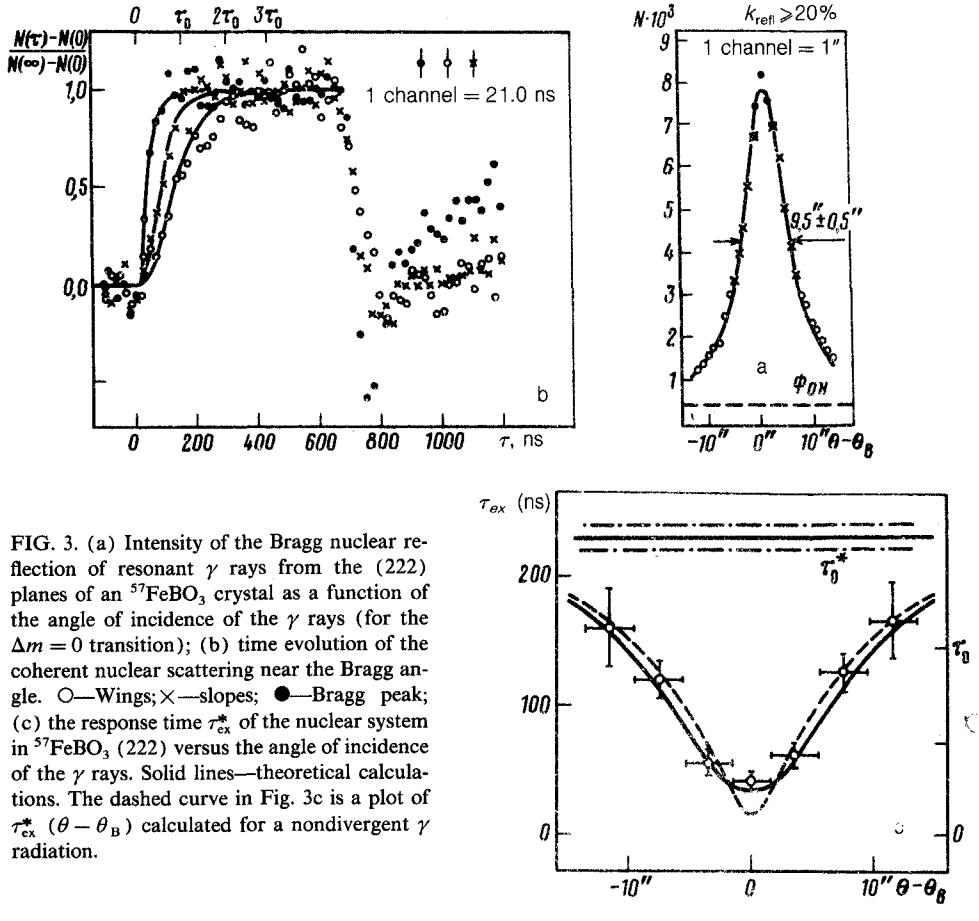

FIG. 3. (a) Intensity of the Bragg nuclear reflection of resonant γ rays from the (222) planes of an $^{57}FeBO_3$ crystal as a function of the angle of incidence of the γ rays (for the $\Delta m = 0$ transition); (b) time evolution of the coherent nuclear scattering near the Bragg angle. ○—Wings; ×—slopes; ●—Bragg peak; (c) the response time τ_{ex}^{*} of the nuclear system in $^{57}FeBO_3$ (222) versus the angle of incidence of the γ rays. Solid lines—theoretical calculations. The dashed curve in Fig. 3c is a plot of $\tau_{ex}^{*}(\theta - \theta_B)$ calculated for a nondivergent γ radiation.

fact, we conclude that the decay time of a collective nuclear state also decreases as the Bragg angle is approached. This is clearly indicated by the temporal behavior of coherent scattering after a γ-ray beam is rapidly chopped by a shutter at the time $\tau = 720$ ns (Fig. 3b).[1)]

Analysis of the two-dimensional dependence $I(\tau, \theta - \theta_B)$ also shows that a reduction of the collective response time of the nuclear system (Fig. 3, band c) is accompanied by a sharp increase in the maximum intensity of the response (Fig. 3a). Such a relation reveals the physical cause for the acceleration, clearly attributable to the intensification of the coherent elastic channel during scattering.

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[1]Shortly after the completion of this experiment, the DORIS synchrotron was used to measure the time evolution of the decay of the collective nuclear excitation produced in the $^{57}FeBO_3$ crystal near the Bragg angle by synchrotron-radiation pulses.[13] In the exact position of the Bragg angle, the half-life of the excited state was 12 ns and at half-maximum of the Bragg peak it was 18 ns.

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