Energy spectrum of γ rays passing anomalously through resonantly absorbing Fe^{57} crystals

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The suppression of nuclear reactions was investigated by a novel method in which a measurement was made of the energy spectrum of 14.4-keV Mössbauer γ rays passing through an Fe^{57} crystal under the conditions of Laue diffraction. It was found that the component of the γ-ray beam corresponding exactly to the resonance energy was transmitted through the crystal with little attenuation even though the crystal exhibited very strong resonance absorption. This is interpreted as direct evidence for the strong suppression of the inelastic channel of the (γ, e^-) nuclear reaction.

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The suppression of the inelastic (γ, e^-) channel in the interaction between resonance γ rays and nuclei, which was predicted by Kagan and Afanas'ev,[1] has been investigated experimentally by several workers.[2–8] The gist of the effect is that, when the diffraction conditions are satisfied for resonance γ rays, a γ ray can assume a superposition state in the crystal in which the amplitude for the excitation of nuclei in the crystal is zero.

It is well known that recoil-free γ rays emitted by Mössbauer sources are highly monochromatic but do, nevertheless, have a finite energy spread corresponding to the Lorentz line shape.

So far, investigations of the suppression effect have not been concerned with the particular part of the energy distribution to which γ rays undergoing anomalous transmission through the crystal can be assigned. These studies have, in fact, been confined to the integrated effect of the entire distribution. On the other hand, it is quite clear that, when the conditions for nuclear resonance are satisfied, the most interesting aspect of the suppression effect is the contribution of photons corresponding to the central part of the distribution, for which the resonance capture cross section is particularly large. However, it is precisely these photons which are the first to be removed from the incident flux when the conditions ensuring the suppression effect are even slightly violated. This is illustrated in Fig. 1, which shows the energy distribution of photons transmitted through absorbers of different thickness. It is found that, beginning with $\mu t = 2$, the shape of the distribution is distorted to the extent that a central valley appears upon it.[1)]

In our previous work,[9] we took special measures to separate photons belonging to the central part of the distribution, i. e., those which experienced strong resonance interaction with the nucleus, and investigated the suppression effect for these photons alone.

In the present paper, we report a new method of observing and studying the suppression effect. The principle is to use the energy spectrum of photons transmitted by the crystal to analyze the interaction between photons and nuclei in the crystal. The scale of the resonance absorption of photons by the crystal can be directly estimated by comparing this spectrum with the undisturbed energy distribution of photons in the beam incident on the crystal. The energy distribution of recoil-free photons and the fraction of the recoil-free component in the beam which has undergone the interaction with the crystal directly reflect the character of the interaction between the photons and the system of nuclei in the crystal. In this sense, the proposed method involves the direct detection of the suppression effect. It makes use of a Mössbauer absorber which analyzes the spectral composition of the γ-ray beams.[2)]

The principle of the experiment is illustrated in Fig. 2. The suppression effect was investigated for 14.4-keV photons from Fe^{57} interacting with resonance nuclei in an Fe + 1% Si crystal. The concentration of Fe^{57} nuclei in the crystal was 85%. For resonance photons, the crystal is a black absorber. The Mössbauer analyzer was introduced into the radiation transmitted through the crystal and was in the form of a 2.9-μ iron foil, 20% enriched with the resonance isotope. The crystal and analyzer have identical Mössbauer spectra, so that their absorption lines coincided for zero relative velocity of crystal and analyzer. The relative position of the emission and resonance lines for the crystal and analyzer is shown in the insert in Fig. 2. The first vibrator was used to place the source line in the position of the $-\frac{1}{2} \to -\frac{1}{2}$ nuclear transition, and remained stationary relative to the spectrum of the crystal during the measurement period. The analyzer absorption line os-

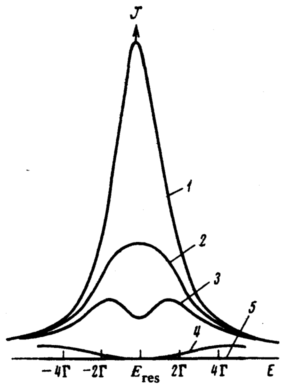

FIG. 1. Distribution of the energies of γ rays transmitted through absorbers of different thickness: 1) incident beam; 2) $\mu t = 1$; 3) $\mu t = 2$; 4) $\mu t = 10$; 5) $\mu t = 65$.

cillated about the position of rest, and the second vibrator was used to displace the iron foil in accordance with a constant acceleration law. The amplitude of the velocity variation was roughly half the distance to the neighboring absorption lines.

The Co^{57} in Cr had an activity of 500 μCi and the 14.4-keV radiation was separated from the resultant flux by (002) Bragg reflection from pyrolitic graphite crystal. The $(1\bar{1}0)$ planes of the iron crystal were perpendicular to the crystal surface and the [001] direction was perpendicular to the plane of scattering. Preliminary measurements showed that the magnetization directions in the domains were prependicular to the plane of scattering.[9] With this type of crystal magnetization, it was necessary to tune to the $-\frac{1}{2} \to -\frac{1}{2}$ nuclear transition to ensure that only the π component of the beam took part in the interaction with the nuclei.[3)] It is precisely for this component that complete suppression of the nuclear reaction could, in principle, be realized in our case.

To ensure that the analyzer was sensitive to the radiation interacting with nuclei in the crystal (i.e., to the π component), it was magnetized to saturation in a field perpendicular to the plane of scattering.

The directly measured quantity was the intensity of γ rays transmitted by the analyzer as a function of the analyzer velocity. The resulting absorption spectra are illustrated in Fig. 3. The peaks shown in these figures can be interpreted as the relative photon energy distributions in the beam incident on the analyzer.

For the reference spectrum, we used the energy distribution of collision-free π-polarized photons in the beam incident on the Fe^{57} crystal, i.e., the undisturbed distribution. This was determined in the absence of the Fe^{57} crystal. The result is shown in Fig. 3a. It takes the form of a symmetric maximum centered on the resonance energy corresponding to the $-\frac{1}{2} \to -\frac{1}{2}$ nuclear transition. The slight increase in the intensities in the wings of the spectrum is due to the σ-polarized beam photons. The latter begin to interact with the analyzer as a result of the $-\frac{1}{2} \to +\frac{1}{2}$ and $-\frac{1}{2} \to -\frac{3}{2}$ nuclear resonances as the latter approach the emission line.

Next, we measured the distribution in the beam transmitted by the crystal with the latter taken out of the Bragg position (Fig. 3b). In this case, we observed the

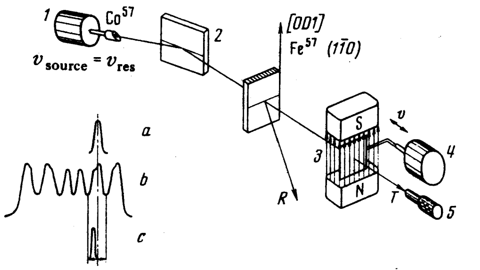

FIG. 2. Experimental arrangement: 1) first vibrator; 2) collimator (pyrolitic graphite); 3) Mössbauer analyzer; 4) second vibrator; 5) detector. Insert shows source line (a), the spectrum of the Fe^{57} crystal (b), and the analyzer line (c).

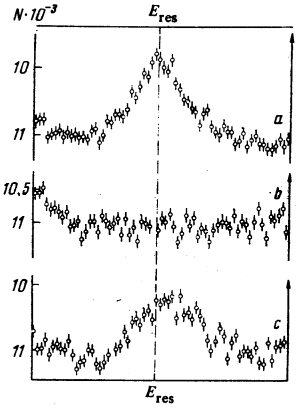

FIG. 3. Energy distribution for γ rays transmitted by the analyzer.

usual absorption of photons by nuclei in the crystal. As can be seen, the π-polarized photons did not succeed in passing through the crystal. In actual fact, at the center of the resonance, $\mu t = 65$. At the same time, recoil-free σ-polarized photons, which did not interact with the nuclei, were transmitted by the crystal and this was indicated by the increase in intensity in the wings of the spectrum.

Finally, the third measurement was carried out with the crystal in the (110) Bragg position. For π-polarized photons, the superposition of coherent waves scattered under these conditions in the forward directions and at the Bragg angle could result in the appearance of a state in which there was no interaction with the nuclei and the photons could freely pass through the entire crystal. Photons undergoing anomalous transmission through the crystal were separated into two beams, designated T and R.

The T beam propagated in the direction of the incident beam and the R beam was deflected from the incident direction by twice the Bragg angle (Fig. 2). The measurements were performed in the deflected beam to increase the signal-to-background ratio. The observed distribution is shown in Fig. 3c. It is radically different from the distribution in Fig. 3b, in which the γ rays are practically absent, and is only slightly distorted as compared with the undisturbed distribution in Fig. 3a, even though the γ rays have passed through a thick crystal exhibiting resonance absorption. The degree of suppression of nuclear absorption can be determined by comparing the experimental distribution with calculations for absorbers of different thickness (Fig. 1). The distribution in Fig. 3a corresponds to an undisturbed distribution with $\mu t = 0$; the distribution measured under the conditions of anomalous transmission lies between the $\mu t = 0$ and $\mu t = 1$ curves, and we may therefore conclude that the nuclear absorption factor is reduced from the normal value of 65 down to an effective value less than unity. This is in good agreement with the results obtained for the same crystal in[9].

We thus have, for the first time, a direct observation of the suppression effect for photons of strictly resonant energy: the transmitted photons are those that are most highly absorbed under normal conditions. This phenomenon is the most striking manifestation of the suppression effect. The fact that resonance photons can be transmitted by a thick crystal is due to the unique feature of the suppression effect, namely, the fact that the effect depends on the thermal vibrations of the nuclei. To see this in its proper perspective, we note that, in typical cases of the Borrmann effect, the residual absorption factor connected with the thermal vibrations of the atoms is about 5% of the normal. If an analogous situation were to be characteristic for the suppression effect, then the residual factor would be 3 in our case, which would result in a reduction of the recoil-free component of the beam transmitted by the crystal by a factor of roughly 6–7, as compared with the corresponding quantity in the incident beam.

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1)A similar spectrum shape was observed by Mössbauer *et al.*[10]
2)Mössbauer analysis was first used in connection with the resonance scattering of γ rays in[11,12].
3)For this polarization, the magnetic field vector oscillates at right-angles to the plane of scattering.

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Melting curve of hydrogen up to 10 kbar

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The melting point of molecular normal hydrogen was measured by the piston-displacement method. The range of the investigation was extended beyond those used by others, to $P_m = 10$ kbar and $T_m = 112$ K. The molar volumes of the solid phase on the melting curve were determined experimentally.

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Experimental data on the melting of hydrogen at high pressures are very skimpy. There is only one 1930 study, in which the melting curve of hydrogen was measured up to 5 kbar.[1] In the remaining studies[2,3] the pressure did not exceed 3.6 kbar. This large gap in the experimental material, compared with other substances,[4,5] is attributed to experimental difficulties faced when the hydrogen density is increased at high pressures[6] and to the well-known hydrogen brittleness of steel at temperatures above 120 K.

We present here the results of measurements of the melting point of hydrogen of purity 99.8% up to 10 kbar. The initial hydrogen had an equilibrium ortho-para composition at room temperature.1) The measurements were performed with a cylinder + piston type of apparatus, in which hydrogen precompressed to 2 kbar was fed through a capillary with the aid of a thermocompressor and a gas booster. The high-pressure vessel was thermostatically controlled with an automatic temperature regulator accurate to ±1°. During the time of the experiment, we measured the displacement L of the piston as a function of the applied load F at a fixed temperature. The melting was revealed by the discontinuity of

