Observed strengthening of radiative mechanism for a nuclear reaction in the interaction of γ radiation with nuclei in a vibrating absorber

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After an opaque resonant absorber of stainless steel was driven into vibration with a frequency $f = 23.79$ MHz, it began to emit resonant γ rays with energies $E_0 \pm 2\pi n\hbar f$ (E_0 is the energy of the incident radiation, and $n = 1,2,...$) in the primary direction. The intensity of this secondary emission reached 37.8% of the incident intensity, providing direct evidence of an intensification of the radiative mechanism in the scattering reaction studied.

The effect of ultrasound on the spectra of Mössbauer radiation has been studied in many experiments.[1–4] In the presence of ultrasound of sufficiently high frequency f, an isolated resonance line splits, and the emission spectrum contains, in addition to the fundamental line at E_0, some satellites at the positions $E_0 \pm 2\pi nf\hbar$ ($n = 1,2,...$). As Mössbauer radiation interacts with an absorber in which ultrasonic vibrations are excited,[5,6] the same sort of splitting of the resonance absorption line occurs. At a given frequency, the structure of the absorption spectrum—the number of lines and their relative intensities—is determined primarily by the vibration amplitude, but the degree of uniformity of the vibrations over the sample is also important. Many experimental studies have been devoted to these features of the absorption spectra. To the best of our knowledge, the question of the spectrum of the radiation which passes through the absorber under these conditions has never been raised. A study in this direction could evidently provide additional information about the nature of the interaction of the Mössbauer radiation with the nuclear lattice excited by the ultrasound. In the present study we have taken up specifically the problem of determining the energy spectrum and the intensity of the γ radiation which is transmitted through a resonant absorber vibrating at an ultrasonic frequency.

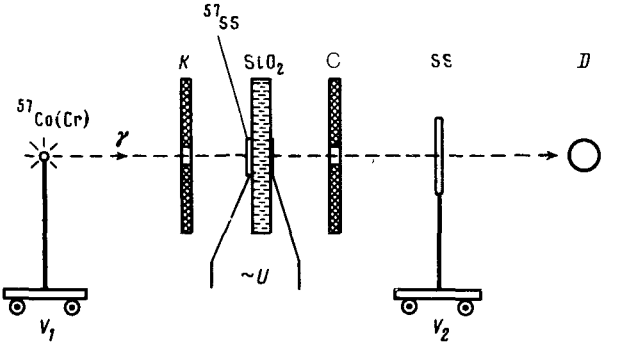

FIG. 1. Experimental layout. The vibrator V_Z and the resonant filter-analyzer SS were in place only in the second stage of the experiments: during the measurement of the spectra of the radiation emitted from the ^{57}SS target.

Figure 1 is a cutaway diagram of the experimental apparatus. To the well-known layout of a transmission Mössbauer spectrometer we have added a new element: a spectrum analyzer to analyze the spectrum of the resonant γ radiation which is emitted from the test sample in the primary direction. This analyzer includes a vibrator V_2 with corresponding electronic control and a resonant filter which performs the analysis. This filter is a stainless-steel (SS) foil 16 μm thick with the natural abundance of the isotope ^{57}Fe. The ^{57}Co(Cr) source is put in motion independently by its own vibrator (V_1). The linewidth of the source is 0.14 mm/s. The test sample is made of stainless steel enriched to 95% in the isotope ^{57}Fe (^{57}SS), in the form of a foil 12 μm thick with a diameter of 6 mm (the weight is 2.4 ± 0.1 mg). We are thus using a thick target, in which the resonant absorption of γ rays should be close to saturation ($\mu t\, 60$). The foil is cemented to a quartz piezoelectric plate (X-cut, 18 mm in diameter$\times$0.12 mm) by means of BF-2 cement. The resonant vibration frequency of the piezoelectric crystal, with the foil cemented in place, is $f = 23.79$ MHz. The γ radiation is detected by a scintillation counter with a NaI(Tl) crystal (D). The cross-sectional area of the incident beam is limited to a diameter of 3 mm by a collimator C, so only the central part of the target is exposed. The solid angle, in which the radiation emerging from the target in the primary direction is received, is 4×10^{-5} sr.

In preliminary measurements, we did not place the analyzer in the beam; we recorded ordinary absorption spectra of Mössbauer radiation in the test sample. Figure 2a shows the spectrum of the ^{57}SS foil in the case in which it is not excited by ultrasound. From this spectrum we can see the scale of the saturation of the resonant absorption in the particular nuclear target which we used. After the source line was subtracted, the width of the absorption line was found to be 1.11 mm/s, or $\approx$5 times the intrinsic width of the nuclear resonance in the ^{57}SS sample (the latter was determined by means of a conversion-electron Mössbauer spectrometer, i.e., by a method free of the broadening associated with the thickness of the absorber). Subsequent measurements were carried out with the excited piezoelectric crystal.

Figure 2, b–d, shows Mössbauer spectra recorded at various amplitudes U of the sinusoidal voltage applied to the plates of the piezoelectric crystal. As expected, additional resonances appear in the absorption spectrum during the excitation of ultrasonic

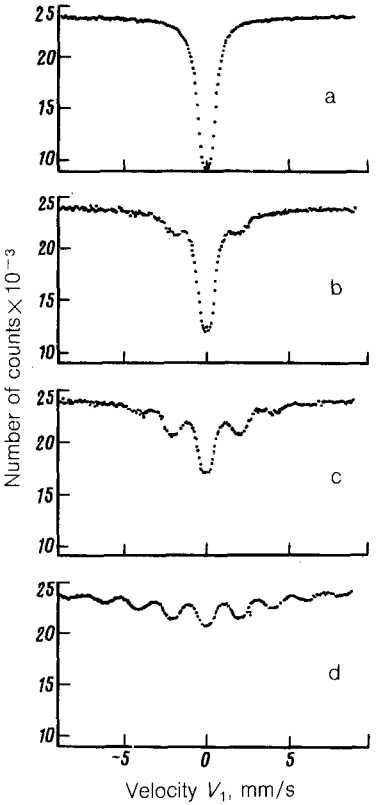

FIG. 2. Absorption spectrum in the ^{57}SS target, attached to an X-cut pizoelectric quartz plate. a—Target at rest; b–d—a sinusoidal voltage with a frequency $f = 23.79$ MHz is applied to the piezoelectric plate; b—the amplitude of this voltage is $U = 0.63$ V; c—1.38 V; d—2.45 V.

vibrations. As the amplitude of the ultrasound is increased, the number and intensity of the satellite lines increase. There is an interesting feature in these spectra: The width of the central absorption line remains essentially the same as the ultrasonic amplitude is increased, and the satellite lines which are created have roughly the same width. This circumstance is evidence that the resonant absorption reaches saturation in the test sample even during the excitation of ultrasonic vibrations. On the other hand, it is clear from Fig. 2, b–d, that the depth of the central line decreases with increasing vibration amplitude, so a target which is tuned to resonance with the γ radiation becomes progressively more transparent for the radiation. How can these two facts be reconciled?

If the resonant γ rays passed through the target, they could be detected by the Mössbauer analyzer. Resolving this question was the purpose of a second series of experiments. In it we used a filter-analyzer for the resonant γ radiation which was put in constant-acceleration motion. The Mössbauer absorption spectra in the analyzing foil demonstrate that resonant γ rays are indeed present in the beam incident on this foil, i.e., in the beam emerging from the vibrating target in our case. Figure 3 shows

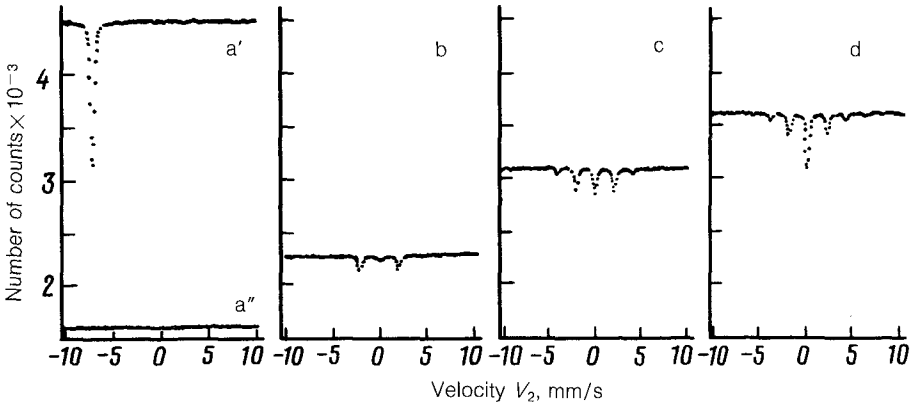

FIG. 3. Spectra of the γ radiation emitted in the forward direction from the ^{57}SS target, attached to the X-cut piezoelectric quartz plate. *a'*—Target at rest, ^{57}Co(Cr) source moving at a constant velocity $V_1 = -7.0$ mm/s; *a''*—the same, but with $V_1 = 0$; b–d—$V_1 = 0$, but a sinusoidal voltage with a frequency $f = 23.79$ MHz is applied to the piezoelectric quartz plate; b—the amplitude of this voltage is $U = 0.63$ V; c—1.38 V; d—2.45 V. The duration of the measurements was the same for all of the spectra.

the resulting absorption spectra. In view of the discussion above, we see that they fairly accurately reflect the energy spectra of the γ radiation emerging from the target.

We first measured the spectrum of the γ radiation which was transmitted through the sample far from resonance (Fig. 3a'). In this case the source velocity was a constant -7.0 mm/s. The resulting spectrum determines the source lineshape and reveals the intensity of the resonant radiation from the source, with allowance for the absorption of γ rays by electrons in the target. In subsequent measurements, the radiation was observed at resonance with ^{57}Fe nuclei. The source was at rest in this case.

Figure 3a'' shows the spectrum of the radiation emitted from the target in the absence of ultrasonic excitation. A comparison of the spectra in Figs. 3a' and 3a'' demonstrates directly the extent to which the resonant target under study is opaque. Only a small fraction (3.5%) of the radiation from the source belonging to the wings of the energy distribution could pass through it. We turn now to the results found when the ultrasonic excitation was turned on.

Even at a low excitation amplitude, $U = 0.63$ V (Fig. 3b), we see that lines with a shifted frequency appear in the spectrum and immediately become predominant. These lines are in the same places as the absorption lines in the vibrating target. Note, however, that the widths of the lines in the spectrum of the radiation emitted from the target are the same as the width of the source line. As the ultrasonic amplitude is increased, the number and intensity of the shifted lines increase. In addition to the shifted lines, a central line appears, having the same energy position as the incident radiation. The total areas under the shifted lines in the spectrum of the transmitted γ radiation, divided by the area in the spectrum of the incident radiation (Fig. 3a'), are 23.7% in Fig. 3b, 35.1% in Fig. 3c, and 37.8% in Fig. 3d.

These experiments have thus provided data which make it possible to answer the question of the origin of the γ radiation which emerges from the vibrating target. The measured spectra clearly show that we are dealing with a secondary, inelastically scattered resonant γ radiation. The scattering process involves an absorption or creation of ultrasonic phonons: one, two, or more of them. Scattering in the primary direction with momentum transfer could occur only through the formation of an intermediate excited nuclear state. In a control experiment, we observed no contribution of small-angle electron scattering to the spectra of the inelastic scattering. The spectra are thus shaped by scattering by nuclei. The fact that the relative weight of the secondary resonant γ radiation exceeds the limit set by the electron-conversion process for the given nuclear scattering reaction $[\Gamma_\gamma/\Gamma_0 = (1+\alpha)^{-1} = 0.11]$ is evidence of a substantial intensification of the radiative mechanism for the scattering. Since the reradiation of photons by nuclei is concentrated in a small solid angle (i.e., is directional) in our case, we are justified in speaking in terms of a coherent nature of the inelastic scattering of the γ radiation by the nuclear target. The observed intensification of the radiative mechanism is therefore a consequence of a coherent inelastic scattering of γ rays by nuclei in a vibrating target. A theoretical analysis of the phenomenon and a detailed experimental study of it will be published in the near future.

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[1]S. L. Ruby and D. I Bolef, Phys. Rev Lett. **5**, 5 (1960).
[2]J. E. Monahan and G. J. Perlow, Phys. Rev. A **20**, 1499 (1979).
[3]G. J. Perlow *et al.*, J. Phys. (Paris) **41**, C1-85 (1980).
[4]E. N. Du Marchie van Voorthuysen, Phys. Rev. A **30**, 2356 (1984).
[5]A. R. Mkrtchan *et al.*, Phys. Status Solidi B **92**, 23 (1979).
[6]R. Koch and E. Realo, in: *Proceedings of International Conference on Applications of Mössbauer Effect*, Alma-Ata, 1983, Gordon & Breach, London, 1985, p. 34.

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