Relativistic scattering of Mössbauer γ rays by moving inhomogeneities in a medium

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An experiment with modulated Mössbauer radiation has demonstrated the interference betweeen waves passing through the medium without scattering and waves scattered by moving microinhomogeneities in the medium. The observed change in the sign of the asymmetry in Mössbauer absorption spectra when the direction of the velocity of the medium is changed is explained in terms of the redistribution of the density of microinhomogeneities.

Relativistic scattering by moving objects, studied in astrophysics, can be observed directly in the laboratory by examining the variation in the spectrum of resonance absorption of Mössbauer γ-rays. We have observed this physical phenomenon experimentally.

A mechanical chopper in the form of a rotating disk with radial slots was used in a study of nonstationary processes involving the resonance interaction between γ-rays and matter, e. g., in an experiment designed to verify the uncertainty relation $\Delta\omega\Delta t \sim 1$ for the photon.[1] It was found that, when the linear velocities were high, microinhomogeneities in the form of metal particles, 0.1–1.0 μm in diameter, tended to accumulate on the slits and were mixed with the lubricant of the electric drive. These microinhomogeneities unavoidably appear in choppers working in a nonevacuated volume. When Mössbauer radiation passes through the chopper slots, the γ-rays undergo small-angle coherent scattering by these moving microinhomogeneities.

Figure 1 shows schematically the experimental setup with a mechanical chopper of the γ-ray flux (described in detail in Ref. 2).

The electrodynamic vibrator 1, carrying the ^{57}Co Mössbauer source in a rhodium host, had an activity of 500 MBq. The resonant absorber 3 was made of stainless steel, 15 μm thick and 20%-enriched with ^{57}Fe. The whole assembly was located in an evacuated chamber. The mechanical chopper 4 in the form of a rotating steel disk with 64 slots, 0.3 mm wide, was placed between the source and the absorber. γ-rays passing through the absorber were recorded by the proportional counter 5. The Mössbauer absorption spectra of stainless steel for the γ-rays from ^{57}Fe* were measured at different angles during the rotation of the chopper for linear velocities of the disk edge between 200 and 0.1 m/s.

Figure 2 shows the recorded spectra (a-linear velocity of the disk edge 0.1 m/s, b and c—200 m/s with the direction of rotation reversed). It is clear from the figure that, when the velocity is high (200 m/s), the fraction of absorbed γ-rays is substantially reduced (by about 20% at resonance). The minima of the distributions in spectra b and c in Fig. 2 are shifted relative to one another by about 0.1 mm/s and the spectra exhibit considerable asymmetry whose sign changes when the direction of rotation of the chopper is reversed. The character of this asymmetry clearly illustrates the difference between the experimental absorption spectra.

Figure 3 shows the experimental Mössbauer absorption spectra of stainless steel, or the radiation from ^{57}Fe* recorded for the same velocities but after careful washing of the disk, which was then placed in an evacuated chamber. It is clear that the measured spectra are symmetric and the reduction in the fraction of absorbed γ-rays at resonance is about 8%, which is in good agreement with calculations performed with allowance for the frequency and spatial modulation of the Mössbauer radiation.[1]

These experimental results can be interpreted as follows. When the chopper rotates with a high angular speed, the distribution of the inhomogeneity (microparticle) density in the slots becomes nonuniform. The γ-rays undergo small-angle coherent scattering by these nonuniformly distributed microinhomogeneities. Because of the Doppler effect, the energy distribution of the scattered radiation is shifted toward higher or lower energies, depending on the direction of rotation, by the amount

$$b=2\frac{v}{c}\frac{\omega_0}{\Gamma}\sin\chi,$$

where ω_0 is the energy of the resonant transition in the source, Γ is the level width in the source and absorber, v is the velocity of the microinhomogeneities in the slots and χ is

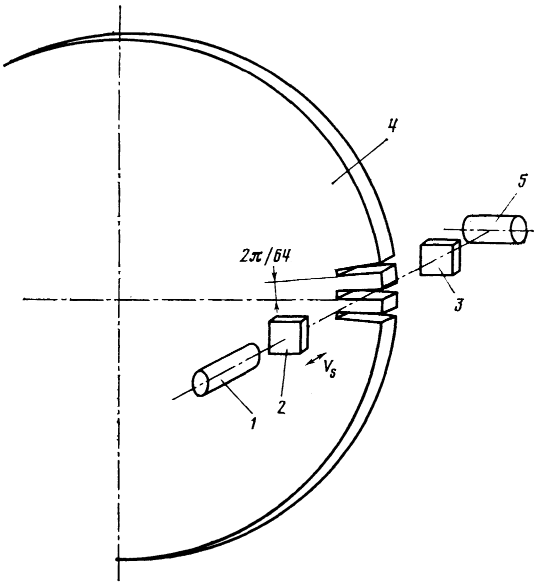

FIG. 1. Schematic illustrating the principle of the experiment (see text).

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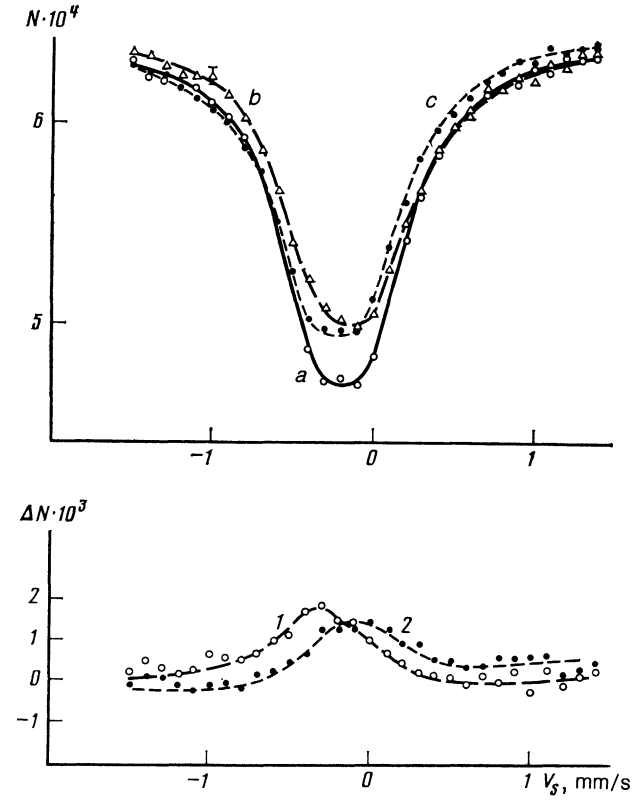

FIG. 2. Experimental Mössbauer absorption spectra recorded for linear velocities of the chopper disk edge (in m/s) as follows: 0.1 (a), 200 (b), − 200 (c), and the difference between the spectra: 1—($b - a$); 2—($c - a$).

the angle between the direction of emission of the photon from the point source (see Fig. 1) and the normal to the disk surface. Part of the radiation is displaced (in energy) well away from the resonance region, and its absorption by the resonance absorber is accordingly reduced. The observed asymmetry in the spectra for high velocities of the scattering microinhomogeneities is due to interference between the waves scattered in the resonance region and waves that have not been scattered.

Let us examine this interference in greater detail. We shall consider the interference effect for one moving slot. The intensity of the radiation of frequency

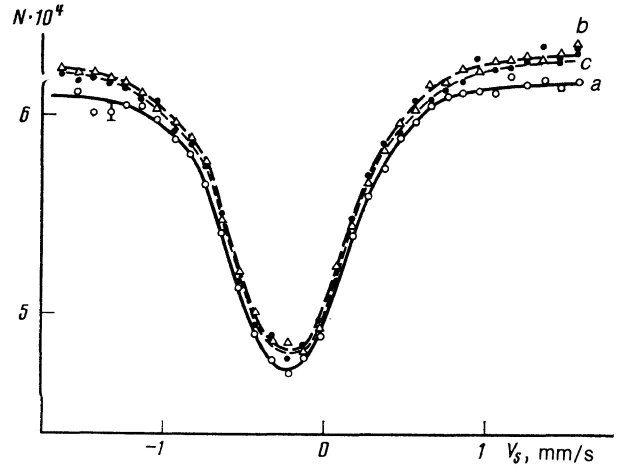

FIG. 3. Mössbauer absorption spectra recorded for the chopper in an evacuated chamber. Points—experimental, curves—calculated. The notation is the same as in Fig. 2.

$y = 2(\omega - \tilde{\omega}_0)\Gamma^{-1}$ that has passed through the slot is determined by the square of the modulus of the sum of the amplitudes of scattered and direct radiation ($\tilde{\omega}_0 = \omega_0 + s$, where s is the Doppler frequency shift of the source radiation due to the motion of the vibrator). The Mössbauer absorption spectrum of resonance radiation from the source, recorded by the detector, is given by the following integral in the thin-absorber approximation:

$$I(s) \infty \int dy \frac{\sigma_0 nf}{(y+\delta)^2+1} \left| \frac{1}{y+i} + \frac{A}{y-b+i} \right|^2, \tag{1}$$

where σ_0 is the maximum resonance absorption cross section, f is the Mössbauer factor, n is the density of resonant nuclei in the absorber, $\delta = 2(\tilde{\omega}_0 - \omega_1)\Gamma^{-1}$, and ω_1 is the energy of the resonant transition in the absorber. We shall assume that the intensity due to small-angle coherent Rayleigh scattering of the γ-rays by moving microinhomogeneities is small in comparison with the source intensity. The angular size of the slot, as seen from the point source, is 2Δ. The final expression for the shape of the absorption line must include an integral with respect to the photon angle of emission χ:

$$I(s) \infty I_0(\delta) \left\{ 1 + \frac{A}{\Delta} \int_{-\Delta}^{\Delta} d\chi n(\chi) \frac{\delta b^3+\delta^2 b^2+8\delta b+8\delta^2+32}{(b^2+4)[(b+\delta)^2+4]} \right\}, \tag{2}$$

where $I_0(\delta) = \sigma_0 nf/(\delta^2 + 4)$, $n(\chi)$ is the density of the microinhomogeneities as a function of angle, $A \sim \sigma_R^{1/2}$, and σ_R is the γ-ray Rayleigh scattering cross section of the atoms in the microinhomogeneities. For an arbitrary distribution $n(\chi)$, the expression in (2) must be integrated numerically. To analyze the resulting expression for the absorption line shape (2) in a qualitative way, we shall assume that the microinhomogeneity distribution in the slot is described by a simple step function

$$n(\chi) = \begin{cases} n_1, & -\Delta \leqslant \chi \leqslant 0 \\ n_2, & 0 < \chi \leqslant \Delta \end{cases}. \tag{3}$$

Integrating (2), we then obtain

$$X = I(s) - I_0(\delta) = \frac{A}{\Delta\tilde{\beta}} [n_2 \Phi(\Delta\tilde{\beta}) - n_1 \Phi(-\Delta\tilde{\beta})] I_0(\delta),$$

$$\Phi(x) = 2 \operatorname{arctg} \frac{x}{2} + \frac{\delta}{2} \ln \left| 1 + \frac{x^2+2\delta x}{\delta^2+4} \right|$$

$$+ \frac{2}{\delta} \ln \left| 1 + \frac{2\delta x}{x^2+4} + \frac{4\delta^2}{(x^2+4)(\delta^2+4)} \right|, \tag{4}$$

where $\tilde{\beta} = 2(\omega_0/\Gamma)(v/c)$.

When the direction of rotation is reversed, $\tilde{\beta} \to -\beta$ and the expression in (4) remains the same if the microinhomogeneity distribution in the slot is reversed. The experimentally observed change in the shape of the absorption line when the direction of rotation is reversed can therefore be explained exclusively by the fact that the microinhomogeneity distribution in the slot either changes to a lesser extent or remains unchanged. The difference curve for the absorption line shape then has the form

$$\Delta X \infty \frac{A}{2\Delta|\beta|(\delta^2+4)} [(n_2 - n_1') \Phi(\Delta|\beta|)$$

$$-(n_1 - n_2') \Phi(-\Delta|\beta|)], \tag{5}$$

where n_1' and n_2' are the corresponding microinhomogeneity densities for different directions of rotation.

In our case, $\Delta|\tilde{\beta}|\gg 1$. This gives the following approximate expression:

$$\Delta X \approx \frac{A\delta}{2(\delta^2+4)}[(n_2-n_2')-(n_1-n_1')]\frac{\tilde{\beta}/|\tilde{\beta}|}{\Delta|\tilde{\beta}|}, \qquad (6)$$

which is in qualitative agreement with the experimental results shown in Fig. 2.

The scattering of the electromagnetic waves by a moving object, and its interference with the unscattered waves observed under laboratory conditions, can be used, at least in principle, in the interferometry of small objects and the holographic recording of such microobjects in the frequency representation. In the present case, the unscattered wave is the reference wave and the scattered wave arrives from the object under analysis.

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[2]V. K. Voitovetskiĭ, V. V. Karmaz', I. L. Korsunskiĭ, *et al.*, Prib. Tekh. Eksp. No. 2, 59 (1980).

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