Observation of intensified forward γ-ray emission in spontaneous nuclear decay

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A nuclear target which is an essentially black absorber for resonant γ-ray emission becomes a strong emitter of γ rays in the forward direction after irradiation of this target is ended abruptly. A magnetic-resonance device was used to chop a γ-ray beam in order to observe this effect. The operating time of this chopper is much shorter than the time scale of the spontaneous decay of the excited nuclear state.

The spontaneous decay of an excited intermediate state formed in the scattering of a γ ray in a macroscopic system of nuclei must occur by a coherent mechanism if the phase correlation of the nuclear excitations which arises upon the capture of the original γ ray is retained over the lifetime of the excitation. In this case the γ ray is emitted in the forward direction[1] or at the Bragg angle.[1,2] There is a significant increase in the branching ratio for a radiative decay mechanism in comparison with the branching ratio for internal conversion. The physical reason for the intensification of the radiative mechanism lies in the nature of the interaction which arises between the macroscopic system of nuclei and the intrinsic radiation field of this system.

A spontaneous decay of nuclei accompanied by the emission of γ rays at the Bragg angle was observed in Refs. 3 and 4. Emission in the forward direction, on the other hand, has so far been observed in the decay of an intermediate excited state only in the presence of the primary γ-ray emission that excites the nuclei. Forward-scattered secondary γ-ray emission can be manifested only through an interference with the primary radiation.[5–8] Only recently has it been found possible to observe forward emission in its pure form, i.e., under the conditions corresponding to spontaneous nuclear decay, because of the use of short exciting pulses of synchrotron radiation.[9]

In this letter we are reporting observation of a forward-directed reradiation of γ rays during the spontaneous decay of nuclei excited by Mössbauer radiation. To observe this effect, we used a magnetic-resonance device to chop the γ-ray beam. The operating time of this chopper was much shorter than the time scale for the decay of the excited nuclear state. The experiment was designed to make it possible not only to observe the spontaneous forward emission but also to detect the amplification of the radiative decay mechanism—in the case at hand, to estimate the intensity of the forward-reradiated γ rays with respect to the intensity of the γ radiation exciting the nuclei.

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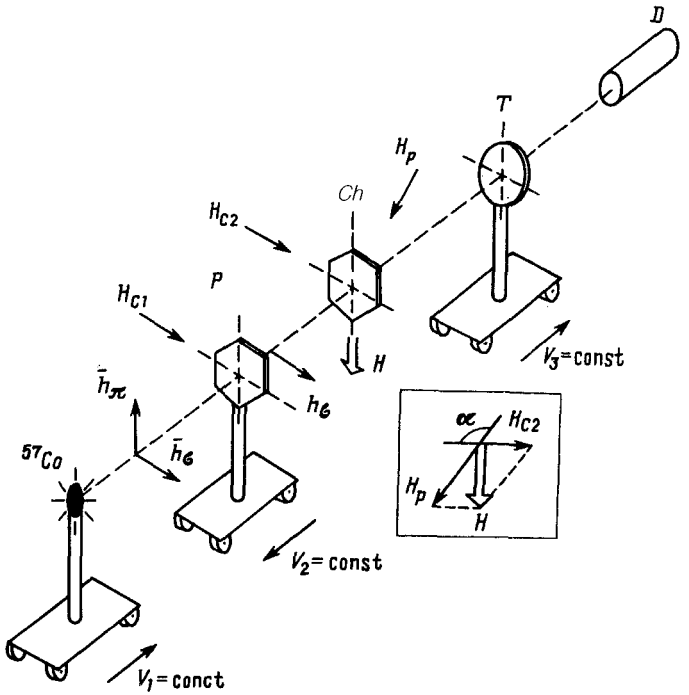

FIG. 1. Experimental layout. 14.4-keV source of Mössbauer γ rays [^{57}CO(Cr)]; radiation polarizer P ($^{57}FeBO_3$); radiation chopper Ch ($^{57}FeBO_3$); nuclear-resonance target T $\{K_2Mg[^{57}Fe(CN)_6]10H_2O\}$; γ detector D (NaI).

Figure 1 shows the experimental layout. Positioned in succession along the optical axis are a 14.4-keV source of Mössbauer γ rays [^{57}Co(Cr)], a radiation polarizer P (a $^{57}FeBO_3$ crystal), a radiation chopper Ch (also a $^{57}FeBO_3$ crystal), the nuclear target T ($K_2Mg[^{57}Fe(CN)_6]10H_2O$), and a γ detector D. The detector detects only the γ rays propagating in the primary direction. It has a sensitive solid angle $\cong 5\times 10^{-5}$ sr. Three Mössbauer vibrators are used in the apparatus. All operate in synchronization in a constant-velocity regime. The first vibrator, V_1, tunes the isolated line from the source, with a width $\Gamma_s = 0.2$ mm/s, to resonance with nuclei in the $^{57}FeBO_3$ chopper crystal in order to excite the transition $+1/2 \Rightarrow +1/2$ in it. The nuclear resonances in the chopper are shifted slightly from those in the polarizer through a heating of the chopper crystal by means of multiple magnetization reversal. The fine tuning of the positions of the resonances used in the polarizer and the chopper is achieved by moving the polarizer by means of a vibrator provided for the purpose, V_2. Finally, the nuclear target is put in motion by a third vibrator, V_3, in order to bring the nuclear resonance in the target into coincidence with the source emission line. After the necessary tuning of the vibrator velocities, the Mössbauer γ rays emitted by the source are thus at resonance with all the nuclear-resonance objects in the experimental layout.

The polarizer is a $^{57}FeBO_3$ crystal with a thickness $L_p = 35$ μm, magnetized along the horizontal direction by a magnetic field H_{c1}. During excitation of the transition $\Delta m = 0(+1/2 \Rightarrow +1/2)$, this polarizer absorbs the π-polarized component of the incident radiation. The resonant-absorption factor is $\mu L_p = 98$. The degree of polarization of the transmitted beam, $N^\sigma - N^\pi/(N^\sigma + N^\pi)$, is $\cong 0.90$.

A key element of the apparatus is the fast radiation chopper. The chopper is a $^{57}FeBO_3$ crystal controlled by external magnetic fields H_{c2} and H_p. The fast chopping is achieved through a reorientation of the fast-response spin system of the iron atoms in the $^{57}FeBO_3$ crystal by means of a magnetic field.[10,11] The crystal is originally magnetized along the horizontal axis by a static magnetic field $H_{c2} \cong 21$ Oe, produced in a volume $\cong 150$ cm^3 by large Helmholtz coils. At a certain time, a field $H_p \cong 26$ Oe making an angle $\alpha = 150°$ with $\overline{H}_{c2}$ is applied very rapidly, in $\leqslant 5$ ns. This field is produced by small Helmholtz coils in a volume $\cong 0.5$ cm^3. The strengths of the fields and the angle between the fields are chosen in such a way that the resultant field $\overline{H} = \overline{H}_{c2} + \overline{H}_p$ is perpendicular to $\overline{H}_{c2}$, and the magnetization vector of the $^{57}FeBO_3$ crystal (Ch) is rotated through 90°. Beginning at this time, the chopper absorbs the σ-polarized component of the γ radiation selected by the polarizer. The system of two crystals (polarizer + chopper) must therefore become opaque to the Mössbauer radiation. Figure 2a shows the time evolution of the chopping of the γ radiation. For measurement of this time evolution, a nuclear-resonance target was brought into resonance with the incident radiation. The rise time of the chopping was no longer than 10 ns, i.e., much shorter than the lifetime of the first excited state of the ^{57}Fe nucleus: $\tau_0 = 141$ ns. This cutoff rate was achieved (first) because it was possible to rapidly reorient the magnetization of the crystal and (second) by virtue of the large nuclear-resonance absorption factor in the sample itself.[11] For the $\Delta m = 0$ transition, and for a crystal thickness $L_{Ch} = 30$ μm, this factor was $\mu L_{Ch} = 84$. After 0.5 μs, the field H_p was turned off, and the chopper crystal returned to its original state, transparent to the σ-polarized component of the γ radiation (this transient process is not shown in Fig. 2a). The chopping was repeated every 2 μs.

The target was made of a finely divided powder of potassium ferrocyanide, enriched to 95% in the resonant isotope. The absorption spectrum consisted of an isolated line. The target thickness in terms of resonant nuclei was 0.82 mg/cm^2; this thickness corresponds to a resonant-absorption factor $\cong 11$. The time evolution of the γ radiation emitted by the nuclear target in a narrow solid angle $\cong 5 \times 10^{-5}$ sr in the primary direction was measured. The corresponding detection system was similar to that described in Refs. 4 and 11. The time resolution of the detector was 5.5 ns. The results of these measurements are shown in Fig. 2b.

Comparing the sequence of events in Figs. 2a and 2b, we clearly see that the target itself becomes a radiation source for a brief time after the chopping of the γ-ray beam incident on the target. The peak of the emission from the target is delayed 10 ns with respect to the end of the chopping of the γ-ray beam. This delayed spontaneous emission from the target can be explained only by a decay of previously excited nuclei in the target. The decay of the nuclei occurs spontaneously. An important point is that the peak intensity of the radiation released by the target is comparable to the intensity of the absorbed radiation (the spectra shown have been normalized to a common

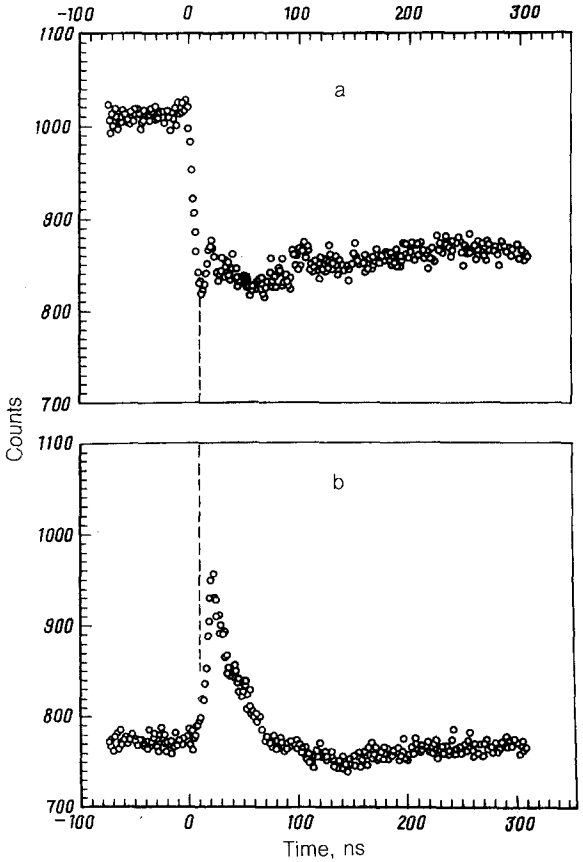

FIG. 2. a: Time evolution of the chopping of the 14.4-keV Mössbauer γ radiation. For the measurement of this time evolution, the nuclear target T was tuned away from resonance with the γ radiation incident on it. b: Time evolution of the γ radiation emitted in the forward direction from the nuclear target T. The target was tuned to resonance with the incident γ radiation. The number of counts in each plot has been normalized to a measurement time of 2 h.

measurement time). This fact is evidence that much of the stored energy is liberated as γ radiation during the decay of the nuclei. This radiation lies in a narrow solid angle around the primary direction. We conclude from this result that the delayed emission from the target is directional. In addition, the emission is released over a time shorter than the lifetime $\tau_0 = 141$ ns of the excited state of an isolated ^{57}Fe nucleus. Consequently, the characteristics of a spontaneous coherent decay of an excited nuclear state discussed in the theory of Ref. 1 are present: a large branching ratio for the radiative decay channel and a directionality of the radiation. While such a decay has been observed previously in the Bragg directions in single crystals,[3,4] it is being seen for the first time in the present experiments, as in Ref. 9, along the direction of the primary beam. A result which goes beyond those of Ref. 9 is the direct observation of an

intensification of the radiative mechanism during the spontaneous nuclear decay. We note in conclusion that a coherent spontaneous decay of an excited nuclear state can be observed in the forward direction in both regular and irregular nuclear systems.

We will report additional experimental data in a subsequent paper, along with a more comprehensive interpretation of the spectra and a theoretical analysis.

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