Photoactivation of isomeric levels in ^{113}In and ^{87}Sr

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A ^{60}Co source has been used to photoactivate the 392 keV ($T_{1/2} \sim 99.5$ min) isomeric level of ^{113}In and the 388 keV ($T_{1/2} \sim 2.8$ h) isomeric level of ^{87}Sr. As observed in investigations of ^{115}In and ^{111}Cd, nonresonant processes were found to make significant contributions to the excitation of isomeric levels.

I. INTRODUCTION

The photoactivation of isomeric levels by ^{60}Co γ rays has been investigated for several decades. It has usually been assumed that the excitation mechanism involves photons, in the lower energy tail associated with the intense sources used in photoactivation, exciting higher levels via nuclear resonance fluorescence, and that these levels then decay to the isomeric level. However, recent investigations of the photoactivation of isomeric levels of ^{115}In and ^{111}Cd have shown that nonresonant processes make significant contributions.[1–3] With the expectation that data for other nuclei will help us to understand the mechanisms involved in the nonresonant contributions, we have used the γ rays from ^{60}Co to photoactivate the 392 keV ($T_{1/2} \sim 99.5$ min) isomeric level of ^{113}In and the 388 keV ($T_{1/2} \sim 2.8$ h) isomeric level of ^{87}Sr. Our experimental technique allows estimates to be made of both the resonant and nonresonant contributions.

II. EXPERIMENTAL TECHNIQUE

If we assume that one level is dominant in the resonance fluorescence contribution, the probability P of exciting an isomeric level per unit time is given by

$$P = \phi_R(E_R)\sigma_R + \phi_{NR}\sigma_{NR}^T ,$$

where

$$\sigma_R = \pi g \lambda\!\!\!^{-2} \Gamma_0 \Gamma_{iso}/\Gamma$$

represents an integrated cross section for the resonant contribution. The parameters g, Γ_0, Γ_{iso}, and Γ are, respectively, the statistical weight, the ground state transition width of the resonance level, the partial width for decay to the isomeric level, and the total width of the resonance level. $\lambda\!\!\!^{-}$ is the wavelength (divided by 2π) of the photons which excite the resonance level at the energy E_R. $\phi_R(E_R)$ is the flux of photons per unit area, energy, and time and ϕ_{NR} is the flux of nonresonant photons per unit area and time. σ_{NR}^T is the cross section for the nonresonant excitation of the isomeric level.

In addition to the 1173-1332 keV cascade, ^{60}Co emits γ rays with energies of 347, 826, 2159, and 2506 keV.[4] The intensities of the γ rays are many orders of magnitude below those of the 1173 and 1332 keV γ rays, and it has been assumed that their contributions can be neglected. The intense, collimated ^{60}Co beam had a low energy tail, and this is allowed for in our analysis. ϕ_{NR} is assumed to be due to the 1173 and 1332 keV photons. Ex-

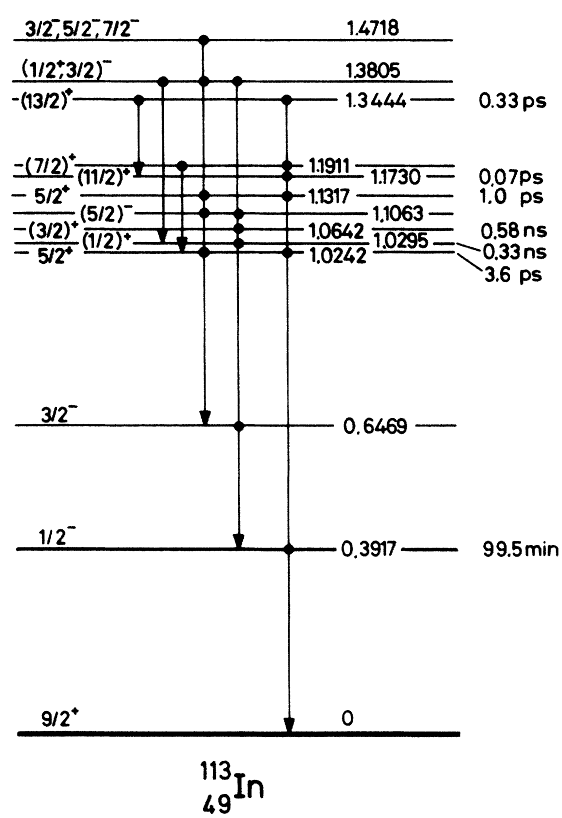

FIG. 1. The level structure and γ-ray branching scheme of ^{113}In.

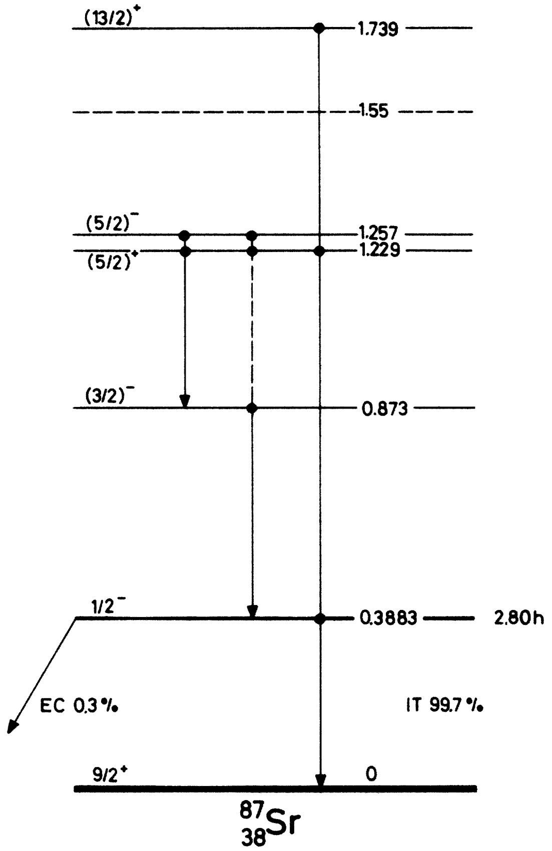

FIG. 2. The level structure and γ-ray branching scheme of ^{87}Sr.

periments with bremsstrahlung from a variable energy electron beam have shown that direct-resonant excitations of the isomeric levels, without a mechanism involving higher levels, are negligible.[5]

While electrons produced in the absorbers and the sample can excite the isomeric levels, the experiments of Booth and Brownson[5] with variable energy electron beams show that activations of the isomeric levels are negligible until the electron energy is sufficient to excite higher levels which couple strongly to the ground state, and deexcite to populate the isomeric level. In the case of ^{115}In we have considered the possibility of the 1078 keV level, which decays to populate the 336 keV isomeric level, being excited by electrons produced when the ^{60}Co γ rays interact in the sample via the photoelectric effect, the Compton effect, and pair production. Our investigations, which involved indium-lead alloy samples of various compositions, showed that possible contributions from electrons are many orders of magnitude below the level necessary to explain the σ_{NR}^{T} value. We expect similar situations for ^{87}Sr and ^{113}In.

The experimental method, which has been described previously,[1–3] involves interposing lead absorbers between the ^{60}Co and the sample to vary the relative values of $\phi_R(E_R)$ and ϕ_{NR}, and allows an estimate of the resonant and nonresonant contributions. The effects of the absorbers and the sample on the photon energy distribution are investigated using a small ^{60}Co source, which in contrast to the source used for photoactivation, has a negligible low energy tail.

The samples were irradiated with a 1.12×10^{14} Bq ^{60}Co source which, according to the manufacturer's specifications, had a low energy tail intensity k which was 0.19 of the full energy photon intensity. In each case the source to sample separation was 22 cm and, in addition to irradiations without absorbers, irradiations were made with 0.4, 0.8, 1.2, and 1.6 cm of lead between the source and sample. The natural indium sample was a 0.4 cm thick, 2.54 cm diameter disk. The strontium in the form of SrF_2 was contained in a 0.1 cm thick aluminum cylinder, 3.2 cm in diameter, and 2.6 cm long. Irradiations were made for about 13 h, and the subsequent decays of the isomeric levels were measured with a Ge(Li) detector.

The level structure and γ-ray branching schemes[4] for the nuclei are given in Figs. 1 and 2. The analysis for

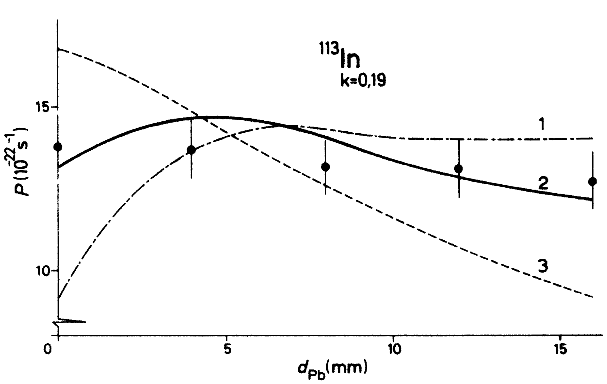

FIG. 3. A comparison of the experimental and calculated values of the ^{113}In isomeric level excitation probability as a function of d_{Pb}, the lead absorber thickness. The lines for the calculated values are hand drawn through five values. The values obtained for χ^2, σ_R, and σ_{NR}^{T} are the following: (1) $\chi^2=27.4$, $\sigma_R=12.4\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=0$; (2) $\chi^2=2.94$, $\sigma_R=8.1\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=2.0\times10^{-32}$ cm^2; (3) $\chi^2=36.0$, $\sigma_R\times=3.0\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=4.0\times10^{-32}$ cm^2.

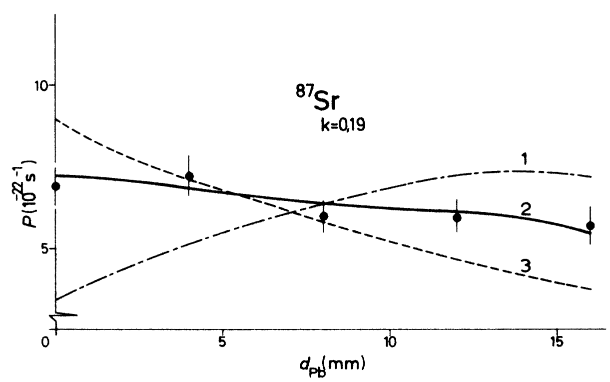

FIG. 4. A comparison of the experimental and calculated values of the ^{87}Sr isomeric level excitation probability as a function of d_{Pb}, the lead absorber thickness. The lines for the calculated values are hand drawn through five values. The values obtained for χ^2, σ_R, and σ_{NR}^{T} are the following: (1) $\chi^2=61.4$, $\sigma_R=10.4\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=0$; (2) $\chi^2=1.8$, $\sigma_R=4.7\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=3.2\times10^{-32}$ cm^2; (3) $\chi^2=27.6$, $\sigma_R=0.4\times10^{-29}$ cm^2 keV, $\sigma_{NR}^{T}=5\times10^{-32}$ cm^2.

TABLE I. Experimental results for the photoactivation cross section of the 338 keV isomeric level of ^{87}Sr.

Reference	Photoactivation cross section (10^{-29} cm^2 keV)
5	8.5^{+4}_{-3}
6	30 ± 8
7	$5 \rightarrow 6.2$
8	42 ± 6^{a}
	56 ± 8^{b}
Our result	4.7 ± 0.7

[a]Assumes a value of $g\Gamma_0 = 10^{-3}$ eV for the 1229 keV level.
[b]Assumes a value of $g\Gamma_0 = 10^{-4}$ eV for the 1229 keV level.

each nucleus assumed that one level was dominant in the resonance fluorescence process. In the case of ^{113}In it has been shown that the activation of the isomeric level is dominantly associated with the resonant excitation of a level at 1132 keV, and for ^{87}Sr that a level at 1229 keV is dominant in the resonant excitation of the isomeric level.[5]

In each case a χ^2 analysis of the experimental data was made with k, σ_R, and $\sigma_{\rm NR}^T$ as variable parameters, and the best σ_R and $\sigma_{\rm NR}^T$ values were obtained from the minimum χ^2 value.

III. RESULTS

A. Photoactivation of ^{113}In

The sensitivity of the method for ^{113}In is illustrated in Fig. 3. The best χ^2 value of 2.95 corresponded to a k value of 0.19, which is in excellent agreement with the source specifications, and cross sections of $\sigma_R = (8.1 \pm 0.1) \times 10^{-29}$ cm^2 keV and $\sigma_{\rm NR}^T = (2.0 \pm 0.3) \times 10^{-32}$ cm^2 were obtained. Our results can be compared to the value of $(7^{+4}_{-3}) \times 10^{-29}$ cm^2 keV obtained by Booth and Brownson.[5] We find that when no lead absorber is interposed, only 45% of the excitations of the isomeric level proceed via resonance fluorescence of the 1132 keV level.

B. Photoactivation of ^{87}Sr

The sensitivity of the method for ^{87}Sr is illustrated in Fig. 4. The best χ^2 value of 1.8 corresponded to a k value of 0.19, and cross sections of $\sigma_R = (4.7 \pm 0.7) \times 10^{-29}$ cm^2 keV and $\sigma_{\rm NR}^T = (3.2 \pm 0.4) \times 10^{-32}$ cm^2 were obtained. Other results which have been obtained are given in Table I. When no lead absorber is interposed, only 22% of the excitations of the isomeric level proceed via resonance fluorescence of the 1229 keV level.

IV. CONCLUSIONS

The cross sections for the nonresonant excitations of isomeric levels of ^{113}In and ^{87}Sr are the same order of magnitude as those found for ^{115}In (Ref. 1) and ^{111}Cd (Ref. 2). Our results indicate that, in many experimental arrangements, nonresonant processes make significant contributions to the photoactivation of isomeric levels. Additional experimental work and theoretical analyses will be needed if we are to understand the mechanisms for the nonresonant contributions.

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[1]A. Ljubičić, K. Pisk, and B. A. Logan, Phys. Rev. **C 23**, 2238 (1981).
[2]M. Krčmar, A. Ljubičić, K. Pisk, B. A. Logan, and M. Vrtar, Phys. Rev. **C 25**, 2079 (1982).
[3]A. Ljubičić, M. Krčmar, K. Pisk, and B. A. Logan, in Proceedings of the Second International Symposium on Radiation Physics, 1982, Penang, Malaysia, p. 177.
[4]*Tables of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).
[5]E. C. Booth and J. Brownson, Nucl. Phys. **A98**, 529 (1967).
[6]K. Yoshihara, Isot. Radiat. Technol. 3, 472 (1960).
[7]A. Veres, private communication, quoted in Ref. 8.
[8]Y. Watanabe and T. Mukoyama, Nucl. Sci. Eng. **80**, 92 (1982).