Photoactivation of $^{111}Cd^{m}$ without a "nonresonant" contribution

I. Bikit,[a] J. Slivka,[a] I. V. Aničin,[b] L. Marinkov,[a] A. Rudić,[c] and W. D. Hamilton[d]
[a]*Institute of Physics, University of Novi Sad, Novi Sad, Yugoslavia*
[b]*Boris Kidrič Institute, Vinča, Belgrade, Yugoslavia*
[c]*Institute for Nuclear Medicine, Sremska Kamenica, Yugoslavia*
[d]*University of Sussex, Physics Division, Brighton BN1 9QH, England*
(Received 2 September 1986)

The photoactivation of ^{111}Cd with a ^{60}Co source and a set of intervening iron absorbers has been studied. The induced activity of $^{111}Cd^{m}$ is interpreted completely by assuming resonant excitation of the 1330 keV state followed by decay to the isomeric state, thereby discounting the necessity of any "nonresonant" photoexcitation process.

Activation of low-energy nuclear isomeric states by photoexcitation of higher-energy states which subsequently decay via the isomer has been used for some time[1–3] as a means to excite the isomeric state. It has been shown[4] that the technique is especially suited for the study of nuclear states that are not easily excited otherwise. Gangrsky *et al.*[5] noted the activation of low-energy isomers after irradiating targets with high-energy gammas from various radioactive sources. During the years it became established that the excitation of a nuclear level of energy E_r and width Γ, upon irradiation with gamma rays of an energy $E > E_r$, is realized by resonant absorption of Compton scattered photons that fall within the energy range $E_r + \Gamma/2$. In a number of recent investigations,[6–8] however, it has been shown that the results of photoactivation of isomers with radiations from radioactive sources cannot be explained completely by resonant absorption to higher energy states and a subsequent decay. It has been found that in order to explain the results of photoactivation of $^{115}In^{m}$, $^{111}Cd^{m}$, $^{113}In^{m}$, and $^{87}Sr^{m}$ it was necessary to introduce the so-called "nonresonant" absorption term that would describe a contribution of a yet unknown interaction between the nucleus and a gamma ray. Having in mind the potential importance of these findings, we considered it worthwhile to try to improve on experimental conditions as well as on data analysis and thus make an independent check.

In order to make comparisons between the results of our measurements and those of Ref. 7 more direct, we used essentially the same technique. We have attempted to establish and determine the resonant and "nonresonant" absorption contributions from a ^{60}Co source by changing the ratio of resonant to nonresonant photons. This was achieved by interposing metal plates between the source and the material to be activated. We have studied the photo activation of ^{111}Cd, whose decay scheme is shown in Fig. 1. As has been shown before,[4,9] the population of the 396 keV isomeric level occurs predominantly via the deexcitation of the 1330 keV state which is by far the most strongly excited in the photoactivation process, although the exact way of populating the isomeric state is not known.

We have determined the cross section for the photoactivation of the 1330 keV state by measuring the activation of the 396 keV 48.6 min isomer in accordance with Ref. 7. The activation was made with a ^{60}Co source,

The experimental procedure was as follows:

Disks of natural cadmium 2.1 mm thick and of 23 mm radius were irradiated by a ^{60}Co source of 2000 Ci. Source to disk separation was 33.5 cm and exposure time was 7200 s. From the Z dependence of the cross sections for Compton scattering and the photoelectric effect, it is obvious that a material of the low Z and the high density is best for the absorber-scatterer if the intensity of the low-energy tail of the 1.332 keV ^{60}Co photon is to be kept at its maximum and the loss of overall intensity at its minimum. This is why we decided to use iron absorbers as irradiators between the source and the disks, instead of lead ones, which were used in Refs. 6–8. We made four

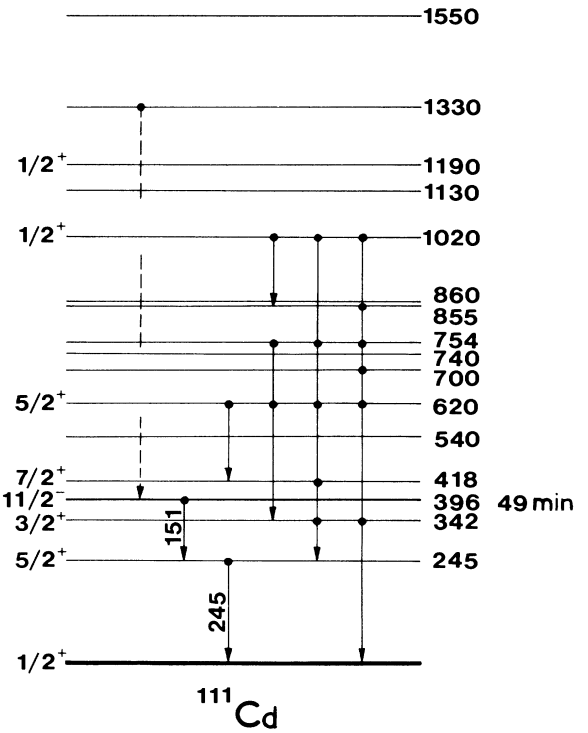

FIG. 1. The decay scheme of ^{111}Cd.

activations with iron irradiators 5, 15, 25, and 40 mm thick and one without any iron. The induced $^{111}Cd^m$ activity in the irradiated disks was determined by the intensity of 151 and 245 keV gamma rays (Fig. 1). After a cooling time of 15 min, the intensities of these radiations were measured using an absolutely calibrated Ge spectrometer in a low-background shield.[10] For the given background level and half-life, the optimum measuring time was determined to be 4000 s. Only the two characteristic γ rays were detected in the recorded spectra. After allowing for the detection efficiency, transparency of the disks,[11] irradiation time,[6] cooling and measuring times, gamma intensities, and conversion coefficients, the saturation activities of $^{111}Cd^m$ obtained from the two lines agreed satisfactorily. This confirms that the processes effecting detection and self-absorption in cadmium were correctly taken into account. It should be mentioned that the effects of self-absorption in the Cd disks are significant and that for the 245 keV radiation they amount to 40% attenuation.

The values of the saturation activities of $^{111}Cd^m$, $A_s(E_\gamma)$, as obtained for different iron absorber thicknesses d, are presented in Table I (columns 2 and 3). In column 4 the values of the reaction rate, or the number of photoactivations per atom per second, $P(d)$, are given. These were obtained by dividing the weighted average from the two radiations by the number of atoms per target.

The continuous low-energy tail formed by γ rays passing through the iron absorbers was investigated in a transmission experiment using a point ^{60}Co source of 10 μCi. The characteristic quantity that was measured is defined as

$$F(E,d)=\frac{N(E,d)}{\Delta E\, N(E_0,d)} , \tag{1}$$

where $N(E,d)$ is a number of gamma rays in an energy interval ΔE wide around energy E and $N(E_0,d)$ is the number of 1332 keV gamma rays. Measurements were made at 1300 and 1310 keV and were extrapolated to 1330 keV using the Klein-Nishina formula. The extrapolated values, $F(1330,d)$ which differ very little from the values for $F(1300,d)$ and $F(1310,d)$, are also presented in Table I, column 5.

If, following Ref. 7, we allow for a "nonresonant" contribution to the excitation of the isomeric state, the reaction rate can be written as

$$P(d)=\sigma_R\phi_R(d)+\sigma_{NR}\phi_{NR}(d) , \tag{2}$$

where $\phi_R(d)$ is the number of photons of resonant energy $E_r=1330$ keV per unit energy interval, per unit area and per second, i.e.,

$$\phi_R(d)=\frac{N(E_r,d)}{\Delta E\, St} , \tag{3}$$

and $\phi_{NR}(d)$ is the number of nonscattered gamma rays from the ^{60}Co source with the original energy, $E_0=1332$ keV, per unit area and per second:

$$\phi_{NR}(d)=\frac{N(E_0,d)}{St} . \tag{4}$$

The cross sections σ_R and σ_{NR} are defined as in Ref. 7. The relative intensity of the low-energy tailing is usually described by the ratio:

$$K'=\frac{N(\Delta' E)}{2N(E_0)} , \tag{5}$$

where $N(\Delta' E)$ is the number of scattered 1173 and 1332 keV photons into the energy range 0–1100 keV and $2N(E_0)$ is the number of nonscattered gamma rays of both energies. For strong commercial ^{60}Co sources this ratio is stated to be 10–20%.

We wish to estimate the extent of the energy tail in the region of 1330 keV and we may define a parameter K, similar to K', such that

$$K=\frac{N(E_r)}{2N(E_0)}\frac{\Delta' E}{\Delta E} . \tag{6}$$

The value of K can be determined by fitting the experimental data while using the commercially available value of K' as an indication of the validity of the set of values obtained.

If the linear attenuation coefficients are approximately equal, $\mu(E_r)\cong\mu(E_0)=\mu$, then from Eqs. (3), (4), and (6) it follows that

$$\phi_R(d)=\frac{A}{4\pi r^2(1+K)}e^{-\mu d}\left[\frac{2K}{\Delta' E}+F(E_r,d)\right] \tag{7}$$

and

$$\phi_{NR}(d)=\frac{A}{4\pi r^2(1+K)}e^{-\mu d} , \tag{8}$$

where A is the activity of the ^{60}Co source. The first term in Eq. (7) describes the attenuation of resonant photons emitted by the source and absorbed in iron irradiators while the second describes the creation of resonant pho-

TABLE I. Saturation activities, reaction rates, and F values for different iron absorber thicknesses.

d (mm)	$A_s(151)$ (s^{-1})	$A_s(245)$ (s^{-1})	P (10^{-23} s^{-1})	$F(E_r,d)$ (10^{-4} keV^{-1})	$\phi_R(d)$ (10^6 $keV^{-1}s^{-1}cm^{-2}$)
0	3.8(9)	2.7(3)	13(1)	0.0(1)	0.92
5	2.7(10)	4.3(4)	19(2)	1.7(1)	1.44
15	4.8(10)	4.6(4)	22(2)	4.1(1)	1.66
25	6.3(12)	5.0(5)	24(2)	6.9(1)	1.66
40	4.2(10)	4.2(2)	20(2)	11.1(2)	1.40

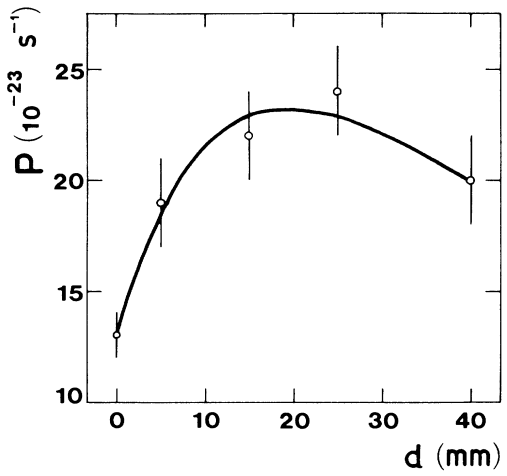

FIG. 2. The least-squares-fitted curve to the experimental values of the reaction rate vs the iron absorber thickness.

tons in the iron. Using Eqs. (7) and (8) the reaction rate, Eq. (2), becomes

$$P(d)=\frac{A}{4\pi r^2(1+K)} \times e^{-\mu d}\left\{\sigma_{\mathrm{NR}}+\left[\frac{2K}{\Delta' E}+F(E_r,d)\right]\sigma_R\right\} . \quad (9)$$

The three parameters, K, σ_R, and σ_{NR} can be determined by the least-squares-fitting procedure, using the experimental values for $P(d)$ and $F(E_r,d)$ as given in Table I. The resonant photon flux, as derived from Eq. (7), is also listed in Table I, column 6. The curve fitted to the experimental points is shown in Fig. 2 and the corresponding values of the fitted parameters are listed in Table II, where they are also compared with the values from Ref. 7.

As can be seen from Table II, our result for the resonant part of the cross section, σ_R, is twice that of Ref. 7. Also, our result for the "nonresonant" cross section, σ_{NR}, is an order of magnitude smaller than that obtained in Ref. 7 and it includes zero within its one standard deviation error limits. This means that our results, obtained using very much the same technique as was used before and having the same statistical significance (same χ^2), do not indicate a need to introduce any "nonresonant" processes.

TABLE II. Comparison of the derived parameters for photoexcitation of $^{111}Cd^m$.

	Our results	Results of Ref. 7
K (%)	10(1)	18
σ_R (10^{-29} cm^{2}keV)	14(1)	5.8(8)
σ_{NR} (10^{-32} cm^2)	0.1(2)	1.6(2)
χ^2	1.3	1.32

However, the authors in Refs. 6–8 do not quote explicitly the expression on which their least-squares analysis is based, so that direct comparisons between their work and ours is not possible. The resonant cross section determined in this experiment is equal to

$$\sigma_R=\pi^2\lambda^2 g\frac{\Gamma_0\Gamma_{\mathrm{iso}}}{\Gamma} , \quad (10)$$

where Γ_0 and Γ_{iso} refer to the partial widths of the 1330 keV state for decay to the ground state and to the isomeric state, and Γ is the total width of the 1330 keV state. Now since the spin of the 1330 keV state and the branching ratio $\Gamma_{\mathrm{iso}}/\Gamma$ are not known, we can only try to estimate the half-life of the 1330 keV state and thus *a posteriori* justify the assumption that the excitation of the isomer goes dominantly via that particular state. To do this we assume that the spin of the state which is so favorably resonantly excited cannot differ much from the ground state spin, i.e., the statistical factor g, Eq. (10), is of the order of 1. If so, the population of the isomer by the decay of this state would proceed either via a sequence of low multipolarity transitions cascading from states with lower spin values to states with higher spin values, or via the emission of a single high multipolarity gamma ray. For both processes the probability would be low and for the purpose of an estimate we take generously $\Gamma_{\mathrm{iso}}/\Gamma\approx 0.01$. Under these assumptions and with our value of the resonant cross section, the total width of the 1330 keV state would be $\Gamma(1330\ \mathrm{keV})\approx 10^{-2}$ eV, with the corresponding half-life $T_{1/2}(1330\ \mathrm{keV})\approx 10^{-14}$ s, which seems short enough to justify the initial assumption.

To understand the peculiarities of this particular state, it would be useful to study its excitation and decay in other processes, such as in the neutron capture by ^{110}Cd. It is also necessary to examine other cases where the existence of "nonresonant" processes have also been suggested and determine if the problem may be resolved as in the case of ^{111}Cd.

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