Population of the metastable state of ^{111}Cd via photoactivation by ^{60}Co source

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New levels and transitions are suggested which are associated with the population of the 48.54 min isomeric state of ^{111}Cd via photoactivation by ^{60}Co source. The proposed new levels are 1330 keV; $\frac{5}{2}^+$ and 705 keV; $\frac{7}{2}^+$. The former was identified as the first strong activation level, the latter as an intermediate level. Two weaker activation levels were also identified: 1130.4 keV; $\frac{5}{2}^+$ and 736 keV; $\frac{5}{2}^+$. Half-lives of the activation levels and the relevant metastable state feeding branching ratios were deduced to be 1 ps, 0.14; 80 ps, 0.01; and >1 ns, <0.01, respectively. The proposed new transitions are 1330→0 ($E2$), 1330→705 ($E2+0.5\%M1$), 1130→705 ($E2$), 736→0 ($E2$), 736→705 ($E2+0.8\%M1$), 705→680 ($M1$).

Photoactivation of ^{111}Cd^m has been studied by many authors.[1–13] Strong population of the metastable state after ^{60}Co excitation[2–10] clearly indicates that activation levels lie below 1332 keV. The bremsstrahlung experiments of Boivin *et al.*[13] have indicated two weak and one strong activation level at 740±10 keV, 1120±10 keV, and 1330±10 keV, respectively. The last of these was also observed by Chertok and Booth.[12] However, neither any of the activation levels nor the depopulating cascades were identified and little is known about the level parameters (width, half-life, branching ratios).

Recently Bikit *et al.*[10] estimated the total level width (Γ) and the half-life ($T_{1/2}$) of the 1330 keV activation level as well as the branching ratio populating the metastable state (Γ_{iso}/Γ). Their $T_{1/2}$ and Γ_{iso}/Γ values seem to have been underestimated by an order of magnitude if one compares them with the same parameters of the first strong activation level of several nuclides having an atomic number close to that of cadmium (Table I). On comparing the results of their own self-absorption and resonance scattering experiments Zaparov *et al.*[5] reported Γ_{iso}/Γ to be 0.14 which matches well the Γ_{iso}/Γ values listed in Table I. The goal of this paper is to survey the possible cascades populating the metastable state and to reestimate the parameters of the activation level.

Our work is based on the assumption that photoactivation takes place via the well-known resonant process. Recently the dominance of nonresonant processes was reported for four nuclides.[9,19,20] However, these observations are disproved by the most recent (γ,γ') studies[10,21,22] so only the resonant excitation mechanism is assumed.

The level structure of ^{111}Cd was investigated by β-decay experiments,[23–25] Coulomb excitation,[26–29] (d,p) and (d,t),[30] $(\alpha,3n\gamma)$,[31] (d,d'),[32] (p,p'),[33] $(\bar{n}_{res},\gamma)$,[34] and $(n,n'\gamma)$ (Ref. 35) reactions. More than 20 levels are known below 1332 keV but little is known about the γ transitions. The level scheme of ^{111}Cd compiled by us is shown in Fig. 1. Eight new levels and ten new or certain spin assignments are introduced compared with the Nuclear Data Sheets' level scheme.[14] Seven of the new levels were established by the investigations of Singh *et al.*[29] and Baskova *et al.*[34,35] while the remaining one was deduced by us as is described below.

When reconstructing the cascades which populate the isomeric state we first make an effort to find the level(s) which connect the activation level and the metastable level. There may be one or more of these intermediate levels but one of them has to have a spin of $\frac{7}{2}^-$ or $\frac{9}{2}^\pm$, bearing in mind the $\frac{5}{2}^+$ or $\frac{3}{2}^+$ spin of the activation levels and the

TABLE I. Comparison of the $|J_a-J_0|$, Γ_{iso}/Γ, and $T_{1/2}$ values of the first strong activation levels of nuclides having atomic numbers close to that of cadmium. J_a and J_0 stands for the spin of the activation level and the ground state, respectively. The asterisk indicates that $T_{1/2}$ is calculated by the authors from the cross-section data of the former and branching ratio data of the latter reference.

Nuclide	Activation level (keV)	$\lvert J_a-J_0\rvert$	Γ_{iso}/Γ	$T_{1/2}$ (ps)	References
^{77}Se	1187	2	0.66	0.4	5,15*
^{87}Sr	1228	2	0.11	0.1	5,16*
^{113}In	1131	2	0.16	0.97	17
^{115}In	1078	2	0.157	0.86	18
^{111}Cd	1330		0.01	0.01	10
			0.14	2.2	5*

$\frac{11}{2}^-$ spin of the isomeric state. (We suppose $E1$, $M1$, or $E2$ transitions only.) There are three known levels with the required spin: 680.4 keV; $\frac{9}{2}^-$, 986.4 keV; $\frac{9}{2}^+$, and 1126.6 keV; $(\frac{7}{2})$.

Population of the 986.4 keV state was reported in $(\alpha,3n\gamma)$ reaction but Ohya *et al.*[31] did not observe a 986 keV $\rightarrow \ldots \rightarrow$396 keV cascade so we can exclude it. The 1126.6 keV state cannot be the intermediate of the two

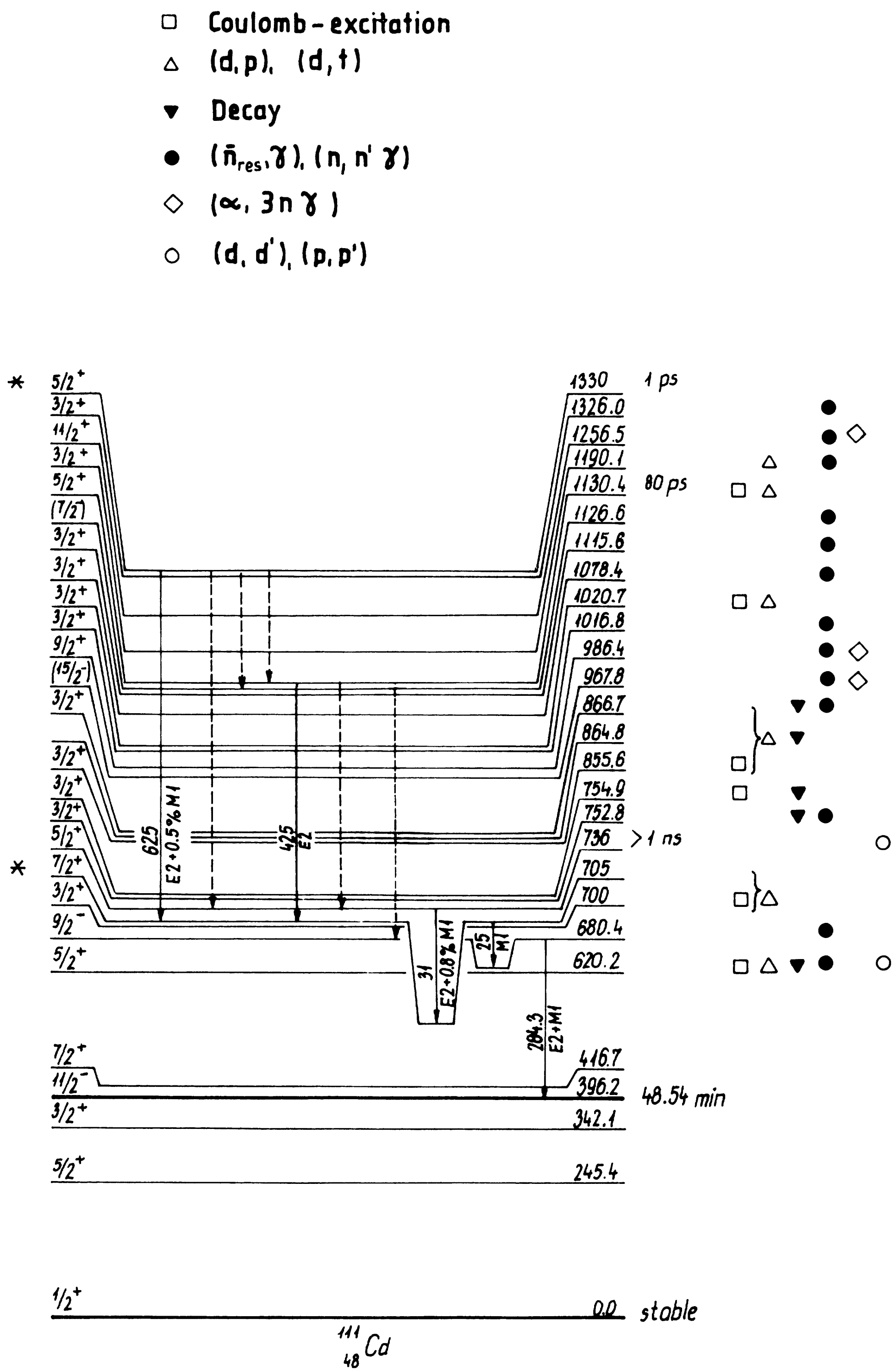

FIG. 1. Level structure of ^{111}Cd. Data from Refs. 14, 29, and 34–36. Levels assigned by asterisk, half-lives, as well as all indicated transitions, except the 284.3 keV $E2+M1$ one reported by Baskova *et al.* (Ref. 35), are introduced by us. Cascades feeding the isomeric state are shown only. Transitions indicated by dotted arrows are believed to have minor or negligible contribution. Reaction types which populated the individual levels are also displayed above 600 keV.

weak activation levels. If we identify the second one as the 1130.4 keV; $\frac{5}{2}^+$ level it has to have a Γ_{iso}/Γ ratio of less than 10^{-5} in view of the Weisskopf-estimated half-lives and the fact that the Weisskopf formula underestimates the $E1$ half-lives by more than two orders of magnitude.[37] Taking into account this extremely low branching ratio together with the fact that the 1126.6 keV level lies higher than the first activation level we can also exclude it.

The 680.4 keV; $\frac{9}{2}^-$ state was first observed by Baskova *et al.*[34] They found a strong 284.3 keV $E2$ transition which was placed between the 680.4 keV and the isomeric states. If one recalls that the 680.4 keV level was not seen in the ^{110}Pd$(\alpha,3n\gamma)$ experiment,[31] where the high spin states were populated (which indicates that this level is fed from lower spin states), one can identify it as the sought intermediate level. However, bearing in mind that we restrict ourselves to $E1$, $M1$, and $E2$ transitions only, the $\frac{9}{2}^-$ spin requires the existence of a further intermediate level. This level is expected to lie below 740 keV but above 681 keV and to have $\frac{7}{2}^\pm$ or $\frac{9}{2}^+$ spin. Besides the logical necessity for this level to exist, there is also a positive indication: viz. Rosner,[30] in his (d,p) and (d,t) experiments, observed a level at 700±10 keV and found the spin exchange to be (4). If this value is correct, a level different from 700 keV; $\frac{3}{2}^+$ state is (also) populated which establishes a level with $\frac{7}{2}^+$ or $\frac{9}{2}^+$ spin. (To distinguish the deduced level from the 700 keV one, the former is assigned as 705 keV.)

The second step is to identify the activation levels. It is easy to do for the two weak levels. The 740±10 keV first one[13] must be the same as the 736±10 keV state observed by Koike in (p,p') reaction[33] and the 730±10 keV state seen by Jolly *et al.* in (d,d') excitation.[32] The two-units spin exchange reported by Koike[33] supports the expected $\frac{5}{2}^+$ spin assignment. The second activation level must be the 1130.4 keV; $\frac{5}{2}^+$ state which was observed by Singh *et al.*[29] in Coulomb excitation, and by Rosner[30] in (d,p) and (d,t) reactions. One can rule out the other candidate, the 1115.6 keV; $\frac{3}{2}^+$ level because it decays by strong transitions to the ground and 416.7 keV states.[14,35]

The strong activation level cannot be the 1326.0 keV; $\frac{3}{2}^+$ state observed by Baskova *et al.*[34] considering that feeding of an intermediate level after its deexcitation was not reported by them although this state showed the strongest direct population in the $(\bar{n}_{res},\gamma)$ experiment. Moreover, glancing at Fig. 1, where the reaction types which populate the individual levels are also indicated (above 600 keV), one can find a strange "anticoincidence": viz., states populated by Coulomb excitation[26–29] are not populated by $(\bar{n}_{res},\gamma)$ (Ref. 34) and $(n,n'\gamma)$ (Ref. 35) reactions and vice versa. Since the levels associated with the (γ,γ') excitation (activation levels, 705 keV level) do not appear in neutron reactions we assume that the activation level sought is not the 1326.0 keV; $\frac{3}{2}^+$ one. It means that we cannot refine the energy value given by Boivin *et al.*,[13] but we suggest $\frac{5}{2}^+$ spin, bearing in mind that the first strong activation level ground-state spin differences tend to be 2 (see Table I). The proposed metastable state feeding cascades are shown in Fig. 1.

The (γ,γ') cross-section data together with a knowledge of deexciting cascades enable us to estimate the parameters of the activation levels by means of the formula

$$\Gamma_0(\Gamma_{iso}/\Gamma)=\sigma_{int}/(g\pi^2\lambda^2)\ , \tag{1}$$

where Γ_0 is the ground-state transition width, σ_{int} is the integrated (γ,γ') cross section, λ is the wavelength of the incident photon divided by 2π, and

$$g=(2J_a+1)/(2J_0+1)$$

is the statistical factor. J_a and J_0 is the spin of the concerned activation level and the ground state, respectively. We calculated with $\sigma_{int}(1330)=(10.2\pm2.6)\times10^{-26}$ cm^2 eV (Lakosi *et al.*[7]) which is approximately the same as the average of the available $\sigma_{int}(1330)$ values;[2,3,5,7,8,10,12,13] while for $\sigma_{int}(1130)$ and $\sigma_{int}(736)$ data of Boivin *et al.*[13] are accepted.

We performed a Weisskopf estimation of the relevant transitions and calculated Γ_0's according to the expression $\Gamma_0=\hbar\times\ln2/[2(T_{1/2})_0]$, where $\hbar$ is the Planck constant and $(T_{1/2})_0$ is the partial half-life of the ground-state transition. Γ_{705}/Γ_0 ratios were also calculated which are expected to be equal with the relevant Γ_{iso}/Γ values obtained from Eq. (1) within 1 order of magnitude.

Comparing the Γ_{705}/Γ_0 and Γ_{iso}/Γ ratios, their striking deviation in the case of the 1330 and 736 keV levels led us to suppose $M1$ admixture for the 625 and 31 keV transitions. Its consequence is a certain $\frac{7}{2}^+$ spin assignment for the 705 keV level. Comparing the calculated level and decay parameter values with the experimental data and considering the values of the same parameters in other nuclides around $A=100$, we deduce an enhancement factor of 4±2 for the 1330 keV transition and retardation factors of 8 and >10 (order of magnitude estimations) for the 1130.4 and 736 keV transitions, respectively. The relevant Γ_{iso}/Γ ratios are 0.14, 0.01, and <0.01, respectively. Other calculated parameters are indicated in Fig. 1.

Though our proposed decay scheme seems to be self-consistent and agrees with the experience gained from other nuclides, experimental confirmation would be welcomed. It would be useful if the final result of the $(n,n'\gamma)$ experiment of Baskova *et al.*[35] were to be published as well as further investigations, mainly an in-beam (γ,γ') study, for definitely identifying the isomeric state cascades. Theoretical interpretation of the strange "anticoincidence" which divides into two groups the levels of ^{111}Cd is urged.

Note added in proof: After the manuscript was submitted we observed the papers of Smith *et al.*[38,39] dealing with the fast neutron excitation of ^{111}Cd^m. Dropping their incorrect assumption that decay of the 700, 754, and 867 keV levels feeds the metastable state, we find their carefully measured excitation function in agreement with our proposed level scheme, viz., the small jumps at 684 (Ref. 38) and 707 keV (Ref. 39) as well as the steep increase at 789 (Ref. 38) and 750 keV (Ref. 39) are interpreted as evidences for the population of the 680 and 705 keV levels, respectively. The second large jump between 893 and 1493 keV (Ref. 38) is believed to be predominantly caused by the 1330 keV level. We note that none of the levels corresponding to the feeding of the isomer state was observed by Wang *et al.*[40] in their recent $^{110}Pd(^{3}He,2n\gamma)^{111}Cd$ study.

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