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Production Cross Sections and Isomeric Ratios for the Isomeric Pair $^{110m}\text{In}/^{110g}\text{In}$ Formed in Cd (d, xn) Reactions

By O. HERREROS USHER, E. MACEIRAS, M. C. SARAIVI and S. J. NASSIFF, Comisión Nacional de Energía Atómica, Argentina

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Abstract

Excitation functions and isomeric cross sections ratios have been measured for the ^{110}Cd (d, 2n) and ^{111}Cd (d, 3n) reactions in which the isomeric pair $^{110m}\text{In}/^{110g}\text{In}$ is produced. Isomeric ratios show different trends in the case of (d, 2n) and (d, 3n) reactions.

Introduction

Although a study of excitation functions and the isomeric cross section ratios does not lead to detailed analysis of reaction mechanisms, it is useful to test the validity of theoretical models. The isomeric ratios, for example, provide information about some parameters of the statistical theory, specially about those related to the angular momentum distribution.

The metastable state of a nuclide differs from the ground state in spin value (and sometimes parity assignment) and often in excitation energy. The ratio of their formation cross sections represents the net result of angular momentum effects in the processes taking place during the nuclear reaction.

Experimental data about (d, xn) reactions that produce isomeric pairs are actually scarce. Some of them are listed in references [1–6].

Specifically, in this study, we have investigated the variation of isomeric yield ratios as a function of bombarding energy. The cross sections and the isomeric ratio for the production of $^{110m/g}\text{In}$ in (d, xn) reactions on natural cadmium are reported.

Experimental

a) Irradiations

Cross sections were experimentally determined by the activation method. Irradiations of natural cadmium were performed with the external beam of the synchrocyclotron of Comisión Nacional de Energía Atómica. The stacked foil technique was applied and the reaction products were measured via gamma ray spectroscopy.

Natural cadmium foils of 25.6 mg/cm^2 thickness were stacked with aluminum foils (16.56 mg/cm^2) with the purpose of monitoring the deuteron flux by measuring the activity of ^{24}Na formed in the ^{27}Al (d, αp) reaction [7]. The activities of the nuclides produced in the cadmium foils relative to that of ^{24}Na in the aluminum monitoring foils provide a method of obtaining absolute cross sections for the nuclear reactions involved.

The energy of the incident deuteron beam was 27.5 MeV with an uncertainty estimated below 1%. The energy of the deuteron at the middle of each foil of the target was determined from range-energy tables [8]. Uncertainties in the values of the beam energy at the position of a particular foil result from two sources; the magnification of the spread in the energy of the incident beam by energy loss fluctuations and the uncertainty in the thickness of the target foil.

Corrections for energy spread due to nonuniformity in foil thicknesses were not applied. Losses in reaction products due to recoil were assumed to be negligible.

b) Counting

After irradiation gamma spectra were measured without any prior chemical treatment, since interfering activities were negligible. Absolute decay rates were measured with a Ge(Li) detector coupled to a multichannel analyzer.

The spectrometer was calibrated with standard radioactive sources. Gamma-ray detection efficiencies were obtained from several series of measurements; the obtained values agree within 1%. For efficiency interpolation the equation $\Sigma(E_\gamma) = KE_\gamma^{-n}$ was used.

The nuclides were identified by photopeak energy and half-life. The latter was carefully measured during several half-lives in order to identify the nuclides without any doubt.

Photopeak areas were calculated by Wasson's method [10–11]. Absolute activities were obtained by using the decay scheme data in refs. [12, 13].

Cross sections and their isomeric ratios are based on the 657.7 keV gamma-ray activity, by measuring spectra successively and extrapolating the activities with half-lives of 4.9 h and 69.1 min to the end of irradiation, since there is no genetic relation between the ^{110}In isomeric levels [12]. Cross sections for the ^{110m}In ($T_{1/2} = 4.9 \text{ h}$)

production were also calculated using the 997.2 keV gamma-ray activity. Both sets of values agree within the experimental error.

The over-all error of each measurement was estimated on the basis of the possible errors in counting statistics, photopeak areas, detector efficiencies, foil thicknesses and areas, decay scheme data and timing. In the calculation of isomeric cross section ratios from the same gamma ray, only errors of photopeak areas and timing play a part.

Results and conclusions

In the energy range considered the isomeric pair $^{110m/g}\text{In}$ is produced via $^{110}\text{Cd}(\text{d}, 2\text{n})$, $^{111}\text{Cd}(\text{d}, 3\text{n})$ and $^{112}\text{Cd}(\text{d}, 4\text{n})$ reactions, with threshold energies of 7.1, 14.1 and 23.8 MeV, respectively.

In Table 1 and Figs. 1 and 2 proportional values to the production cross sections for ^{110m}In and ^{110g}In are shown. Production cross sections are obtained by multiplying these values by the average atomic weight (\bar{A}) and dividing by the isotopic abundance ($\sum_i a_i$).

$$\bar{A} = \frac{\sum_i A_i a_i}{\sum_i a_i}$$

were A_i and a_i are the atomic weight and the isotopic abundance of the target nuclides, respectively.

Dashed lines represent an estimate of the contribution of each possible reaction to the production of each isomeric level. This estimate was performed on the basis of systematic studies of excitation functions with charged particles [14–16].

Table 1. $\sigma_p(\text{mb}) \sum_i a_i / \bar{A}$ for the production of both ^{110}In isomeric levels

E_d (MeV)	$\sigma_p(\text{mb}) \sum_i a_i / \bar{A}$	
	^{110m}In	^{110g}In
27.28	0.991 ± 0.036	0.327 ± 0.024
26.37	0.973 ± 0.036	0.267 ± 0.020
25.48	0.966 ± 0.034	0.302 ± 0.022
24.495	0.931 ± 0.034	0.245 ± 0.018
23.55	0.893 ± 0.032	0.266 ± 0.020
22.49	0.890 ± 0.032	0.231 ± 0.018
21.41	0.790 ± 0.028	0.247 ± 0.018
20.29	0.780 ± 0.028	0.165 ± 0.012
19.20	0.664 ± 0.024	0.285 ± 0.022
17.94	0.539 ± 0.020	0.369 ± 0.032
16.665	0.430 ± 0.016	0.312 ± 0.024
15.37	0.332 ± 0.140	0.322 ± 0.026
13.93	0.244 ± 0.100	0.307 ± 0.028
12.40	0.161 ± 0.080	0.270 ± 0.026
10.77	0.066 ± 0.080	0.213 ± 0.030

Solid lines represent the absolute cross sections obtained from the curves evaluated in this way correcting for the ratio of atomic weight to isotopic abundance of the target nuclide involved. These values and also their ratios between higher spin ($T_{1/2} = 4.9$ h) and lower spin ($T_{1/2} = 69.1$ min) levels are shown in Tables 2 and 3.

Isomeric ratios show different trends in the case of (d, 2n) and (d, 3n) reactions (Fig. 3).

For (d, 2n) reaction the ratio increase with the deuteron energy, in agreement with the compound nucleus model that predicts a favoured angular momentum transfer to residual nucleus at higher particle energies.

For (d, 3n) reaction the σ_H/σ_L ratio decreases with increasing deuteron energies. In the $^{90}\text{Zr}(\text{d}, 3\text{n})$ $^{89m,g}\text{Nb}$ reaction [2] the same effect was observed.

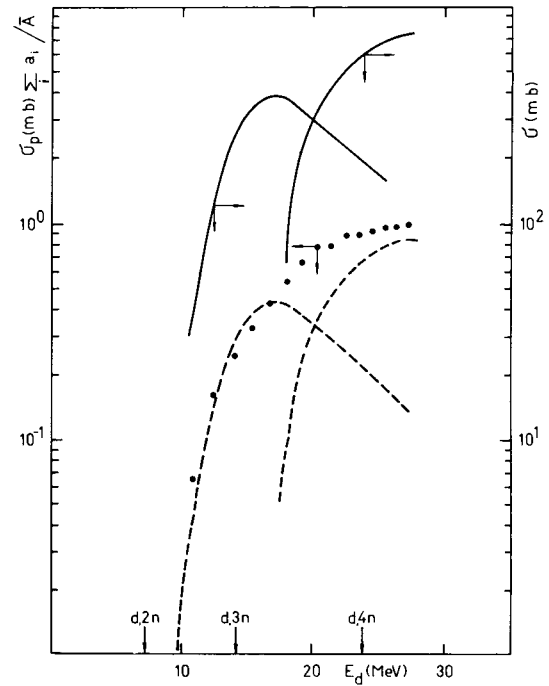


Fig. 1. $\sigma(\text{mb}) \sum_i a_i / \bar{A}$ for the ^{110m}In

----- Contribution of each possible reaction based on refs. [14–16]
 ———— Excitation Functions

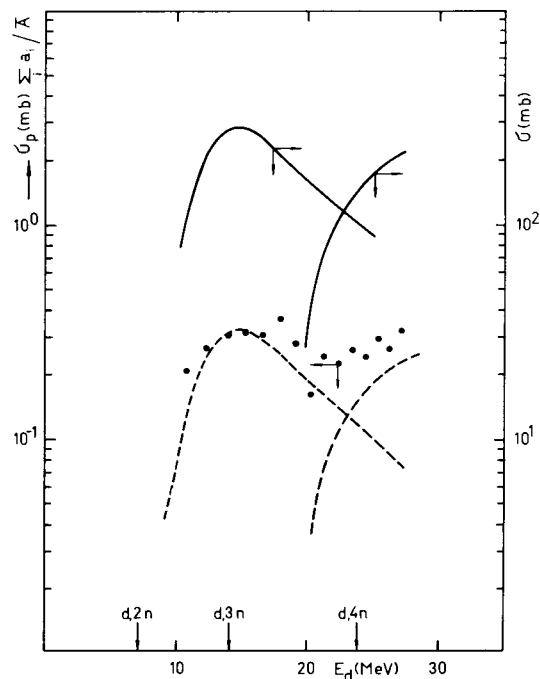


Fig. 2. $\sigma(\text{mb}) \sum_i a_i / \bar{A}$ for ^{110g}In

----- Contribution of each possible reactions based on refs. [14–16]
 ———— Excitation Functions

This trend could be explained by taking into account other reaction mechanisms; i. e. direct reactions (stripping) in which the angular momentum transfer to the residual nucleus is much less than in compound nucleus reactions. On other hand, DEMEYER [3] has proved that the decreasing isomeric ratio at higher excitation energies would be explained by introducing the effect of limits of spin (Yrast levels).

Table 2. Absolute cross sections and isomeric ratios for the ^{110}Cd (d, 2n) $^{110m/g}\text{In}$ reaction

E_d (MeV)	σ (mb)		σ_H/σ_L
	^{110m}In	^{110g}In	
24.495	177.4	97.6	1.82
23.55	201.4	110.0	1.83
22.49	227.1	124.2	1.83
21.41	259.9	143.7	1.81
20.29	292.7	164.1	1.78
19.20	332.6	186.3	1.78
17.94	375.2	221.8	1.69
16.665	390.3	257.2	1.52
15.37	345.9	292.7	1.18
13.93	257.2	283.8	0.91
12.40	120.6	212.9	0.57
10.77	39.9	110.0	0.36

Table 3. Absolute cross sections and isomeric ratios for ^{111}Cd (d, 3n) $^{110m/g}\text{In}$ reaction

E_d (MeV)	σ (mb)		σ_H/σ_L
	^{110m}In	^{110g}In	
27.28	735.0	200.9	3.66
26.37	726.3	182.7	3.98
25.48	687.2	164.4	4.18
24.495	635.0	135.7	4.68
23.55	574.1	112.2	5.12
22.49	500.2	89.6	5.58
21.41	408.8	29.6	13.8
20.29	321.8		
19.20	217.5		
17.94	82.6		

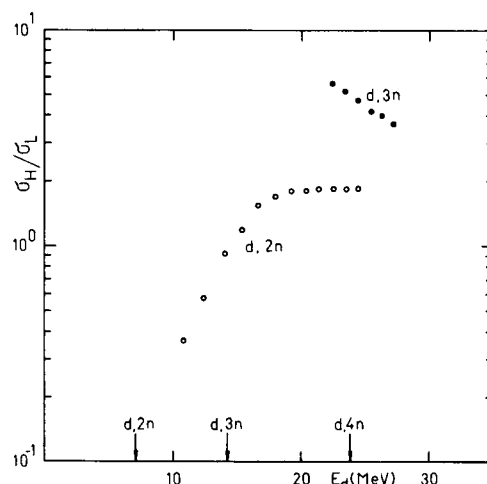


Fig. 3. Isomeric ratios for (d, 2n) and (d, 3n) reactions

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