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Production Cross Sections of ^{109g}In, ^{111g}In, ^{113m}In and ^{115g}Cd Formed by Deuterons on Cadmium

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Abstract

Production cross sections for Cd (d, xn) ^{109g}In, Cd (d, xn) ^{111g}In, Cd (d, xn) ^{113m}In and Cd (d, pxn) ^{115g}Cd were measured by the foil activation method, up to 27.5 MeV deuterons.

Introduction

Cross section data are useful in different fields of science and technology:

a) Knowledge of radioisotopes formation cross sections is a prerequisite when working in charged particles activation analysis in order to predict both expected sensitivity and possible interferences [1, 2].

b) Their comprehension is also a prerequisite for development work on radionuclide production by means of charged particle bombardment [3].

c) Knowledge of their values is most useful in order to reliably predict residual radioactivity levels within accelerator facilities [4, 7].

d) Last not least, even though detailed knowledge of integrated cross sections does not allow for a very clear interpretation of the involved reaction mechanisms, it does provide a useful background for further study of nuclear reactions. Furthermore, it furnishes information on cross section systematics as well as on the involved parameters [8, 9].

This paper reports on the production cross sections of ^{109g}In, ^{111g}In, ^{113m}In and ^{115g}Cd as obtained through deuteron irradiation of natural cadmium. Our results are then compared with those obtained from the systematics [8, 9] as well as with data from other authors [10].

Experimental

a) Irradiations

The experimental method used here is basically the same as cited in Refs. [11–15].
Stacks of natural cadmium foils were exposed to the syncrocyclotron deuteron beam. In each case the target stack was thick enough to stop the 27.5 MeV deuteron external beam. Maximum uncertainty in the incident beam energy was estimated as being lower than 1%.
Cadmium foils were spectroscopically analysed for interfering impurities which were found to be negligible. Target foils were placed between aluminium foils of known thicknesses, intended for degradation of deuteron energy.

The deuteron energy at the midpoint of each target thickness was calculated from the range-energy tables [16].

The uncertainty in the incident particle energy for each data point arises from the energy spread of the incident deuteron beam as well as from the energy straggling losses. The latter was estimated as about 0.5 MeV [17].
The excitation function of the ^{27}Al (d, αp) ^{24}Na reaction [18] being well known, a comparison of the yields of the radioactive isotopes formed in their radiation of cadmium with that of ^{24}Na yield in aluminium foils allows to obtain the absolute cross section values for the concerned reactions resulting from deuteron irradiation of cadmium.

b) Counting

Production cross sections were measured by the activation method.
After bombardment, gamma ray spectra of each foil were measured with a high resolution Ge (Li) detector coupled to a multichannel pulse height analyser.
Enough data were taken at time intervals suitable for nuclide identification. A check of half-life and gamma ray energies was carried out. The spectrometer was calibrated to allow both gamma energy and peak intensity measurements.
Absolute detection efficiency was determined using calibrated sources of known activity. Most efficiency determinations agreed within the statistical error of 3%.
Efficiency $\epsilon\,(E\gamma)$ was calculated for other energies using:

$$\epsilon(E\gamma) = C \cdot E_\gamma^{-n} .$$

After each photopeak was recorded, the respective values of counts per unit time were corrected following Wasson's method.
Relative activities corresponding to the final irradiation times were calculated from extrapolations of decay curves.
Values of detector absolute efficiency, as well as data read from the decay schemes, allowed a conversion of the peak count rate into nuclide decay rates.
Foil thicknesses and deuteron flux were measured and used to calculate production cross sections for each of the active isotopes found in each foil.

No corrections were made either for the energy spread at each foil (as resulting from foil thickness variations) or for energy losses at the preceding foils. The eventual losses of reaction products by recoil were assumed to be negligible. As for any reactions that might be due to secondary neutrons, additional foils were set up beyond the range of deuterons. Spectra from those foils showed no significant contribution to our data.

Results and conclusions

Let several isotopes of a given element be simultaneously submitted to charged particle irradiation, thereby yielding the same radionuclide. When measuring activity (A_0) of the latter

$$kA_0 = \sigma_p \frac{\sum_i^n a_i}{\bar{A}} = \sum_i^n \frac{a_i \sigma_i}{A_i} .$$

This is a linear expression of σ, which allows to evaluate the respective contributions to the total activity, using LANGE and MÜNZEL systematics.

The respective contributions of those target isotopes towards total activity are shown in Figs., 1 to 4 as dashed curves; they show $\frac{a_i}{\bar{A}} \sigma$ as a function of energy, E. Such figures allow for getting σ values after a simple multiplication.

Proportional values to the production cross sections $\sigma_p\,(\mathrm{mb}) \sum_i \frac{a_i}{\bar{A}}$ measured during this work are shown in in Figs. 1 to 4. Here ($\bar{A}$) is the average atomic weight:

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

with A the atomic weight, and a_i the isotopic abundance of the target nuclides involved in the residual nuclei production.

The expression $\sigma_p\,(\mathrm{mb}) \sum_i \frac{a_i}{\bar{A}}$ is used because it allows to evaluate the respective contributions of possible reactions. when following LANGE and MÜNZEL systematics [8].

Threshold energies from KELLER, LANGE and MÜNZEL Tables [23] for some reactions that could produce the nuclides are shown on the respective graphs. From these threshold it is possible to draw some conclusions as to which reactions are expected to give higher contributions to the low energy parts of the curves.

Decay schemes were taken from Ref. [22]; conversion coefficients and other decay data were taken from Ref. [21].

Uncertainties in the cross section values were estimated as 15% or less. The former wer obtained by propagating

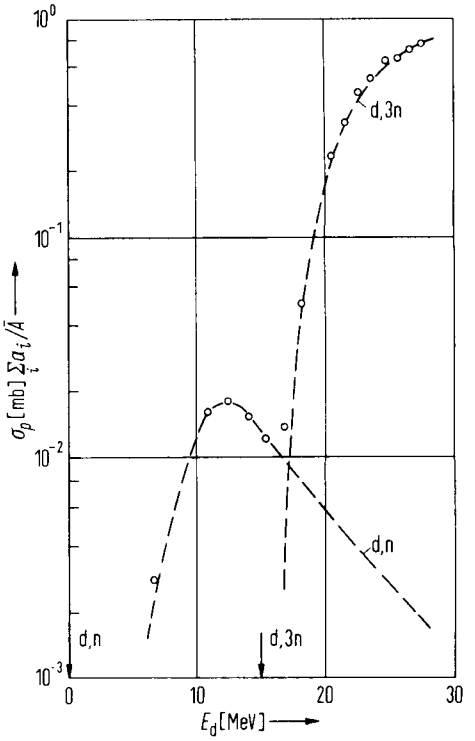

Fig. 1. σ_p (mb) $\sum a_i/\bar{A}$ for ^{109g}In. Dashed lines represent the estimates of different possible reactions

in quadrature the contributions from both decay curve and peak analyses (the latter including counting statistics), absolute detector efficiencies, disintegration schemes, target thicknesses and deuteron flux.

Radiochemical techniques deal only with residual nuclei, and not with the emitted particles; they are therefore not intrinsically able to discriminate between possible reaction modes or to find out which reaction is really involved, especially in those cases where several reactions producing the same alternatives are energetically feasible.

In some cases, different reactions starting from different isotopes contribute towards forming the same nuclide; no corrections were made to allow for the respective atomic weight and isotopic abundance of the respective species. However, in order to evaluate their contributions, excitation functions as shown by LANGE and MÜNZEL [8] were used.

Absolute cross sections for a given reaction can thus be deduced from the curves evaluated in this way by correcting for the ratio atomic weight to isotopic abundance of the target nuclide involved.

Excitation functions may in some instances include contributions arising from short lived precursors decay.

Fig. 1 displays σ_p (mb) $\sum_i a_i/\bar{A}$ for the production of ^{109g}In as a function of deuteron energy over the depicted energy interval. ^{109g}In is produced through both (d, n) and (d, 3n) reactions; dashed curves represent estimates of different possible reactions. Cross section values include contributions from both 0.21 sec and 1.34 min isomeric states.

^{111g}In (Fig. 2) would be partially generated by ^{111m}In by disintegration of the shorter-lived isomer ($T_{\frac{1}{2}}$ = 7.6 min).

The respective contributions of (d, n), (d, 2n) and (d, 3n) reactions were estimated using the systematic work by MÜNZEL *et al.* [8, 9]. Their results are plotted in Fig. 2 (dashed lines).

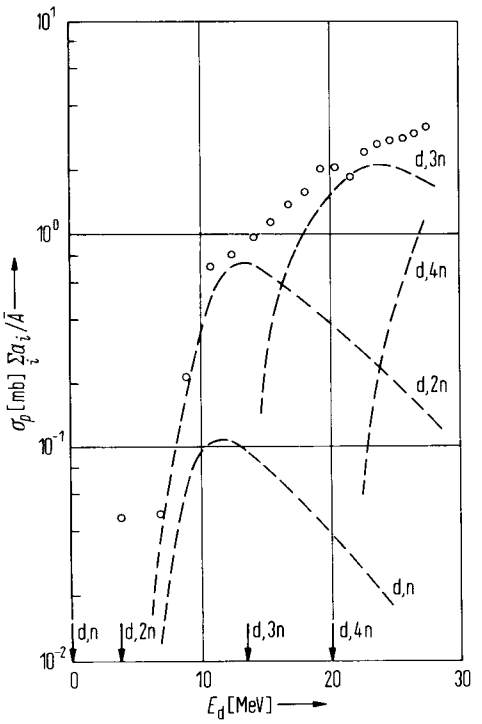

Fig. 2. σ_p (mb) $\sum a_i/\bar{A}$ for ^{111g}In. Dashed lines represent the estimates of different possible reactions

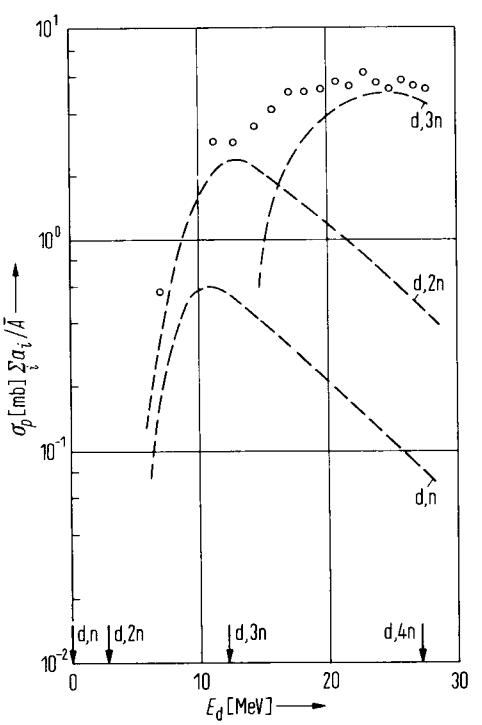

Fig. 3. σ_p (mb) $\sum a_i/\bar{A}$ for ^{113m}In. Dashed lines represent the estimates of different possible reactions

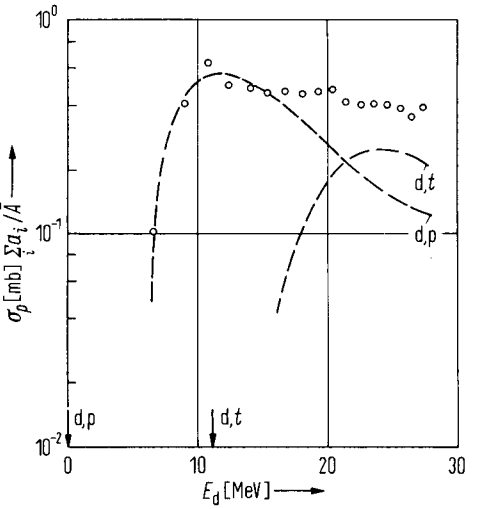

Fig. 4. σ_p (mb) $\sum a_i/\bar{A}$ for ^{115g}Cd. Dashed lines represent the estimates of different possible reactions

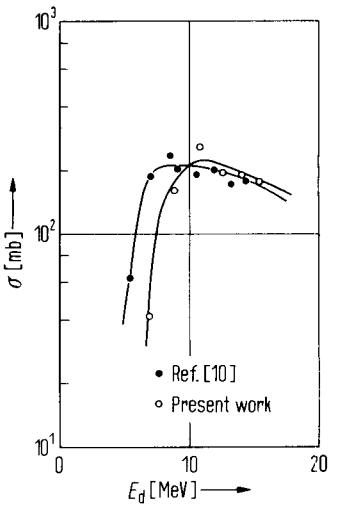

Fig. 5. Absolute cross sections for ^{114}Cd (d, p) ^{115g}Cd reaction

The results for ^{113m}In are plotted in Fig. 3. Contributions from ^{112}Cd (d, n), ^{113}Cd (d, 2n) and ^{114}Cd (d, 3n) were estimated.

Fig. 4 displays the σ_p (mb) $\sum_i a_i/\bar{A}$ for ^{115g}Cd produced by Cd (d, p) and ^{116}Cd (d, t) reactions. Dashed lines represent their estimated contributions. In Fig. 5 our results for the (d, p) reaction are compared with those from NATOWITZ and WOLKE [10].

Absolute cross section values as calculated from our data and corrected for the isotopic abundance and atomic weight were compared with the systematics of excitation functions [8, 9]. Good agreement was found.

Within the frame of this work no attempt was made to clarify the reaction mechanisms involved.

The target yield for ^{111g}In ($T_{\frac{1}{2}}$ = 2.8 days) production was calculated through numerical integration applying experimental cross sections values obtained in the present

Table 1

Range energy	Thickness of the target	$\sigma_p \sum a_i/\bar{A}$	Saturation activity	$\sum$ Saturation activity	$\sum A_{t/10}$	$\sum A_{1h}$
(MeV)	(mg/cm²)	(mb)	(μCi/μA)	(μCi/μA)	(μCi/μA)	(μCi/μAh)
27.5–26	84.04	3.08	2.5915×10^4	1.52649×10^5	1.0222×10^4	1.5499×10^3
26–25	53.40	2.90	1.5775×10^4	1.26314×10^5	8.4588×10^3	1.2825×10^3
25–24	51.90	2.80	1.4784×10^4	1.10559×10^5	7.4037×10^3	1.1225×10^3
24–23	50.40	2.65	1.3588×10^4	9.5774×10^4	6.4137×10^3	9.724×10^2
23–22	48.80	2.48	1.2313×10^4	8.2186×10^4	5.5037×10^3	8.344×10^2
22–21	47.30	2.30	1.1068×10^4	6.9873×10^4	4.6792×10^3	7.094×10^2
21–20	45.70	2.12	9.8570×10^3	5.8946×10^4	3.9380×10^3	5.970×10^2
20–19	44.10	1.92	8.6145×10^3	4.8948×10^4	3.2779×10^3	4.970×10^2
19–18	42.50	1.74	7.5236×10^3	4.0333×10^4	2.7009×10^3	4.095×10^2
18–17	40.90	1.57	6.5330×10^3	3.2809×10^4	2.1972×10^3	3.331×10^2
17–16	39.20	1.41	5.6234×10^3	2.6277×10^4	1.7597×10^3	2.668×10^2
16–15	37.60	1.25	4.7818×10^3	2.0653×10^4	1.3831×10^3	2.097×10^2
15–14	35.90	1.08	3.9443×10^3	1.5871×10^4	1.0629×10^3	1.611×10^2
14–13	34.20	0.93	3.2359×10^3	1.2072×10^4	8.084×10^2	1.226×10^2
13–12	32.50	0.78	2.5791×10^3	8.8364×10^3	5.917×10^2	8.97×10
12–11	30.70	0.65	2.0302×10^3	6.2573×10^3	4.190×10^2	6.35×10
11–10	29.00	0.51	1.5047×10^3	4.2271×10^3	2.831×10^2	4.29×10
10–9	27.10	0.37	1.0202×10^3	2.7224×10^3	1.823×10^2	2.76×10
9–8	25.30	0.26	6.692×10^2	1.7022×10^3	1.140×10^2	1.73×10
8–7	23.30	0.18	4.267×10^2	1.0330×10^3	6.920×10	1.05×10
7–6	21.49	0.13	2.842×10^2	6.063×10^2	4.060×10	6.20
6–5	19.46	0.10	1.980×10^2	3.221×10^2	2.160×10	3.30
5–4	17.43	0.07	1.241×10^2	1.241×10^2	8.30	1.30

work (Fig. 2) into MÜNZEL and SVOBODAs method [8, 3], for which a computer program [24] was developed.
Values for energy integration ranges are listed in Table 1. It ought to be kept in mind that for thick targets results, isotopic abundance was assumed as $\sum_i a_i = 0.615$. Our results are shown as a plot of yield vs. deuteron energy (Fig. 6). P. P. DIMITRIEV *et al.* [25], reported on ^{111g}In yields as related to deuteron energy, when irradiating thick cadmium metal targets. Comparison with our results shows that the latter values are higher, probably on acount of data taken from the excitation function we arise to.

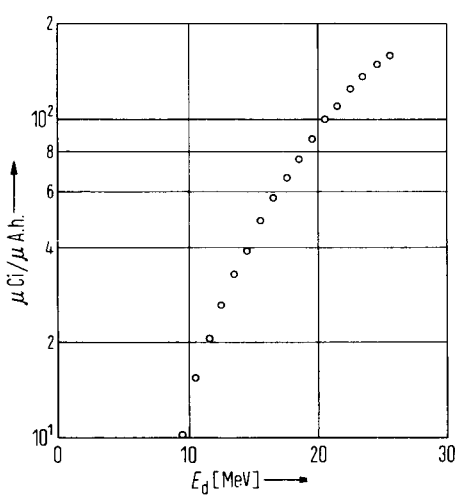

Fig. 6. Thick-target yields for the ^{111g}In production [derivatived from the last column of Table 1, $d(\sum A_{1h})/dE_d$]

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