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Extension of activation cross-section data of deuteron induced nuclear reactions on cadmium up to 50 MeV

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ABSTRACT

The excitation functions for $^{109,110g,111m+g,113m,114m,115m}$In, ^{107,109,115m,115g}Cd and ^{105g,106m,110g,111}Ag are presented for stacked foil irradiations on ^{nat}Cd targets in the 49–33 MeV deuteron energy domain. Reduced uncertainty is obtained by determining incident particle flux and energy scale relative to re-measured monitor reactions ^{nat}Al(d,x)^{22,24}Na. The results were compared to our earlier studies on ^{nat}Cd and on enriched ^{112}Cd targets. The merit of the values predicted by the TALYS 1.6 code (resulting from a weighted combination of reaction cross-section data on all stable Cd isotopes as available in the on-line libraries TENDL-2014 and TENDL-2015) is discussed. Influence on optimal production routes for several radionuclides with practical applications (^{111}In, ^{114m}In, ^{115}Cd, ^{109,107}Cd. . ..) is reviewed.

1. Introduction

As an extension of our systematic study on excitation functions of deuteron induced reactions we present a complement on our previous results on ^{nat}Cd [1] with cross-sections up to 50 MeV and partly validate our recent results on enriched ^{112}Cd targets [2]. No studies by other groups were published since 2007 and the few earlier publications on selected enriched Cd-isotopes and ^{nat}Cd (only three publications in the lower energy region with a limited number of activation products: Usher et al. [3], Nassif et al. [4] Mirzaei et al. [5]) were discussed in [1].

Comparison of the experimental results of this study and those published in [1] with calculated values available in the on-line libraries TENDL-2014 and TENDL-2015, allows to evaluate the evolution of the latest version of the TALYS nuclear reaction code (version 1.6) for deuteron induced reactions.

2. Experimental techniques and data evaluation

Stacked foil irradiation followed by non-destructive γ-spectrometry, as described in several of our recent publications [1,2,6] was used to determine the excitation functions. The targets, consisting of a fourteen times repeated sequence of 15.9 μm ^{nat}Cd foils interleaved with Sn-foils and Al (50.0 μm) monitor/degraders, were irradiated with a deuteron beam (nominal incident energy 50 MeV) at the CGR-90 cyclotron in Louvain la Neuve (LLN). All foils were commercially available and are high purity (>99.5%, Goodfellow, UK). The targets were mounted in a water-cooled, Faraday-cup like holder provided with a long collimator defining a beam of 6 mm diameter. Incident beam current was kept constant at about 50 nA (±5%, continuous measurement of current) during the 2400 s irradiation. After a short cooling period the dismantled targets were transported to the VUB premises for assessment of the activity of the induced radionuclides by HPGe γ-spectrometry (Canberra detectors and MCA, GENIE acquisition software), without chemical separation.

The identification and quantification of the activation products with half-life longer than two hours were performed in four series of measurements. Because of the time needed for transfer, separation of target foils and limited capacity of the detector systems, the first series started about 10 h after EOB and only the even foils were measured for 10 min each (7 foils) while measurement of the odd foils started at EOB + 20 h. A second series started at EOB + 48–52 h (20–40 min), a third at EOB + 11–14 d (2–4 h) and a last series (long measurements of 5–10 h) was performed at 40–46 d after EOB. The sample – detector distance was reduced from an initial 15 cm to 5 cm in order to keep dead-time corrections between 8 and 0.5%. The detector efficiency ε(E) was determined by repeated measurements of calibrated standard sources and a polynomial fit ε(E) = f(lnE) allowed knowledge of the efficiency at any γ-ray energy. The countrates in the different full energy peaks (often several energy lines for a given activation product) were obtained from the peak fitting algorithm included in

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the GENIE-software package. The LIVE TIME option was used for dead-time correction.

The activation formula, with measured activities, surface density of target nuclei and number of incident particles as input parameters, was used to calculate the cross-sections. The decay characteristics of the assessed activation products were taken from the on-line version of NUDAT2.6 [7] and are presented in Table 1, together with the energy thresholds of the contributing reactions

Table 1
Decay data of the radionuclides studied and contributing reactions with their thresholds (or Q-values if positive).

Nuclide	$T_{1/2}$	E_γ (keV)	I_γ (fraction)	Contributing reactions	Threshold (MeV)
^{109g}In	4.17 h	203.5	0.735	^{108}Cd(d,n)^{109g}In	Q = 1.497 MeV
		623.5	0.055	^{110}Cd(d,3n)^{109g}In	15.21
β^+: 4.56%				^{111}Cd(d,4n)^{109g}In	22.31
ε: 95.44%				^{112}Cd(d,5n)^{109g}In	31.87
				^{113}Cd(d,6n)^{109g}In	38.52
				^{114}Cd(d,7n)^{109g}In	47.72
^{110m}In	1.15 h	657.75	0.9774	^{110}Cd(d,2n)^{110g}In	7.01 + (0.062)
2^+		1125.77	0.014	^{111}Cd(d,3n)^{110g}In	14.11
62 keV				^{112}Cd(d,4n)^{110g}In	23.67
β^+: 61.3%				^{113}Cd(d,5n)^{110g}In	30.32
ε: 38.7%				^{114}Cd(d,6n)^{110g}In	39.52
^{110g}In	4.92 h	641.68	0.26	^{110}Cd(d,2n)^{110g}In	7.01
		884.67	0.93	^{111}Cd(d,3n)^{110g}In	14.11
ε: 100%		937.48	0.684	^{112}Cd(d,4n)^{110g}In	23.67
		657.75	0.98	^{113}Cd(d,5n)^{110g}In	30.32
				^{114}Cd(d,6n)^{110g}In	39.52
^{111g}In	67.32 h	171.28	0.907	^{110}Cd(d,n)^{111g}In	Q = +3.11 MeV
		245.35	0.94	^{111}Cd(d,2n)^{111g}In	3.94
ε: 100%				^{112}Cd(d,3n)^{111g}In	13.50
				^{113}Cd(d,4n)^{111g}In	20.15
				^{114}Cd(d,5n)^{111g}In	29.35
				^{116}Cd(d,7n)^{111g}In	44.44
^{113m}In	1.68 h	391.7	0.649	^{112}Cd(d,n)^{113m}In	Q = 3.854
$1/2^-$				^{113}Cd(d,2n)^{113m}In	2.73
391.7 keV				^{114}Cd(d,3n)^{113m}In	11.93
IT: 100%				^{116}Cd(d,5n)^{113m}In	27.03
^{114m}In	49.51 d	190.29	0.156	^{113}Cd(d,n)^{114m}In	Q = 4.59 MeV
5^+		558.46	0.0324	^{114}Cd(d,2n)^{114m}In	4.53
190.3 keV				^{116}Cd(d,4n)^{114m}In	19.63
IT: 96.75					
ε: 3.25%					
^{115m}In	4.49 h	336.24	0.458	^{114}Cd(d,n)^{115m}In	Q = 4.58 MeV
$1/2^-$				^{116}Cd(d,3n)^{115m}In	10.43
336.2 keV				Decay of ^{115g}Cd	
IT: 95%					
β^-: 5%					
^{107}Cd	6.50 h	Daughter ^{107m}Ag		^{106}Cd(d,p)^{107}Cd	Q = 5.70 MeV
β^+: 0.1%		93.12	0.047	^{108}Cd(d,p2n)^{107}Cd	12.79
ε: 99.9%				^{110}Cd(d,p4n)^{107}Cd	30.34
				^{111}Cd(d,p5n)^{107}Cd	37.44
				^{112}Cd(d,p6n)^{107}Cd	46.997
				Decay of ^{107}In	
^{109}Cd	461.4 d	Daughter ^{109m}Ag		^{108}Cd(d,p)^{109}Cd	Q = 5.098 MeV
		88	0.037	^{110}Cd(d,p2n)^{109}Cd	12.36
ε: 100%				^{111}Cd(d,p3n)^{109}Cd	19.46
				^{112}Cd(d,p4n)^{109}Cd	29.02
				^{113}Cd(d,p5n)^{109}Cd	35.67
				^{114}Cd(d,p6n)^{109}Cd	44.87
				Decay of ^{109}In	
^{115g}Cd	53.46 h	336.24	0.459	^{114}Cd(d,p)^{115g}Cd	Q = 3.92 MeV
β^-: 100%		492.03	0.0803	^{116}Cd(d,p2n)^{115g}Cd	11.11
		527	0.2745		
^{115m}Cd	44.8 d	934	0.02	^{114}Cd(d,p)^{115g}Cd	Q = 3.92 MeV
β^-: 100%				^{116}Cd(d,p2n)^{115g}Cd	11.11
^{105g}Ag	41.29 d	280.41	0.302	^{106}Cd(d,2pn)^{105g}Ag	9.76
ε: 100%		344.52	0.41	^{108}Cd(d,2p3n)^{105g}Cd	28.36
^{106m}Ag	8.3 d	221.70	0.066	^{106}Cd(d,2p)^{106m}Ag	1.66
6^+		429.60	0.132	^{108}Cd(d,2p2n)^{106m}Cd	20.27
89.7 keV		450.98	0.282	^{110}Cd(d,α2n)^{106m}Ag	9.00
ε: 100%		717.34	0.289	^{111}Cd(d,α3n)^{106m}Ag	16.10
		1045.80	0.296	^{112}Cd(d,α4n)^{106m}Ag	25.66
				^{113}Cd(d,α5n)^{106m}Ag	32.31
				^{114}Cd(d,α6n)^{106m}Ag	41.51