Investigation of cross sections of deuteron induced nuclear reactions on selenium up to 50 MeV

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Abstract In the frame of a systematic study of deuteron induced nuclear reactions on all elements, activation cross sections on ^{nat}Se were investigated. Excitation functions were measured up to 50 MeV particle energy for production of ⁸²Br(m+), ^{80m}Br, ⁷⁷Br(m+), ⁷⁶Br(m+), ⁷⁵Br, ⁷⁵Se(cum), ⁷³Se(cum), ⁷⁶As, ⁷⁴As, ⁷³As(cum), ⁷²As and ⁷¹As(cum) by using the activation method through stacked foil irradiation followed by off-line gamma-ray spectrometry. The experimental results were compared to the earlier experimental data and to excitation functions calculated with the ALICE-D and EMPIRE-D theoretical model codes and data given in the TENDL-2019 on-line library based on TALYS calculations.

1 Introduction

The main motivation for the present measurement was to produce a more complete and reliable database for activation cross-sections of deuteron induced nuclear reactions useful for practical applications and can also serve as a base for improvement of the description by theoretical codes.

In the literature only a few works containing data on deuteron induced activation cross sections on selenium were found. Some of the earlier measurements were done on enriched monoisotopic targets (Miskel [1], Debuyst [2], Paans [3], Qaim [4], Dmitriev [5] and Vakilova [6] are limited to low energy and all are related to study of medical radioisotope production and nuclear reaction mechanisms or nuclear structure studies.

We present here for the first time experimental activation cross section data on natural selenium up to 50 MeV together

with a comparison with the earlier experimental results and with predictions of the latest model codes.

2 Experimental technique and data evaluation

The activation cross sections on natural selenium (for isotopic composition see Table 1) were measured by using the activation method and the standard stacked foil irradiation technique combined with off-line high-resolution gamma-ray spectrometry. The irradiation, the activity measurement and the data evaluation were similar as described in more detail in our earlier works on systematic study of deuteron induced nuclear reactions on numerous targets (around 650 reactions induced on 62 target elements). Thin Se targets (2.5–3.8 μm) were evaporated onto high purity aluminum (99.9%) backings (50.5 μm thickness), and covered with 50.5 μm Al for protection against contamination and surface loss. The backings and the cover foils served also as recoil catchers and were used for monitoring the beam parameters (beam current and energy).

The Se target foils were interleaved with Al (102.6 μm), Ti (10.9 μm) additional energy degrader and/or monitor foils. The Ti foils also served to follow the recoiled radionuclei from the Al monitors. The stack composition is presented in Table 2. Irradiation was performed at the Cyclone 110 cyclotron of the Université Catholique in Louvain la Neuve (LLN) at 50 MeV deuteron energy with a beam current of 20 nA for 40 min. The large number of monitor foils allowed us to follow the beam intensity and the energy degradation along the stack in detail via the simultaneous re-measurement of the excitation functions of the ²⁷Al(d,x)^{24,22}Na. The good reproduction of the standard monitor data is illustrated in Fig. 1. The ²⁴Na excitation function was measured inde-

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Table 1 Decay and nuclear characteristics of the investigated reaction products, contributing reactions and their Q-values

Nuclide spin isomeric level (keV)	Half-life	Decay mode	E_γ (keV)	I_γ (%)	Contributing process	Q-value (keV)
^{83}Br 3/2-	2.374 h	β^- : 100%	529.589	1.3	$^{82}\text{Se}(\text{d,n})^{83}\text{Br}$	6484.0
^{82}Br 5-	35.282 h	β^- : 100%	554.352	71.7	$^{82}\text{Se}(\text{d,2n})^{82}\text{Br}$	− 3102.1
			619.105	43.7		
			698.361	28.4		
			776.511	83.6		
			827.826	24.2		
			1044.005	27.6		
			1317.485	26.9		
			1474.895	16.39		
$^{80\text{m}}\text{Br}$ 5- 85.902	4.4205 h	IT	37.052	39.1	$^{80}\text{Se}(\text{d,2n})^{80\text{m}}\text{Br}$	− 4877.4
					$^{82}\text{Se}(\text{d,4n})^{80\text{m}}\text{Br}$	− 20854.4
^{77}Br 3/2-	57.04 h	ε : 100%	238.98	23.1	$^{76}\text{Se}(\text{d,n})^{77}\text{Br}$	3047.0
		β^+ : 0.73%	281.65	2.29	$^{77}\text{Se}(\text{d,2n})^{77}\text{Br}$	− 4372.0
			297.23	4.16	$^{78}\text{Se}(\text{d,3n})^{77}\text{Br}$	− 14869.0
			520.69	22.4	$^{80}\text{Se}(\text{d,5n})^{77}\text{Br}$	− 31746.0
			578.91	2.96	$^{82}\text{Se}(\text{d,7n})^{77}\text{Br}$	− 47723.0
^{76}Br 1-	16.2 h	ε : 100%	559.09	74.0	$^{76}\text{Se}(\text{d,2n})^{76}\text{Br}$	− 7970.0
		β^+ : 55%	657.02	15.9	$^{77}\text{Se}(\text{d,3n})^{76}\text{Br}$	− 15389.0
			1129.85	4.6	$^{78}\text{Se}(\text{d,4n})^{76}\text{Br}$	− 25886.0
			1216.10	8.8	$^{80}\text{Se}(\text{d,6n})^{76}\text{Br}$	− 42763.0
^{75}Br 3/2-	96.7 m	ε : 100%	141.19	6.6	$^{74}\text{Se}(\text{d,n})^{75}\text{Br}$	1958.0
		β^+ : 75%	286.50	88	$^{76}\text{Se}(\text{d,3n})^{75}\text{Br}$	− 17223.0
			377.39	3.93	$^{77}\text{Se}(\text{d,4n})^{75}\text{Br}$	− 24642.0
			427.79	4.4	$^{78}\text{Se}(\text{d,5n})^{75}\text{Br}$	− 35140.0
			431.75	3.9		
$^{81\text{m}}\text{Se}$ 7/2+ 103.00	57.28 min	β^- : 0.051%	103.01	12.8	$^{80}\text{Se}(\text{d,p})^{81\text{m}}\text{Se}$	4476.3
		IT: 99.949%			$^{82}\text{Se}(\text{d,p2n})^{81\text{m}}\text{Se}$	− 11500.8
^{75}Se 5/2+	119.78 d	ε : 100%	121.1155	17.20	$^{74}\text{Se}(\text{d,p})^{75}\text{Se}$	5803.03
			136.0001	58.5	$^{76}\text{Se}(\text{d,p2n})^{75}\text{Se}$	− 13378.35
			264.6576	58.9	$^{77}\text{Se}(\text{d,p3n})^{75}\text{Se}$	− 20797.21
			279.5422	25.02	$^{78}\text{Se}(\text{d,p4n})^{75}\text{Se}$	− 31294.98
			400.6572	11.41	$^{80}\text{Se}(\text{d,p6n})^{75}\text{Se}$	− 48171.1
					^{75}Br decay	1958.0
^{73}Se 9/2+	7.15 h	ε : 100%	67.07	70	$^{74}\text{Se}(\text{d,p2n})^{73}\text{Se}$	− 14282.0
		β^+ : 64.6%	361.2	97.0	$^{76}\text{Se}(\text{d,p4n})^{73}\text{Se}$	− 33463.0
					$^{77}\text{Se}(\text{d,p5n})^{73}\text{Se}$	− 40882.0
					^{73}Br decay	− 19644.0
^{72}Se 0+	8.40 d	ε : 100%	45.89	57.2	$^{74}\text{Se}(\text{d,p3n})^{72}\text{Se}$	− 22712.2
					$^{76}\text{Se}(\text{d,p5n})^{72}\text{Se}$	− 41893.6
					$^{77}\text{Se}(\text{d,p6n})^{72}\text{Se}$	− 49312.5
					^{72}Br decay	− 32301.0
^{78}As 2-	90.7 min	β^- : 100%	613.8	54	$^{78}\text{Se}(\text{d,2p})^{78}\text{As}$	− 5651.0
			694.9	16.7	$^{80}\text{Se}(\text{d,2p2n})^{78}\text{As}$	− 22527.0
			1308.7	13.0	$^{82}\text{Se}(\text{d,2p4n})^{78}\text{As}$	− 38504.0

Table 1 continued

Nuclide spin isomeric level (keV)	Half-life	Decay mode	E_γ (keV)	I_γ (%)	Contributing process	Q-value (keV)
^{77}As 3/2-	38.79 h	β^- : 100%	161.932	0.146	$^{77}\text{Se}(\text{d},2\text{p})^{77}\text{As}$	– 2125.4
			239.011	1.59	$^{78}\text{Se}(\text{d},2\text{pn})^{77}\text{As}$	– 12623.2
			249.805	0.39	$^{80}\text{Se}(\text{d},2\text{p}3\text{n})^{77}\text{As}$	– 29499.3
			520.654	0.56	$^{82}\text{Se}(\text{d},2\text{p}5\text{n})^{77}\text{As}$	– 45476.4
^{76}As 2-	26.24 h	β^- : 100%	559.10	45.0	$^{76}\text{Se}(\text{d},2\text{p})^{76}\text{As}$	– 4402.8
			657.05	6.2	$^{77}\text{Se}(\text{d},2\text{pn})^{76}\text{As}$	– 11821.6
					$^{78}\text{Se}(\text{d},2\text{p}2\text{n})^{76}\text{As}$	– 22319.4
					$^{80}\text{Se}(\text{d},2\text{p}4\text{n})^{76}\text{As}$	– 39195.6
^{74}As 2-	17.77 d	ε : 66%	595.83	59	$^{74}\text{Se}(\text{d},2\text{p})^{74}\text{As}$	– 2795.4
		β^- : 34%	634.78	15.4	$^{76}\text{Se}(\text{d},2\text{p}2\text{n})^{74}\text{As}$	– 21976.7
					$^{77}\text{Se}(\text{d},2\text{p}3\text{n})^{74}\text{As}$	– 29395.6
					$^{78}\text{Se}(\text{d},2\text{p}4\text{n})^{74}\text{As}$	– 39893.4
^{73}As 3/2-	80.30 d	ε : 100%	53.437	10.6	$^{74}\text{Se}(\text{d},2\text{pn})^{73}\text{As}$	– 10774.0
					$^{76}\text{Se}(\text{d},2\text{p}3\text{n})^{73}\text{As}$	– 29955.0
					$^{77}\text{Se}(\text{d},2\text{p}4\text{n})^{73}\text{As}$	– 37374.0
					$^{78}\text{Se}(\text{d},2\text{p}5\text{n})^{73}\text{As}$	– 47872.0
					^{73}Se decay	– 14282.0
^{72}As 2-	26.0 h	ε : 100%	833.99	81.0	$^{74}\text{Se}(\text{d},2\text{p}2\text{n})^{72}\text{As}$	– 21568.0
					$^{76}\text{Se}(\text{d},2\text{p}4\text{n})^{72}\text{As}$	– 40750.0
					$^{77}\text{Se}(\text{d},2\text{p}5\text{n})^{72}\text{As}$	– 48168.0
^{71}As 5/2-	65.30 h	ε : 100%	174.954	82.4	$^{74}\text{Se}(\text{d},2\text{p}3\text{n})^{71}\text{As}$	– 29976.0
			499.876	3.64	$^{76}\text{Se}(\text{d},2\text{p}5\text{n})^{71}\text{As}$	– 49158.0
					^{71}Se decay	– 35505.0

pendently for the target backing/cover Al foils and for the thick Al degraders and show acceptable agreement.

The activity of the irradiated samples was measured without chemical separation by using the well-calibrated gamma-spectrometry set-ups at VUB Brussels. The decay of activity of the samples was followed by series of measurements to identify and to separate complex gamma-lines and to follow the cumulative effects after decay of short-lived isomeric states and/or parent nuclei. The energy degradation along the stack was initially determined by a stopping calculation and was confirmed on the basis re-measured excitation function of monitor reactions. For initial calculation home made codes STOPPING and STACK have been used, which are based on the Ziegler's tables. For the associated error estimation also the Ziegler's SRIM code was used. The uncertainties on the cross-sections were estimated by using the error propagation of the formula used for calculation (except non-linearly contributing time depending factors). The uncertainties of the contributing factors were: number of bombarding particles (7%), gamma intensity data (3%), detector efficiency (5%), peak area (0.1–10%), number of the target nuclei (5%). The uncertainty of the energy scale was calculated by taking into account the energy uncertainty of the primary beam, the pos-

sible variation in the target thickness and the effect of beam straggling. The used nuclear data were taken from NUDAT 2.6. More details on the experiment and the data evaluation are collected in Table 2.

Abundance of isotopes in natural Se: ^{74}Se – 0.89%, ^{76}Se – 9.37%, ^{77}Se – 7.63%, ^{78}Se – 23.77%, ^{80}Se – 49.61%, ^{82}Se – 8.73% (Chart of Nuclides, e.g.: <https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>).

Increase the Q-values if compound particles are emitted by: np-d, + 2.2 MeV; 2np-t, + 8.48 MeV; n2p- ^3He , + 7.72 MeV; 2n2p- α , + 28.30 MeV. Decrease the Q-values for isomeric states with the level energy of the isomer.

3 Theoretical calculations

The cross sections of the investigated reactions were calculated using the modified pre-compound model codes ALICE-IPPE (Dityuk et al. [17]) and EMPIRE-II (Herman [18]). During the recent analyses of several (d,p) reactions we were confronted with a large underestimation of the measured cross sections by the code results. We came to the conclusion that the experimentally observed cross sections of the (d,p)

Table 2 Main experimental parameters and data evaluation

Experimental parameters		Data evaluation	
Incident particle	Deuteron	Gamma-spectra evaluation	Genie 2000 [7] Forgamma [8]
Method	Stacked foil	Determination of beam intensity	Faraday cup (preliminary) Fitted monitor reaction (final) [9]
Number of Se target samples	21	Decay data	NUDAT 2.6 [10]
Target composition and thickness (μm)	Al (50.5 μm); Se (3.7–2.5 μm); Al (50.5 μm); Al (102.6 + 102.6 μm); Ti (10.9 + 10.9 μm) repeated 21 times	Reaction Q-values	Q-value calculator [11]
Accelerator	Cyclone 110 cyclotron of the Université Catholique in Louvain la Neuve (LLN)	Determination of beam energy	Andersen (preliminary) [12] Fitted monitor reaction (final) [9]
Primary energy (MeV)	50	Uncertainty of energy	Cumulative effects of possible uncertainties
Energy range (MeV)	49.8–8.9	Cross sections	Elemental cross section
Irradiation time (min)	40	Uncertainty of cross sections	Sum in quadrature of all individual linear Contributions [13]
Beam current (nA)	20	Yield	Physical yield [14, 15]
Monitor reaction, [recommended values]	$^{27}\text{Al}(\text{d}, \text{x})^{24,22}\text{Na}$ reaction [16]		
Monitor target and thickness (μm)	Al (50.5 + 50.5), Al (102.6 + 102.6), Ti (10.9 + 10.9)		
Detector	HPGe		
γ –spectra measurements	3 series		
Cooling times (h)	8.1–11.5 44.5–53.9 7710–86316		

reaction cannot be reproduced below 20–30 MeV with the available statistical model codes. It is well known that for the (d,p) reactions at low energies the direct stripping process play a very important role. To achieve better description of available data for (d,p) reactions a phenomenological enhancement factor K has been introduced, as energy dependent and estimated to describe the whole set of the observed (d,p) cross sections for medium and heavy nuclei.

By this improvement, in the ALICE IPPE-D and EMPIRE-D code versions [19] for deuteron induced reactions, the direct (d,p) channel is increased strongly and this is reflected in changes for all other reaction channels in both codes.

The EMPIRE-D and TALYS model codes predict acceptable well the near-threshold section of the neutron emitting

reactions. The ALICE-D predictions are less satisfactory for this energy because of the much simple model of the low-energy discrete levels of the nuclei in question. For determination of the cross sections in the vicinity of the local maxima, a ratio of the level densities of competing channels is important. The seen differences in calculations are the consequences of differences of the default level-density parameters of the particular codes. Discrepancies between calculations with experiment can be improved by the proper adjustments of input parameters. The comments on the (d,pxn) reactions are similar to those discussed above. However, a special attention is paid to the (d, p) reaction. This reaction is dominated by the direct breakup mechanism without the formation of intermediate pre-equilibrium states of the nucleus.

Fig. 1 Application of monitor reactions for determination of deuteron beam energy and intensity

Fig. 2 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,xn)^{82}\text{Br}$ reaction

4 Results-cross sections

The measured experimental cross-section data are shown in Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 together with the results of the earlier measurements and the theoretical calculations. The numerical values are presented in Tables 3, 4 and 5. The isotopic cross sections presented in some earlier published studies were normalized to natural Se abundance.

4.1 Cross sections of residual radionuclides of bromine

The radioisotopes of bromine are produced only by direct (d,xn) reactions. The contributing reactions and the reaction Q-values were presented in Table 1. Due to the long cooling

time needed for transfer of the irradiated targets from LLN to VUB, the formation of short-lived $^{83,84m,84g}\text{Br}$ could not be confirmed.

4.1.1 The $^{nat}\text{Se}(d,xn)^{82}\text{Br}$ process

As the higher energy metastable state of ^{82}Br has a short half-life ($T_{1/2} = 6.13$ min, IT: 97.6%) we present cumulative cross-sections for the ground state ($T_{1/2} = 35.282$ h), measured after ^{82m}Br total decay (Fig. 2). The formation on ^{82}Br occurs only through the (d,2n) reaction on ^{82}Se . Our data point near the threshold seems to be shifted, when compared to the earlier experimental data and to the theory. This discrepancy is partly explained by the large energy uncertainty

Fig. 3 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,xn)^{80m}\text{Br}$ reaction

Fig. 4 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,xn)^{77}\text{Br}$ reaction

(>1 MeV see Table 3) by the last target foil. The experimental data of Miskel et al. [1] and of Debuyst et al. [2], obtained on enriched targets were normalized to the abundance in ^{nat}Se and are reasonably agreeing with our new values below 10 MeV. The theoretical descriptions give a good trend and the TENDL-2009 prediction shows good agreement with the experimental results.

4.1.2 The $^{nat}\text{Se}(d,xn)^{80m}\text{Br}$ process

The radioisotope ^{80}Br has two long-lived isomeric states. The cross section data for production of the metastable state ^{80m}Br (4.4205 h, IT 100%) are shown in Fig. 3. Due to the isomeric decay of the longer-lived isomeric state and to the long cooling time it was impossible to obtain cross sections

for independent formation of the short half-life ground state (17.68 min, β^- : 91.7%, ε : 8.3%). The data of Debuyst et al. [2] were normalized to the abundance in ^{nat}Se . The agreement with the theoretical data is acceptable, as far as the TENDL-2019 regarded.

4.1.3 The $^{nat}\text{Se}(d,xn)^{77}\text{Br}$ process

The measured total cross section of the ^{77}Br ground state (57.04 h) include the complete decay of the ^{77m}Br short half-life (4.28 min, IT: 100%) isomeric state (Fig. 4). The ^{77}Br and ^{77}As are both decaying to the ^{77}Se and have similar half-lives and common gamma-lines: ^{77}Br (ε : 100% 57.04 h, 239 521 keV (23.1%), 520.654 keV (22.4%)) with ^{77}As (38.8 h, β^- : 100%, 239 521 keV (1.59%), 520.654 keV (0.56%)). Taking

Fig. 5 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,xn)^{76}\text{Br}$ reaction

Fig. 6 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,xn)^{75}\text{Br}$ reaction

into account the significantly lower gamma-line intensities and the lower production cross section the contribution of the decay of ^{77}As was neglected. The theoretical predictions slightly overestimate the experimental data.

4.1.4 The $^{nat}\text{Se}(d,xn)^{76}\text{Br}$ process

Most of the gamma-lines of ^{76}Br (16.2 h, ε : 100%) and ^{76}As (26.24 h, β^- : 100%) are common as both decay to ^{76}Se . A few independent lines with low intensity exist but we couldn't identify them in our spectra. Due to the difference in half-life we estimate that in our last series of spectra the contribution of the shorter-lived ^{76}Br to common gamma-lines can be neglected, taking also into account the ratio of cross sections finally derived. In our last series of spectra, the strongest

line of ^{76}As (559 keV) was identified in the high energy samples, and cross sections for production of ^{76}As could be deduced (see Sect. 4.3.1). For correction of the ^{76}As contribution in the 559 keV gamma-line in the first series of gamma-spectra (used to derive ^{76}Br cross sections) we fitted our experimental cross section data to the prediction of ALICE-D, and we calculated the ^{76}As contribution to the 559 keV line (because the ALICE-D prediction is the closest to the experimental values in Fig. 9). The correction was around 5% in average and we deduced cross section for production of ^{76}Br (Fig. 5). No earlier experimental data were found.

Our data show less pronounced differences than the calculated values in contributions of reactions on the different stable Se isotopes and especially the $^{76}\text{Se}(d,2n)$ reaction seems

Fig. 7 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{75}\text{Se}$ reaction

Fig. 8 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{73}\text{Se}$ reaction

to be overestimated by the ALICE-D and EMPIRE-D codes below 30 MeV, but both codes give acceptable estimations above this energy. TENDL-2019 follows the trends of the experiment but shows overestimation in the whole energy range.

4.1.5 The $^{nat}\text{Se}(d,xn)^{75}\text{Br}$ process

The excitation functions of the $^{nat}\text{Se}(d,xn)^{75}\text{Br}$ (96.7 min) reaction are shown in Fig. 6. The earlier experimental cross sections of the $^{74}\text{Se}(d,n)$ reaction measured by Qaim et al. [4] for energies below 18 MeV were normalized to natural Se isotopic composition. From the theoretical descriptions the EMPIRE-D estimation is acceptable.

4.2 Cross sections of residual radionuclides of selenium

The radioisotopes of selenium are produced by direct (d,pxn) reactions and decay of parent isobaric bromine radionuclides. The contributing reactions and the reaction Q-values are presented in Table 1.

4.2.1 The $^{nat}\text{Se}(d,x)^{75}\text{Se}$ process

We can deduce cumulative cross sections for production of ^{75}Se (119.78 d). It includes the complete decay of parent ^{75}Br (96.7 min, ϵ : 100%) (Fig. 7). No earlier experimental data were found. The theoretical data, especially the EMPIRE are in good agreement with the experimental results.

Fig. 9 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{76}\text{As}$ reaction

Fig. 10 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{74}\text{As}$ reaction

4.2.2 The $^{nat}\text{Se}(d,x)^{73}\text{Se}$ process

The measured cross sections for production of ^{73g}Se (7.15 h) are cumulative as they were measured after complete decay of short-lived ^{73}Br (3.4 min, ε : 100%) and ^{73m}Se (39.8 min, ε : 27.4 %, IT: 72.6 %) (Fig. 8). No earlier experimental data were found. All theoretical codes give acceptable trend, TENDL and EMPIRE give good prediction up to 40 MeV, over this energy the ALICE prediction is better.

4.3 Cross sections of residual radionuclides of arsenic

The radioisotopes of arsenic are produced by direct (d,2pxn) reactions and by decay of parent selenium isotopes. The con-

tributing reactions and the reaction Q-values are presented in Table 1.

4.3.1 The $^{nat}\text{Se}(d,x)^{76}\text{As}$ process

To get production cross sections for ^{76}As (26.24 h, β^- : 100%) we have used the activity derived from the 559 keV gamma-line signals assessed in the last series of measurements. The contributions of the contaminating, common gamma-line of ^{76}Br (16.2 h, ε : 100%) were small as estimated on the basis of cross sections and the elapsed time after EOB. Statistically reliable signals for the 559 keV line were identified only in the high energy samples (Fig. 9). Significant disagreement can be observed in the predictions of the different theoretical codes. Some of our data points (i.e.

Fig. 11 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{72}\text{As}$ reaction

Fig. 12 Experimental and theoretical excitation functions for the $^{nat}\text{Se}(d,x)^{71}\text{As}$ reaction

by 48.13, 46.47 and 41.16 MeV fall down from the measured curve. The possible reason could be that the corresponding spectra have been measured by different cooling times and measuring times than the others, and the peak counts were under 100, which could make large statistical error.

4.3.2 The $^{nat}\text{Se}(d,x)^{74}\text{As}$ process

The ^{74}As (17.77 d) is produced only directly. The experimental and theoretical data are shown in Fig. 10. No earlier experimental data were found. ALICE-D gives the best and acceptable prediction.

4.3.3 The $^{nat}\text{Se}(d,x)^{72}\text{As}$ process

The ^{73}As (80.30 d) is produced directly and through the decay of the $^{73\text{m}}\text{Se}$ (39.8 min, ε : 27.4%, IT: 72.6%) and $^{73\text{g}}\text{Se}$ (7.15 h, ε : 100%) parent isomeric states. The cumulative cross sections are shown in Fig. 11. The ALICE-D and TENDL-2019 give the best description.

4.3.4 The $^{nat}\text{Se}(d,x)^{71}\text{As}$ process

We could obtain cumulative cross sections for production of ^{71}As (65.30 h) (Fig. 12), including direct production and complete decay of short-lived parent ^{71}Se (4.74 min, ε :

Table 3 Cross sections of deuteron induced reactions on Selenium for production of $^{82}\text{Br}(m+)$, ^{80m}Br , $^{77}\text{Br}(m+)$, $^{76}\text{Br}(m+)$ radionuclides

E MeV	ΔE	$^{82}\text{Br}(m+)$		^{80m}Br		$^{77}\text{Br}(m+)$		$^{76}\text{Br}(m+)$	
		σ mb	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
49.75	0.30	5.80	0.84	50.29	12.29	157.70	18.93	69.22	8.32
48.13	0.32	5.75	0.86	72.54	15.12	141.35	17.01	74.45	8.94
46.47	0.34	6.26	0.92	59.48	13.02	128.57	15.49	79.55	9.55
44.75	0.36	7.14	1.01	65.67	14.19	119.20	14.38	82.38	9.89
42.98	0.38	6.84	0.99	72.71	16.06	103.35	12.50	86.90	10.43
41.16	0.40	7.12	1.25	80.77	15.74	100.12	12.54	82.97	9.96
39.27	0.43	7.55	1.05	70.47	15.28	98.84	11.94	75.80	9.11
37.31	0.45	6.78	1.04	114.05	23.12	120.06	14.51	73.46	8.84
35.27	0.48	9.06	1.25	102.92	20.76	131.22	15.80	67.15	8.09
33.14	0.51	11.04	1.49	83.58	18.30	150.67	18.15	54.06	6.47
30.90	0.54	9.89	1.38	109.17	22.12	165.11	19.85	50.63	6.07
28.55	0.57	12.97	1.72	80.70	21.28	168.74	20.28	55.65	6.74
26.80	0.61	15.58	2.26	82.25	26.96	172.97	21.24	56.17	6.81
24.97	0.65	16.32	2.19	79.88	29.53	136.46	16.53	53.84	6.57
23.03	0.69	19.53	2.54	153.42	33.17	133.31	16.15	57.54	7.00
20.98	0.73	26.94	3.39	132.37	26.30	105.71	12.88	58.19	7.06
18.77	0.77	36.77	4.55	217.94	37.50	74.51	9.21	57.30	6.95
16.36	0.82	54.46	7.08	343.71	47.56	73.72	9.67	52.74	6.40
13.68	0.87	78.70	9.46	337.89	44.19	74.37	9.05	40.39	4.91
10.58	1.01	93.37	11.27	327.33	54.30	105.87	13.12	16.28	2.10
7.49	1.07	40.16	4.91	59.86	9.07	60.04	7.58	0.23	0.05

Table 4 Cross sections of deuteron induced reactions on Selenium for production of ^{75}Br , $^{75}\text{Se}(\text{cum})$, $^{73}\text{Se}(\text{cum})$, ^{76}As , ^{74}As radionuclides

E MeV	ΔE	^{75}Br		$^{75}\text{Se}(\text{cum})$		^{73}Se		^{76}As	
		σ mb	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
49.75	0.30	39.63	4.84	141.28	17.19	7.796	0.968	31.38	4.61
48.13	0.32	35.75	4.42	136.31	16.50	6.789	0.859	20.03	5.91
46.47	0.34	35.50	4.39	125.57	15.23	5.613	0.719	19.43	4.05
44.75	0.36	34.63	4.31	113.69	13.88	4.736	0.623	32.93	5.49
42.98	0.38	36.08	4.35	121.22	14.75	4.572	0.606	30.35	4.07
41.16	0.40	34.20	4.32	119.91	14.56	3.694	0.513	21.17	8.29
39.27	0.43	34.48	4.37	103.07	12.62	5.129	0.675	29.44	4.49
37.31	0.45	38.41	4.90	117.48	14.28	5.176	0.683	28.35	5.12
35.27	0.48	38.62	4.95	106.96	12.80	5.192	0.694	25.19	4.35
33.14	0.51	35.97	4.74	97.00	11.87	5.450	0.734	23.65	7.32
30.90	0.54	35.60	4.76	88.99	10.79	5.228	0.707	18.39	6.92
28.55	0.57	37.12	5.08	78.31	9.52	3.498	0.535	15.12	6.62

Table 4 continued

E MeV	ΔE	^{75}Br		$^{75}\text{Se(cum)}$		^{73}Se		^{76}As	
		σ mb	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
26.80	0.61	30.27	4.46	67.62	8.11	3.067	0.511		
24.97	0.65	17.98	3.69	46.66	5.63	1.524	0.615		
23.03	0.69	7.23	3.58	32.32	3.93	0.736	0.704		
20.98	0.73			15.88	2.85	0.832	0.280		
18.77	0.77			5.42	0.89				
16.36	0.82			8.68	1.60				
13.68	0.87			3.80	0.79				
10.58	1.01			14.83	2.27				
7.49	1.07			6.46	1.24				

Table 5 Cross sections of deuteron induced reactions on Selenium for production of ^{74}As , $^{73}\text{As(cum)}$, ^{72}As , $^{71}\text{As(cum)}$ radionuclides

E MeV	ΔE	^{74}As		^{72}As		$^{71}\text{As(cum)}$	
		σ mb	$\Delta\sigma$	σ	$\Delta\sigma$	σ	$\Delta\sigma$
49.75	0.30	24.59	3.06	16.52	2.25	8.28	1.03
48.13	0.32	20.50	2.54	13.78	2.05	6.68	0.83
46.47	0.34	19.20	2.39	12.75	1.82	5.46	0.69
44.75	0.36	18.11	2.28	13.28	1.94	4.40	0.55
42.98	0.38	19.13	2.38	13.66	1.96	3.06	0.43
41.16	0.40	18.21	2.28	9.58	1.60	1.29	0.21
39.27	0.43	17.67	2.23	10.34	1.63	0.96	0.19
37.31	0.45	21.08	2.62	8.96	1.63	1.01	0.18
35.27	0.48	19.89	2.39	11.04	1.73	0.67	0.28
33.14	0.51	19.12	2.40	11.09	2.01	0.70	0.27
30.90	0.54	16.53	2.04	5.33	1.44	0.87	0.33
28.55	0.57	13.03	1.64	3.74	1.34	0.92	0.18
26.80	0.61	9.53	1.16			1.06	0.24
24.97	0.65	6.53	0.82			1.12	0.27
23.03	0.69	4.84	0.62			0.53	0.15
20.98	0.73	5.86	0.92				
18.77	0.77	4.49	0.61				
16.36	0.82	4.30	0.63				
13.68	0.87	3.31	0.46				
10.58	1.01	2.32	0.42				
7.49	1.07	0.44	0.34				

100%). In this case TENDL-2019 shows the best agreement with the experimental data.

5 Integral yields

From excitation functions obtained by a spline fit to our experimental cross sections, integral thick target yields were

calculated and are shown in Figs. 13 and 14 as a function of the energy. The so-called physical integral yield Bonardi 1988 [14], Otuka 2015 [15] was calculated (yield at EOB for an instantaneous irradiation, i.e. no decay corrections). For the bromine radio-isotope yields two series of yield measurements have been found for particular bromine isotopes [5,20], both measured by the same group (Dmitriev et al.). The series of data from 1982 for $^{76,77,82}\text{Br}$ and the single

Fig. 13 Integral yields for bromine radioisotopes calculated from the measured excitation functions compared with the literature data

Fig. 14 Integral yields for selenium and arsenic radioisotopes calculated from the measured excitation functions compared with the literature data

point at 22 MeV for $^{76,77}\text{Br}$ are in acceptable agreement with our new results.

For the arsenic and selenium radio-isotopes only the single 22 MeV measurements are available from the literature [20] for ^{75}Se and ^{74}As production. The former is lower and the latter is higher than our new data.

6 Applications

6.1 Activation file

Selenium is used with [bismuth](#) in [brasses](#) to replace more toxic [lead](#). Like lead and sulfur, selenium improves the

machinability of steel at concentrations around 0.15% [21]. Selenium produces the same machinability improvement in copper alloys. The recently measured data can be useful for nuclear activation related applications (activation analysis, accelerator technology).

6.2 Nuclear reaction theory

As was shown in several of our recent investigations the description of activation cross sections of the deuteron induced reactions by model codes is not very successful, due to e.g the fact that the (d,p) reactions are not handled correctly. The D-versions of the EMPIRE and ALICE codes try to improve on it. New experimental data are vitally impor-

Table 6 Summary of production routes of the relevant Br, Se and As medical isotopes studied (present study is in bold)

Nuclide	Half life	Decay mode (%)	E_{bmax}	E_{baver} (MeV)	Main γ -rays keV (% abundance)	Application	Production route
^{75}Br	1.61 h	β^+ (75)	2.04		286.0 (88)	PET	$^{74}\text{Se}(\text{d},\text{n})$
		EC (25)	0.73		511.0 (149)		$^{76}\text{Se}(\text{p},2\text{n})$
							$^{76}\text{Se}(\text{d},3\text{n})$
							$^{78}\text{Kr}(\text{p},\text{x})$
							$^{75}\text{As} (^3\text{He},3\text{n})$
^{76}Br	16.2 h	β^+	3.941		511.0 (109)	PET	$^{75}\text{As} (\alpha,4\text{n})$
		EC (45)	1.18		559.0 (74.0)		$^{76}\text{Se}(\text{p},\text{n})$
					657.02 (15.9)		$^{77}\text{Se}(\text{p},2\text{n})$
					1129.85 (4.6)		$^{76}\text{Se}(\text{d},2\text{n})$
					1216.10 (8.8)		$^{78}\text{Kr}(\text{p},\text{x})$
					1853.67 (14.7)		$^{78}\text{Kr}(\text{d},\text{x})$
							$^{75}\text{As} (3\text{He},2\text{n})$
							$^{75}\text{As} (\alpha,3\text{n})$
							$^{78}\text{Kr}(\text{d},\alpha)$
							$^{77}\text{Se}(\text{p},\text{n})$
^{77}Br	57.04 h	β^+ (0.73)	0.342		238.98 (23.1)	SPECT	$^{78}\text{Se}(\text{p},2\text{n})$
		EC (99.27)	0.151		520.69 (22.4)	Auger	$^{76}\text{Se}(\text{d},\text{n})$
							$^{77}\text{Se}(\text{d},2\text{n})$
							$^{78}\text{Kr}(\text{p},\text{x})$
							$^{75}\text{As} (\alpha,2\text{n})$
							$^{79}\text{Br}(\text{p},3\text{n})^{77}\text{Kr}-^{77}\text{Br}$
							$^{79}\text{Br}(\text{d},4\text{n})^{77}\text{Kr}-^{77}\text{Br}$
							$^{80}\text{Kr}(\text{p},\alpha)$
							$^{80}\text{Kr}(\text{d},\alpha\text{n})$
							$^{80}\text{Se}(\text{p},\text{n})$
$^{80\text{m}}\text{Br}$	4.4205 h	IT (100)			37.052 (39.1)	Auger	$^{80}\text{Se}(\text{d},2\text{n})$
							$^{82}\text{Kr}(\text{d},\alpha)$
							$^{80}\text{Se}(\text{p},\text{n})$
^{80}Br	17.68 min	β^-	1.99		511.0 (4.4)	Therapy	$^{80}\text{Se}(\text{d},2\text{n})$
		ε	0.85				$^{82}\text{Kr}(\text{d},\alpha)$
		β^+					$^{82}\text{Se}(\text{p},\text{n})$
^{82}Br	35.282 h	β^- (100)	0.444		554.352 (71.7)	Therapy	$^{82}\text{Se}(\text{d},2\text{n})$
			0.143		619.105 (43.7)		
					698.361 (28.4)		
					776.511 (83.6)		
					827.826 (24.2)		
					1044.005 (27.6)		
					1317.485 (26.9)		
					1474.895 (16.3)		
^{73}Se	7.15 h	β^+	1.636		67.07 (70)	PET	$^{75}\text{As}(\text{p},3\text{n})$
		EC (35.4)	0.557		361.2 (97.0)		$^{75}\text{As}(\text{d},4\text{n})$
					511.0 (129.2)		$^{70}\text{Ge}(\alpha,\text{n})$
							$^{72}\text{Ge}(\alpha,3\text{n})$
							$^{73}\text{Ge} (^3\text{He},3\text{n})$

Table 6 continued

Nuclide	Half life	Decay mode (%)	E_{bmax} E_{baver} (MeV)	Main γ -rays keV (% abundance)	Application	Production route
^{75}Se	119.78 d	EC (100)		121.1155 (17.20) 136.0001 (58.5) 264.6576 (58.9) 279.5422 (25.02) 400.6572 (11.41)	SPECT	$^{75}\text{As}(p,n)$ $^{75}\text{As}(d,2n)$ $^{72}\text{Ge}(\alpha,n)$ $^{73}\text{Ge}(\alpha,2n)$ $^{73}\text{Ge}(^3\text{He},n)$ $^{74}\text{Ge}(^3\text{He},2n)$ ^{75}Br routes
^{72}As	26.0 h	β^+ EC (12.3)	3.334 1.17	833.99 (0.81)	PET	$^{72}\text{Ge}(p,n)$ $^{72}\text{Ge}(d,2n)$ $^{69}\text{Ga}(\alpha,n)$ $^{71}\text{Ga}(\alpha,3n)$ $^{71}\text{Ga}(^3\text{He},2n)$
^{74}As	17.77 d	β^+ EC (37) β^-	1.54 0.44 1.3528 0.4	15.4 (58) 595.83 (59) 634.78 (15.4)	PET	$^{74}\text{Ge}(p,n)$ $^{74}\text{Ge}(d,2n)$ $^{71}\text{Ga}(\alpha,2n)$ $^{71}\text{Ga}(^3\text{He},n)$ $^{76}\text{Se}(d,\alpha)$

tant to test the present predictions and to further improve the reaction codes and the input parameters.

6.3 Production of medical isotopes

Several of the investigated activation products have applications in nuclear medicine [22–24]. The main important production routes of these isotopes are summarized in Table 6. The production mostly requires monoisotopic targets to assure the radionuclide purity. The present cross section data combined with theoretical results that describe properly the experiments on ^{nat}Se can be useful to estimate production routes yields. The data can also serve as a basis to derive monoisotopic cross sections in the energy range where only one reaction contributes.

7 Summary and conclusion

The excitation functions for $^{nat}\text{Se}(d,x)$ reactions resulting in formation of $^{82}\text{Br}(m+)$, ^{80m}Br , $^{77}\text{Br}(m+)$, $^{76}\text{Br}(m+)$, ^{75}Br , $^{75}\text{Se}(cum)$, $^{73}\text{Se}(cum)$, ^{76}As , ^{74}As , $^{73}\text{As}(cum)$, ^{72}As , $^{71}\text{As}(cum)$ were measured up to 50 MeV in the frame of a systematic study of deuteron induced threshold reactions. The experimental cross section and deduced yield data were compared with some earlier measured low energy values and are showing good agreement. Model calculations were done with the ALICE-IPPE-D and EMPIRE-D code. The ALICE-D and EMPIRE-D theoretical calculations, completed with the

TALYS results from TENDL-2019 on-line library, describing with varying success the shape and the absolute values of the experimental data, especially for $(d,2pxn)$ reactions leading to As radioisotopes. The obtained experimental data provide a basis for improved model calculations and for applications in radioisotope production, in dose calculations, in waste handling, in charged particle activation analysis for thin layer application and for nuclear data validation.

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