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New cross section measurements for production of the positron emitters ^{75}Br and ^{76}Br *via* intermediate energy proton induced reactions[†]

By I. Spahn[1,*], G. F. Steyn[2], C. Vermeulen[2], Z. Kovács[3], F. Szelecsényi[3], H. H. Coenen[1] and S. M. Qaim[1]

[1] Institut für Neurowissenschaften und Biophysik: Nuklearchemie (INB 4), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[2] Radionuclide Production Group, iThemba LABS, Somerset West 7129, South Africa
[3] Cyclotron Department, Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), 4026 Debrecen, Hungary

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Summary. The radionuclides ^{75}Br and ^{76}Br are of considerable interest for application in Positron Emission Tomography (PET). For their production so far mostly low-energy or low-yield production processes have been employed. In this work the production of both isotopes was investigated using intermediate energy proton induced reactions and enriched target materials. Cross section data of the ^{77,78,80}Se(p, xn)^{75}Br processes were measured up to 66 MeV and those of the ^{77,78,80}Se(p, xn)^{76}Br processes up to 85 MeV. The measured excitation functions were compared with calculated results of the nuclear model code ALICE-IPPE. From the experimental excitation curves, thick target yields were calculated. They are fairly high over the investigated intermediate energy ranges. The production possibilities of ^{75}Br and ^{76}Br *via* various routes and the radionuclidic impurities associated with them are discussed.

1. Introduction

There is a longstanding interest in the radioisotopes of bromine for application in nuclear medicine [1–5]. This is based on their versatile decay properties and covalent chemical bonding. The two radionuclides ^{75}Br ($T_{1/2} = 1.6$ h) and ^{76}Br ($T_{1/2} = 16.2$ h) are useful for application in positron emission tomography (PET) by virtue of their high positron emission intensities of 75.5% and 57%, respectively. The high nucleophilicity of bromide bears advantages in synthesis of radiolabelled compounds, and n.c.a. products *via* interhalogen-exchange can be obtained easily [2–4]. Further, it can rather easily be oxidised *in situ*, thus facilitating n.c.a. electrophilic substitution reactions in vinyl and aryl positions [5]. The lighter isotope ^{75}Br with its short half-life, high positron emission intensity and low positron energy, had been extensively evaluated up to about 1990 for its potential use in nuclear medicine [6, 7]. A disadvantage associated with this radionuclide, however, is its decay into the long-lived ^{75}Se ($T_{1/2} = 119.8$ d) which causes extra radiation dose. On the other hand, the physical properties of ^{75}Br make this radionuclide interesting for imaging of fast biochemical processes. In recent years, the radionuclide ^{76}Br has found versatile applications like radiolabeling of antibodies for tumour imaging, or labelling of receptor ligands for brain studies, *cf*. [8]. The important decay properties of both radionuclides are given in Table 1.

For both radionuclides, and in particular for ^{75}Br, a serious drawback is their limited availability. Several routes for the production of ^{75}Br and ^{76}Br had been investigated up to 1986, for reviews *cf*. [9, 10]. They included formation of both the radionuclides directly as well as *via* the precursors ^{75}Kr and ^{76}Kr, respectively, obtained through irradiations with protons, deuterons, ^{3}He- and ^{4}He-particles. The maximum quantities of ^{75}Br and ^{76}Br achieved were about 4 GBq and 0.5 GBq, respectively. Later reports making use of the reactions ^{78}Kr(d, $n\alpha$)^{75}Br [11], ^{78}Kr(p, α)^{75}Br [12], ^{74}Se(d, n)^{75}Br [13] and ^{78}Kr(d, α)^{76}Br [14] led only to limited quantities of about 1 GBq of ^{75}Br and 10 MBq of ^{76}Br. In recent years more attention has been paid to the production of ^{76}Br, particularly *via* the ^{76}Se(p, n)^{76}Br reaction [15, 16]. So far the production of ^{75}Br has been successfully done *via* the ^{75}As(^{3}He, $3n$)^{75}Br and ^{76}Se(p, $2n$)^{75}Br reactions, and that of ^{76}Br *via* the ^{75}As(^{3}He, $2n$)^{76}Br and ^{76}Se(p, n)^{76}Br reactions.

This work is part of a broader study investigating the formation of radiobromine *via* proton induced reactions on enriched selenium targets and focuses on the production possibilities of the two radionuclides ^{75}Br and ^{76}Br using intermediate energy protons. Cross section measurements up to 66 MeV were done on the relevant ^{77,78}Se(p, xn)^{75}Br and the ^{77,78,80}Se(p, xn)^{76}Br processes, using highly enriched target isotopes. In case of the ^{80}Se(p, $5n$)^{76}Br reaction the investigated energy range was extended to 85 MeV. The new excitation functions obtained were compared with results of calculations based on the precompound nuclear model code ALICE-IPPE. The integral yields for the production of the two radionuclides were also calculated, and a discussion of the results with special respect to radionuclidic purity

*Author for correspondence (E-mail: i.spahn@fz-juelich.de).
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Table 1. Decay properties of the radionuclides ^{75}Br and ^{76}Br and their investigated production routes.

	Half-life (h)	Decay mode (%)	$\beta^+{}_{max}$ energy (MeV)	Main γ-rays in keV (%)	Previously investigated production routes	Q-value (MeV)
^{75}Br	1.6	β^+ (75.5) EC (24.5)	1.72	141.3 (6.6) 286.5 (88)	^{78}Kr($d, n\alpha$) ^{78}Kr(p, α) ^{75}As(^{3}He, $3n$) ^{76}Se($p, 2n$)	−2.041 −0.177 −13.176 −14.967 −1.991
^{76}Br	16.2	β^+ (58.2) EC (41.8)	3.94	559.1 (74) 657.0 (15.9)	^{75}As(^{3}He, $2n$) ^{76}Se(p, n) ^{79}Br($p, 4n$)^{76}Kr → ^{76}Br ^{81}Br($d, 7n$)^{76}Kr → ^{76}Br	−3.954 −5.745 −32.051 −52.324

Decay data taken from [27, 28, 29 (β^+ intensity)].

is given. The formation of other radioisotopes of bromine, namely ^{77}Br and ^{80m}Br, and their implication on radionuclidic purity will be discussed in a subsequent paper.

2. Experimental

Cross sections were measured by activation and identification of the radioactive products. The relevant techniques are given below.

2.1 Sample preparation

For investigation of different nuclear processes, targets of enriched elemental ^{77}Se, ^{78}Se and ^{80}Se powder were used, the detailed compositions of which are given in Table 2. In order to obtain thin samples for irradiations, the sedimentation technique described in detail earlier [16, 17] was used. The powder was sedimented from ethanol on a 0.1 mm thick aluminium backing and covered with 0.01 mm thick Al foil for protection. This way sediment layers could be obtained, each with enriched Se isotope content of 2.9 to 28.9 mg/cm^2. The diameter of the deposited layer was either 7 or 10 mm.

2.2 Irradiations and beam current measurement

The samples were irradiated in a stacked-foil arrangement together with different monitor foils. The proton energy degradation within the stack was calculated at Jülich with the computer code STACK which is based on the Bethe formalism and the tables of Williamson *et al.* [18] and with a similar code at iThemba LABS in Somerset West.

Table 2. Isotopic compositions of used enriched Se target material.

	^{76}Se (%)	^{77}Se (%)	^{78}Se (%)	^{80}Se (%)	^{82}Se (%)
^{77}Se^a	1.21	91.77	4.68	1.87	0.41
^{78}Se^a	0.11	0.17	98.58	1.00	0.08
^{80}Se^b	0.01	< 0.005	0.008	99.90	0.07

a: Material provided by Oak Ridge National Laboratory;
b: Material provided by Chemotrade GmbH.

Irradiations up to 45 MeV proton energy were done at the injector cyclotron of COSY of the Forschungszentrum Jülich, Germany. Irradiations in the higher energy region were carried out at the Separate Sector Cyclotron (SSC) of iThemba LABS in Somerset West, South Africa. The proton energy range covered by the irradiations was from 21 to 80 MeV. The thin ^{77}Se and ^{78}Se targets were irradiated at both cyclotrons with protons of energies up to 66 MeV. The ^{80}Se targets were irradiated with energies up to 80 MeV. The energy ranges covered in the stacks were chosen such that they partly overlapped, thereby allowing a comparison of results in the overlapping regions, obtained in independent measurements.

The beam current was measured *via* current integration on one hand, and *via* monitor reactions, on the other. As monitors thin Al, Cu and Ni foils were used, inducing the corresponding ^{27}Al(p, x)^{22}Na, ^{nat}Cu(p, xn)^{62,63}Zn and ^{nat}Ni(p, x)^{57}Ni processes, the cross sections of which are well known [19]. At iThemba LABS current measurement was also done using the Faraday cup described in detail earlier [20]. The two methods of beam current determination showed an agreement within about 5%.

2.3 Measurement of radioactivity

The induced radioactivity was measured using HPGe detector γ-ray spectrometry, analysing all major γ-rays of the investigated radionuclides. Several spectra, registered at various times after the end of bombardment (EOB), were analysed and the results averaged. The peak area analysis was done using either the software Gamma Vision 6.01 (EG&G Ortec) or Emca 2000 2.03.0 (Silena Int. spa). All γ-ray measurements were done non-destructively. Detectors were calibrated and their efficiencies determined using standard sources from PTB Braunschweig and Amersham International. All measurements were done at a minimum distance of between 10 and 50 cm to the detector to avoid coincidence losses.

For the study of ^{75}Br the two strongest γ-rays of energies 141.32 and 286.57 keV were analysed, and for ^{76}Br the 559.10 and 657.36 keV γ-rays were considered. Since both γ-rays are also emitted in the decay of ^{76}As, a small contribution of that nuclide in ^{76}Br cannot be ruled out.

However, this contribution is expected to be small because the cross sections for the nuclear processes ^{77}Se$(p, 2p)^{76}$As, ^{78}Se$(p, ^3$He$)^{76}$As and ^{80}Se$(p, \alpha n)^{76}$As are expected to be rather small, in comparison to the respective (p, xn) reactions leading to the formation of ^{76}Br. To verify this, decay curve analyses were done to check for any deviation in the measured half-life due to contribution of the longer lived ^{76}As ($T_{1/2} = 26.4$ h). The analyses confirmed the literature value with an average uncertainty of 7%, which is well within the experimental uncertainties and can be considered as a maximum possible contamination.

2.4 Calculation of reaction cross sections and uncertainties

Cross sections were calculated using the well-known activation equation. As mentioned above, results obtained from the analysis of several clear γ-lines belonging to the same nuclide were averaged. The enriched isotopes had different abundances. However, all cross section values were normalised to 100% enrichment of the target isotope.

The total uncertainties of the measurements were calculated with the error propagation according to Gauss. They are mainly based on the individual uncertainties concerning the incident proton energies, determination of particle flux and detector efficiency. In general, the total uncertainty in cross section amounted to between 9 and 17%.

3. Results and discussion

3.1 Reaction cross sections

The measured nuclear reaction cross sections relevant to the production of ^{75}Br and ^{76}Br are given in Tables 3 and 4, respectively, together with their corresponding uncertainties. The results of the accomplished experiments, done at two cyclotrons in different facilities, showed good consistency. Regarding the literature data, the formation of ^{76}Br up to 35 MeV was determined well by Hassan *et al.* [16]. Concerning the production of the radionuclide ^{75}Br, results have been reported for proton induced reactions on ^{nat}Se and ^{76}Se up to about 40 MeV [16, 21, 22]. A few other data are also available up to proton energies of 30 MeV [23]. All those data are discussed below. In the higher proton energy range, to date our measurements represent the first (p, xn) reaction cross section data for the production of these radionuclides. Based on those experimental values, obtained using enriched target material, excitation functions could be constructed as shown in Figs. 1–5. For comparison, existing experimental results in the literature are given, where this was possible.

Formation of ^{75}Br

Fig. 1 depicts the cross section data for the production of ^{75}Br *via* the ^{77}Se$(p, 3n)$ process. The excitation curve shows a maximum of about 250 mb at 34 MeV. The previously published data of Levkovskij [23] are rather high. A recent publication by Takács *et al.* [24] suggests a general downward adjustment of those data up to 20%, which is shown in the figure and leads to better agreement with our measurements. The remaining shift in energy may be within the limits of uncertainty, which is, however, not given in the case of the Levkovskij data which were taken from the EXFOR file [28]. The dashed line in Fig. 1 describes theoretical results obtained using the ALICE-IPPE code, as given in the MENDL-2P data file [25]. Evidently, the model calculation reproduces the shape of the excitation function well, but generally overestimates the cross section data.

Table 3. Reaction cross sections in mb for the formation of ^{75}Br.

Energy (MeV)	^{75}Br	
	^{77}Se$(p, 3n)$	^{78}Se$(p, 4n)$
24.3 ± 1.0	27.4 ± 3.6	
26.6 ± 0.8	26.3 ± 3.5	
28.7 ± 0.7	106.7 ± 13.9	
31.1 ± 0.5	178.4 ± 23.2	
31.5 ± 1.0	182.6 ± 23.7	
32.2 ± 0.9		0.5 ± 0.1
32.5 ± 0.6		1.1 ± 0.1
34.2 ± 0.4		0.6 ± 0.1
35.6 ± 0.4		6.9 ± 0.9
35.7 ± 0.4	267.5 ± 34.8	
35.8 ± 0.6		0.4 ± 0.0
37.0 ± 0.4	161.2 ± 21.0	
37.2 ± 0.3		6.3 ± 0.8
38.4 ± 0.3		11.9 ± 1.6
38.6 ± 0.3	188.2 ± 24.5	
39.9 ± 0.3	101.1 ± 13.1	
39.9 ± 0.2		29.5 ± 3.8
39.9 ± 0.5	116.4 ± 104.8	
40.8 ± 0.2		35.7 ± 4.6
41.4 ± 0.2	97.8 ± 12.7	
41.8 ± 0.2		43.1 ± 5.6
42.4 ± 0.2		35.6 ± 4.6
43.2 ± 0.2		53.9 ± 7.0
43.2 ± 0.5		36.3 ± 3.9
43.7 ± 0.2	63.9 ± 8.3	
44.1 ± 0.2		71.6 ± 9.3
44.5 ± 0.2	87.3 ± 11.4	
44.9 ± 0.2		75.8 ± 9.8
48.4 ± 0.5	37.4 ± 6.4	
53.6 ± 0.4		57.6 ± 6.2
56.6 ± 0.3	28.3 ± 4.8	
59.3 ± 0.3		42.8 ± 4.6
64.7 ± 0.2		31.7 ± 3.0

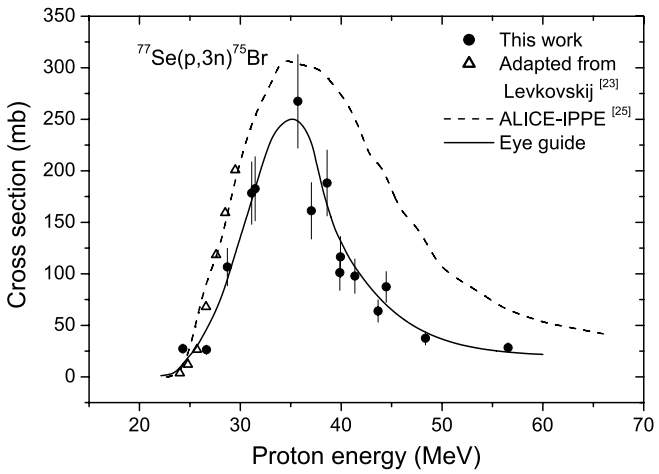

Fig. 1. Experimentally determined excitation function of the ^{77}Se$(p, 3n)$ ^{75}Br reaction together with data from the literature and results of ALICE-IPPE calculation.

Table 4. Reaction cross sections in mb for the formation of ^{76}Br.

Energy (MeV)	^{77}Se(p, 2n)	^{78}Se(p, 3n)	^{80}Se(p, 5n)
21.3 ± 0.9	478.5 ± 43.1		
23.4 ± 0.8		1.0 ± 0.1	
24.3 ± 0.8	446.0 ± 40.1		
25.2 ± 0.6		12.5 ± 1.6	
26.6 ± 0.8	332.7 ± 29.9		
26.8 ± 0.8		5.6 ± 0.5	
26.9 ± 0.5		30.2 ± 3.9	
27.8 ± 0.5		133.3 ± 17.3	
28.7 ± 0.5	157.6 ± 20.5		
29.5 ± 0.5		81.3 ± 10.6	
29.9 ± 0.5		176.2 ± 22.9	
30.9 ± 0.7		66.2 ± 6.0	
31.1 ± 0.5	110.1 ± 14.3		
31.5 ± 0.5	122.0 ± 15.9		
32.2 ± 0.4		233.3 ± 30.3	
32.5 ± 0.4		207.5 ± 27.0	
33.7 ± 0.4	99.2 ± 10.9		
34.2 ± 0.4	64.8 ± 7.1	312.4 ± 40.6	
35.6 ± 0.4		267.2 ± 34.7	
35.7 ± 0.4	87.4 ± 11.4		
37.0 ± 0.3	66.0 ± 8.6		
37.2 ± 0.3		323.0 ± 42.0	
38.4 ± 0.6		222.1 ± 28.9	
38.6 ± 0.3	81.5 ± 10.6		
39.9 ± 0.2	49.1 ± 6.4		
39.9 ± 0.2		265.3 ± 34.5	
39.9 ± 0.5	70.8 ± 6.4		
40.8 ± 0.2		216.8 ± 28.2	
41.4 ± 0.2	47.8 ± 6.2		
41.8 ± 0.2		199.9 ± 26.0	
42.4 ± 0.2		177.7 ± 23.1	
43.2 ± 0.2		164.4 ± 21.4	
43.2 ± 0.5		188.8 ± 17.0	
43.7 ± 0.2	30.9 ± 4.0		
44.1 ± 0.2		121.3 ± 15.8	
44.5 ± 0.2	36.1 ± 4.7		
44.9 ± 0.2		155.8 ± 20.3	
45.0 ± 0.5		131.4 ± 11.8	
46.2 ± 0.4			5.4 ± 0.5
48.4 ± 0.3	37.2 ± 3.3		
48.8 ± 0.3			13.0 ± 1.2
51.3 ± 0.3			20.3 ± 1.8
53.6 ± 0.4		57.9 ± 5.2	
53.9 ± 0.3			49.0 ± 4.4
56.5 ± 0.3			56.9 ± 5.1
56.6 ± 0.2	34.6 ± 3.1		
58.9 ± 0.2			49.2 ± 4.4
59.3 ± 0.3		51.0 ± 4.6	
61.4 ± 0.2			73.1 ± 6.6
64.7 ± 0.2		46.7 ± 5.1	
64.7 ± 0.2		46.7 ± 4.2	
66.5 ± 0.4			73.3 ± 6.6
68.5 ± 0.4			50.9 ± 4.6
70.5 ± 0.4			55.9 ± 5.0
72.4 ± 0.3			53.2 ± 4.8
74.5 ± 0.3			54.9 ± 4.9
76.5 ± 0.3			45.4 ± 4.1
78.5 ± 0.3			28.4 ± 2.6
80.4 ± 0.2			41.3 ± 3.7
82.3 ± 0.2			16.0 ± 1.4
84.2 ± 0.2			22.0 ± 2.0

The experimental results on the formation of ^{75}Br *via* the ^{78}Se(p, 4n) process are shown in Fig. 2. Those cross sections have been measured for the first time using enriched ^{78}Se as target material. The suggested excitation function (Fig. 2)

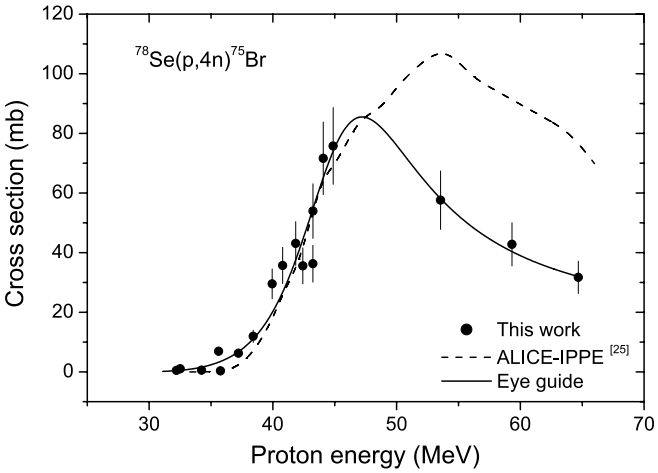

Fig. 2. Experimentally determined excitation function of the ^{78}Se(p, 4n)^{75}Br reaction together with the results of ALICE-IPPE calculation.

shows a maximum value of 80 mb at about 47 MeV proton energy. However, additional experimental work is required to define clearly the cross section maximum. The results of the ALICE-IPPE calculation agree very well with the experimental data up to about 45 MeV, but differ considerably thereafter with regard to both shape and magnitude of the excitation function. The comparison points out the difficulties in modeling multi-particle emission from medium mass target nuclei.

Formation of ^{76}Br

Figs. 3–5 show the measured cross section values for the formation of ^{76}Br *via* three reaction channels, namely (p, 2n), (p, 3n) and (p, 5n), on enriched selenium targets. The existing literature data on the ^{77}Se(p, 2n)^{76}Br reaction given by Hassan *et al.* [16] and Levkovskij [23] are also shown in Fig. 3. The experimental results obtained in this work are not sufficient to indicate a maximum of the excitation function. The literature shows significantly larger values below 30 MeV. However, the data of Levkovskij, decreased by 20% as suggested by Takács *et al.* [24], come nearer to our measurements. Similarly, the high maximum cross

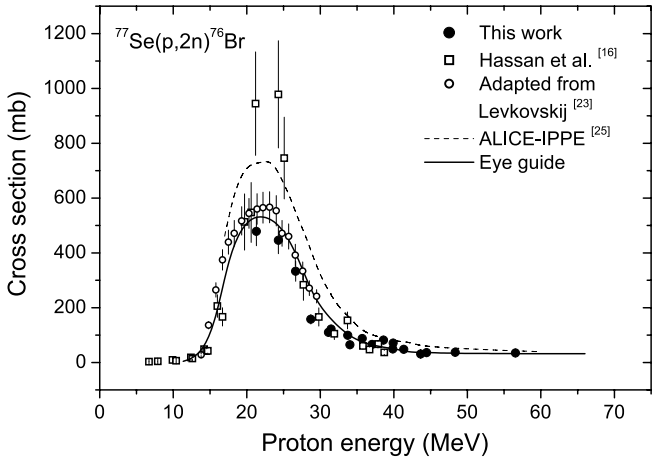

Fig. 3. Excitation function of the ^{77}Se(p, 2n)^{76}Br reaction compared with data from the literature and results of ALICE-IPPE calculation.

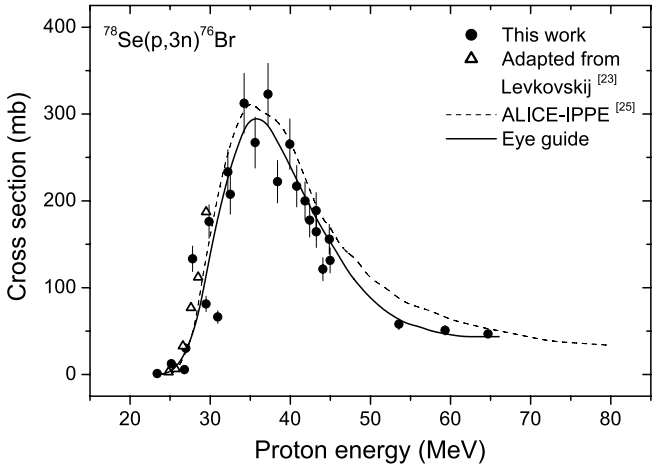

Fig. 4. Experimentally determined excitation function of the ^{78}Se(p, 3n)^{76}Br reaction compared with data from the literature and results of ALICE-IPPE calculation.

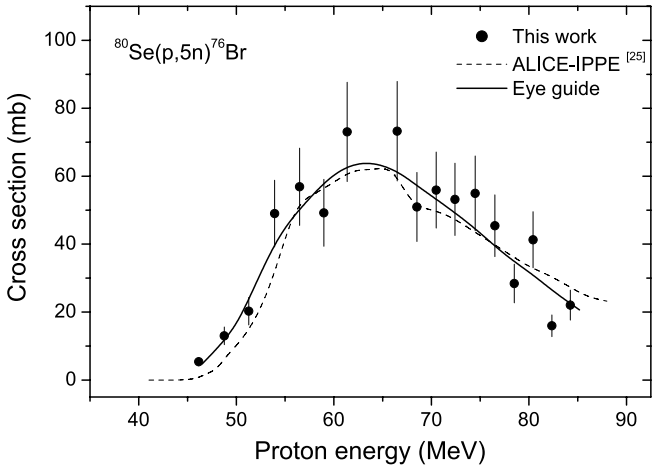

Fig. 5. Excitation function of the ^{80}Se(p, 5n)^{76}Br reaction together with results of ALICE-IPPE calculation.

section of about 900 mb, reported by Hassan *et al.* [16], is based on only 3 points, and may be in error. Our results reported in this work were obtained through three independent experiments in two different laboratories. Therefore there is more confidence in the present values. Thus the eye guide curve shown in Fig. 3 is based on the present data and the adapted values of Levkovskij. As regards the model calculation, again it reproduces the shape of the excitation function well but the magnitude of cross sections is rather high.

The excitation function of the ^{78}Se(p, 3n)^{76}Br reaction is shown in Fig. 4 together with data from the literature and the results of the ALICE-IPPE calculation taken from the MENDL-2P data file [25]. Although the data show some scatter, a clear maximum can be distinguished at 36 MeV. Within the limits of uncertainty the literature data agree well with our results. The agreement between experimental and calculated data is also rather good.

The excitation function of the ^{80}Se(p, 5n)^{76}Br reaction is shown in Fig. 5. No data were found on this nuclear reaction in the literature but the calculated results from the MENDL-2P data file were available and are shown in the figure. The theoretical curve agrees well with the experimental results, which, however, show rather large scatter. Additional measurements in the intermediate energy range are necessary to define this curve more precisely.

3.2 Calculated integral yields

Based on the excitation functions determined in this work, the possible maximum production yields of the two radionuclides ^{75}Br and ^{76}Br were calculated using the whole investigated energy range. The results are given in Table 5 for the respective Se isotope used as target material. For comparison the calculated yields based on the irradiation of enriched ^{76}Se and reported in the literature [26] are also given in Table 5. Evidently, the yield of ^{76}Br *via* the (p, 2n) and (p, 3n) processes is considerably higher than that *via* the (p, n) reaction on ^{76}Se. The production of ^{75}Br *via* the ^{77}Se(p, 3n) and ^{78}Se(p, 4n) processes proves to be less effective than the application of the ^{76}Se(p, 2n)^{75}Br reaction regarding the investigated energy range. Based on the determined excitation functions higher incident proton energies may, however, further increase the yields of the (p, 3n) and (p, 4n) reactions. An estimation of the respective theoretical yields based on the cross section data given by the ALICE-IPPE code [25] supports this conclusion.

Table 5. Calculated total thick target yields of the produced ^{75}Br and ^{76}Br.

Radionuclide	Target nuclide	Energy range [MeV]	Prod. yield [MBq/(μA h)]
^{75}Br [a]	^{77}Se	62 → 20	6153
	^{78}Se	66 → 22	3350
^{76}Br [b]	^{77}Se	66 → 14	1320
	^{78}Se	66 → 24	1118
	^{80}Se	86 → 34	539

a: The calculated yield of ^{75}Br *via* the ^{76}Se(p, 2n)-reaction over E_p = 24 → 21 MeV amounts to 1200 MBq/μA h [26];
b: The calculated yield of ^{76}Br *via* the ^{76}Se(p, n)-reaction over E_p = 15 → 8 MeV amounts to 360 MBq/μA h [26].

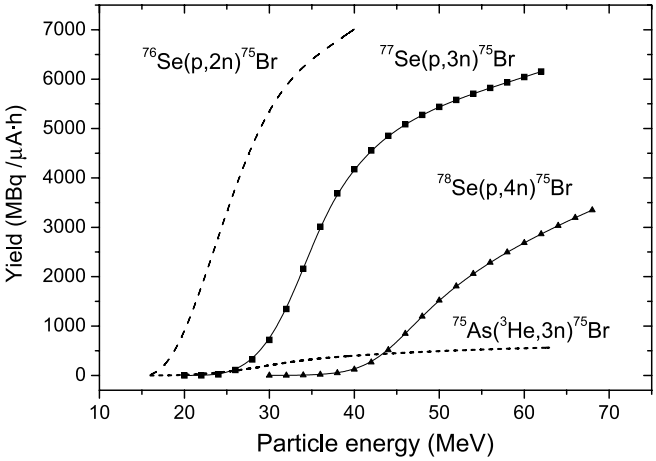

Fig. 6. Integral yields of ^{75}Br in proton induced reactions on enriched ^{77}Se and ^{78}Se calculated from the excitation functions measured in this work. The data for the reactions ^{76}Se(p, 2n)^{75}Br [16, 22] and ^{75}As(^{3}He, 3n)^{75}Br [30] were taken from the literature.

In Fig. 6 the calculated thick target yields of ^{75}Br from all investigated nuclear reaction channels are shown as function of particle energy. Obviously, in the energy range below 30 MeV the ^{76}Se(p, 2n)^{75}Br reaction discussed above is very useful for production. The calculated yield of the ^{75}As(^{3}He, 3n)^{75}Br process [30] is rather low, but this reaction was used for ^{75}Br production due to the advantageous development of high-current As-containing target material. The calculated thick target yields of ^{76}Br are shown in Fig. 7 in comparison with the results of the alternative production routes utilizing the ^{76}Se(p, n)^{76}Br and ^{75}As(^{3}He, 2n)^{76}Br reactions. The yield of the latter is much lower than those of the investigated proton induced reactions.

Concerning the isotopic purity in the production of ^{76}Br with intermediate energy protons, the co-produced ^{75}Br is the most significant radionuclidic impurity. However, its short half-life allows for a nearly complete decay of this impurity within one half-life of the ^{76}Br ($T_{1/2}$ = 16.2 h). The production of radionuclidically pure ^{75}Br on the other hand, is not possible. In Fig. 8 the production yields of ^{75}Br *via* the ^{77}Se(p, 3n)^{75}Br and ^{78}Se(p, 4n)^{75}Br reactions, investigated in this work, are shown again, this time together with the corresponding fraction of co-produced ^{76}Br. The irradiation of a thick ^{77}Se target with 66 MeV protons results in an impurity level of about 21% ^{76}Br. With regard to the bombardment of ^{78}Se, this ratio increases to about 35%. The co-production of the radionuclide ^{77}Br and its effect on the isotopic purity will be discussed in detail in a separate publication, as it is subject to several factors like proton energy and irradiation time.

It can be concluded that the application of protons in the intermediate energy range is advantageous for the production of ^{76}Br. With regard to the production of ^{75}Br, the intermediate energy reactions are inferior to the production *via* the (p, 2n) process on enriched ^{76}Se [26], which is due to the lower radionuclide yield as well as the low radionuclidic purity connected to it.

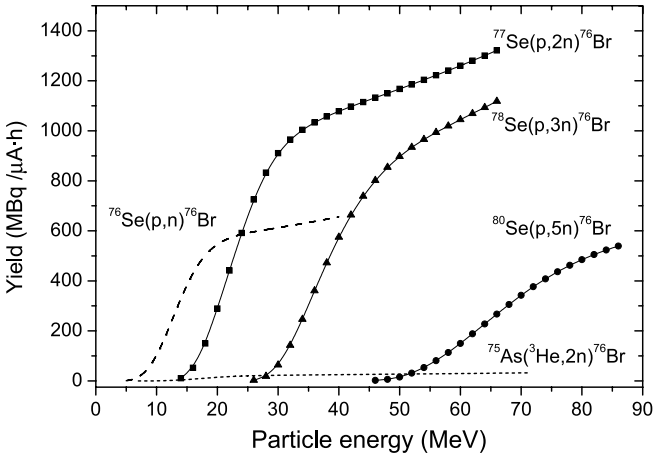

Fig. 7. Integral yields of ^{76}Br in proton induced reactions on enriched ^{77}Se, ^{78}Se and ^{80}Se calculated from the excitation functions measured in this work. The data for the reactions ^{76}Se(p, n)^{76}Br [16, 22] and ^{75}As(^{3}He, 2n)^{76}Br [30] were taken from the literature.

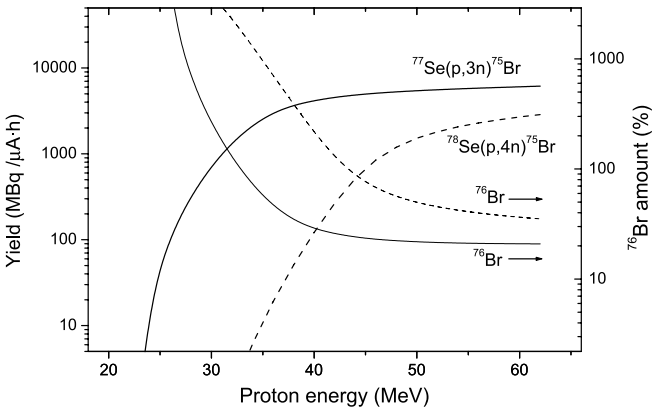

Fig. 8. Calculated thick target yields of ^{75}Br *via* the ^{77}Se(p, 3n) and ^{78}Se(p, 4n) processes, together with the corresponding ratio of the ^{76}Br impurity (in %).

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