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New cross section measurements for the production of the Auger electron emitters ^{77}Br and ^{80m}Br

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Summary. The two Auger electron emitting radionuclides of bromine, namely ^{77}Br ($T_{1/2} = 57.04$ h) and ^{80m}Br ($T_{1/2} = 4.4$ h), are promising candidates for internal radiotherapy. In this work, nuclear reaction cross sections were determined for their production using enriched Se targets. Thin Se samples were irradiated with incident protons of energies up to 85 MeV and the induced radioactivity was measured *via* non-destructive γ-ray spectroscopy, allowing the determination and extension of the excitation functions of the four reactions ^{77,78,80}Se$(p, xn)^{77}$Br and ^{80}Se$(p, n)^{80m}$Br. The possible thick target yields were calculated and the different production routes discussed, especially with regard to the yield and the radionuclidic purity of the produced radionuclides.

1. Introduction

Today, the use of radioactive isotopes is well established in many fields of the life sciences. In particular, the application of radionuclides in diagnostic medical procedures such as positron emission tomography (PET) and single photon emission computed tomography (SPECT), as well as in internal radiotherapy, is becoming increasingly important. Whereas nuclear reactors are still providing the bulk of the production, in recent years the utilisation of accelerators has grown significantly due to an increasing demand for neutron deficient radionuclides and the simpler and less expensive operation of typical medical cyclotron facilities. As a result of this growth in accelerator produced radionuclides in medical applications, the demand on production efficiency while maintaining radionuclidic purity is also increasing. Besides being of interest for the development of nuclear models, the measurement of nuclear reaction cross sections over a broad energy range is also a crucial step in the determination of optimum conditions for a production route.

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The application of radioisotopes of bromine in nuclear medicine is of longstanding interest. The production of the lighter isotopes, ^{75}Br ($T_{1/2} = 1.6$ h) and ^{76}Br ($T_{1/2} = 16.2$ h), and their use in PET imaging has been pursued for quite some time [1–4], and in a recent work [5] we discussed their production possibilities *via* intermediate energy reactions. In contrast, the two Auger electron emitters ^{77}Br ($T_{1/2} = 57.04$ h) and ^{80m}Br ($T_{1/2} = 4.4$ h) investigated in this work are of interest in internal radiotherapy. The utilisation of bromine for radiopharmaceutical synthesis bears some advantages due to its high chemical versatility, including high nucleophilicity and the possibility of in situ oxidation, enabling also electrophilic substitution [2, 6, 7]. The relevant decay properties [Ref. 8] of these two radionuclides are given in Table 1.

The production of ^{77}Br and ^{80m}Br has been investigated using different nuclear processes [9–15] (*cf*. Table 1). Concerning the production of ^{77}Br, several routes have been investigated [9, 10, 14, 15], including proton induced reactions on Se targets, α-particle induced reactions on As (*cf*. [10]) and indirect routes *via* the formation of the precursor ^{77}Kr, utilising the nuclear processes ^{79}Br$(p, 3n)^{77}$Kr $\rightarrow$ ^{77}Br, ^{79}Br$(d, 4n)^{77}$Kr $\rightarrow$ ^{77}Br and ^{nat}Se$(^3$He$, xn)^{77}$Kr $\rightarrow$ ^{77}Br (*cf*. [14, 16–19]). Regarding the production of ^{80m}Br, deuteron induced reactions on Kr were investigated [11]. Although all those production routes lead to high-purity products, the resulting radionuclide yields are rather low. In the case of ^{77}Br, the intermediate energy reaction appears to be promising but the data are scanty. For ^{80m}Br, the production database is rather weak.

The aim of this work was to determine nuclear reaction cross sections using enriched selenium isotopes as target material to be able to develop efficient routes for the production of radionuclidically pure ^{77}Br and ^{80m}Br. The short-lived isotope ^{80g}Br ($T_{1/2} = 17.6$ min) has no relevance for medical applications and was therefore not part of this study. The cross section data for the production of ^{77}Br *via* low energy (p, n) and $(p, 2n)$ reactions have already been well determined [20]. In this work those measurements were extended by studying the nuclear processes ^{77,78,80}Se$(p, xn)^{77}$Br, using enriched target materials. The excitation function of the ^{80}Se$(p, n)^{80m}$Br reaction was determined systematically up

Table 1. Decay properties of the radionuclides ^{77}Br and ^{80m}Br and some of their investigated production routes.[a]

	Half-life (h)	Decay mode	Main γ-rays in keV (%)	Previously investigated production routes	Q-value (MeV)
^{77}Br	57.04	β^+ (0.74%) EC (99.26%) Auger electrons	239.0 (23.1) 520.6 (22.4) 297.2 (4.2)	^{75}As(α, 2n) (*cf.* [10]) ^{79}Br(d, 4n)^{77}Kr → ^{77}Br [15] ^{79}Br(p, 3n)^{77}Kr → ^{77}Br [16] ^{nat}Se(p, xn) [25]	−13.515 −24.983 −22.824 −2.147 to −29.521
^{80m}Br	4.4	IT (100%) Auger electrons	37.05 (39.1)	^{80}Se(p, n) [28] ^{83}Kr(d, αn) [11] ^{nat}Se(p, xn) [25]	−2.652 −1.453 −2.652 to −18.629

a: Data taken from [8, 34].

to 20 MeV for the first time. Based on the experimental cross section data, possible production yields of the investigated radionuclides were deduced. Furthermore, the important issues of radionuclidic purity and optimum production conditions are discussed on the basis of those yield data.

2. Experimental

Cross sections were determined *via* activation and identification of the radioactive products using non-destructive γ-ray spectroscopy. The relevant techniques are given below.

2.1 Sample preparation

For investigation of different nuclear processes, targets of enriched elemental ^{77}Se (91.77%), ^{78}Se (98.58%) and ^{80}Se (99.90%) powder were used, which were obtained from Oak Ridge National Laboratory and Chemotrade GmbH. The preparation of thin samples for irradiations using the sedimentation technique was described in detail in our recent publication [5]. Al foils of 100 μm thickness were used as backings. Sediment layers were obtained, each having an enriched Se isotope content of 2.9–28.9 mg/cm^2. The deposited layer had a diameter of either 7 or 10 mm and was covered by a thin Al foil for protection. This technique enables the preparation of thin Se layers with no or minimal loss of enriched material. However, the obtained samples are sensitive to pressure and interfacial tension. Both effects can potentially lead to the formation of small cracks and inhomogeneity of the target material. Thus handling of the samples had to be done avoiding bending and local pressure.

2.2 Irradiations and beam current measurement

The samples were irradiated in a stacked-foil arrangement together with different monitor foils, namely Al, Cu and Ni (Goodfellow). 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.* [21] and with a similar code at iThemba LABS in Somerset West, based on the stopping power expressions of Anderson and Ziegler [22]. The two sets of calculations were in excellent agreement.

In investigations on the formation of ^{77}Br, irradiations with protons up to an energy of 45 MeV were done at the injector cyclotron of COSY of the Forschungszentrum Jülich, Germany. Irradiations in the higher energy region were carried out at the Separated Sector Cyclotron (SSC) of iThemba LABS in Somerset West, South Africa. The proton energy range covered by the irradiations was from 21 to 85 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 85 MeV. The formation of ^{80m}Br was studied only in the lower energy range up to 19 MeV, utilizing the Compact Cyclotron CV 28 of the Forschungszentrum Jülich. 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 individual beam currents were measured in two different ways, involving current integration on the one hand, and the use of monitor reactions, on the other. The current integration was generally done using Faraday cups, whereas at iThemba LABS an activation chamber called RERAME was used, which is described in detail elsewhere [23]. As monitors, thin Al, Cu and Ni foils were employed, utilizing the ^{27}Al(p, x)^{22}Na, ^{nat}Cu(p, xn)^{62,63}Zn and ^{nat}Ni(p, x)^{57}Ni processes, respectively, the cross sections of which are well known [24]. The two methods of beam current determination generally showed an agreement within about 5%.

2.3 Measurement of radioactivity

The induced radioactivity was measured non-destructively using HPGe detector γ-ray spectrometry, analysing all major γ-rays of the investigated radionuclides. The energy calibration and determination of counting efficiency were done using standard sources from PTB Braunschweig, Germany, and Amersham International, United Kingdom. All irradiated samples were analysed by registering several spectra at various times after the end of bombardment (EOB) and the results were averaged. The peak area analysis was done using either the software GammaVision 6.01 (EG&G Ortec) or Emca 2000 version 2.03.0 (Silena International). In order to avoid losses of events from the relevant photopeaks due to

coincidence summing, all measurements were done at a distance of 10–50 cm from the detector.

For measurements on ^{80m}Br, which emits only a low-energy γ-ray of 37.1 keV, a well calibrated thin HPGe solid state detector (EG&G Ortec) was used, which is equipped with an active diameter of 3.2 cm, a depth of 1.3 cm and an 0.03 mm thick Be cover. Concerning the detection of ^{77}Br, the possibility of interference caused by co-produced ^{77}As had to be considered. This was taken into account by analysing the rather weak 297.2 keV γ-ray of ^{77}Br, which is not shared by its isobar, in addition to the two main γ-rays of energies 239.0 and 520.6 keV. Within the limits of uncertainty, no ^{77}As activity was detected.

2.4 Calculation of reaction cross sections and uncertainties

The total uncertainties of the measurements were calculated according to Gaussian error propagation and are given together with the cross section data in Tables 2 and 3. They are mainly based on the individual uncertainties of the incident proton energies, determination of particle flux and detector efficiency. Concerning the measurement of ^{80m}Br, the efficiency calibration is less precise than in general, leading to higher uncertainties in those cross section data. Largely, the total uncertainty in cross section amounted to between 9 and 20%.

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 and all obtained cross section values were normalised to 100% enrichment of the respective target isotope.

3. Results and discussion

3.1 Nuclear reaction cross sections

The cross sections of the nuclear reactions ^{77}Se$(p, n)^{77}$Br, ^{78}Se$(p, 2n)^{77}$Br, ^{80}Se$(p, 4n)^{77}$Br and ^{80}Se$(p, n)^{80m}$Br were experimentally determined and the data relevant to the production of ^{77}Br and ^{80m}Br are given in Tables 2 and 3, respectively, together with their corresponding uncertainties. The results for the ^{77}Se$(p, n)^{77}$Br reaction between 21 and 35 MeV were corrected for the contribution from the ^{78}Se$(p, 2n)^{77}$Br reaction, since the enriched material ^{77}Se contained 4.7% ^{78}Se. The cross section data for the latter reaction were measured independently in this work (see Sect. 3.1.2). This correction leads to the higher uncertainty given in Table 2. In general, the results for ^{77}Br obtained from experiments done at the two different accelerators show good agreement. The ^{80}Se$(p, 4n)^{77}$Br reaction has been investigated for the first time in this work. Regarding the other reactions, the database was weak. Furthermore, those data were limited to the lower energy range and showed some deviations, which will be discussed in detail below. Most recently, El-Azony *et al.* [25] published their results on the formation of ^{77}Br and ^{80m}Br *via* proton induced reactions on natural selenium up to 63 MeV.

The data measured in this work are shown as a function of proton energy, together with the corresponding literature

Table 2. Measured cross sections for the formation of ^{77}Br, utilising the reactions as indicated.

Proton energy (MeV)	Cross section (mb) ^{77}Se$(p, n)^{77}$Br	^{78}Se$(p, 2n)^{77}$Br	^{80}Se$(p, 4n)^{77}$Br
21.3 ± 0.9	114 ± 24		
23.4 ± 0.8		491 ± 53	
24.3 ± 0.8	42 ± 9		
25.2 ± 0.6		468 ± 51	
26.6 ± 0.8	30 ± 6		
26.8 ± 0.8		196 ± 21	
27.0 ± 0.5		167 ± 18	
28.7 ± 0.5	15 ± 3		
29.5 ± 0.5		110 ± 12	
29.9 ± 0.5		230 ± 15	
30.9 ± 0.7		253 ± 27	
31.1 ± 0.5	16 ± 3		
31.5 ± 0.5	21 ± 4		
32.2 ± 0.4		146 ± 16	
32.5 ± 0.4		117 ± 13	
33.7 ± 0.4	16 ± 3		
34.1 ± 0.4	10 ± 2		
34.3 ± 0.4		132 ± 15	
34.5 ± 0.4			20 ± 2
35.6 ± 0.4		87 ± 10	
35.7 ± 0.4	18 ± 4	100 ± 11	
37.0 ± 0.3	12 ± 3		
37.2 ± 0.3		126 ± 14	
37.4 ± 0.3			98 ± 11
38.4 ± 0.6		60 ± 7	
38.6 ± 0.3	23 ± 5		
39.9 ± 0.2	20 ± 4		
39.9 ± 0.2	12 ± 2	92 ± 10	
40.6 ± 0.5			214 ± 23
40.8 ± 0.2		70 ± 8	
41.4 ± 0.2	15 ± 3		
41.8 ± 0.2		73 ± 8	
42.4 ± 0.2		67 ± 7	
43.2 ± 0.2		75 ± 8	
43.2 ± 0.5		65 ± 7	
43.4 ± 0.5			231 ± 25
43.7 ± 0.2	9 ± 2		
44.1 ± 0.2		52 ± 6	
44.5 ± 0.2	18 ± 4		
44.9 ± 0.2		57 ± 6	
44.9 ± 0.5		77 ± 8	
46.2 ± 0.4			189 ± 21
48.4 ± 0.3	13 ± 3		
48.8 ± 0.3			216 ± 24
51.3 ± 0.3			160 ± 17
53.6 ± 0.4		44 ± 5	
53.9 ± 0.3			174 ± 19
56.5 ± 0.3			122 ± 13
56.6 ± 0.2	12 ± 2		
59.0 ± 0.2			73 ± 8
59.3 ± 0.3		45 ± 5	
60.3 ± 0.3			31 ± 3
61.4 ± 0.2			90 ± 10
62.4 ± 0.2			81 ± 9
63.7 ± 0.2			46 ± 5
64.4 ± 0.2			91 ± 10
64.7 ± 0.2		43 ± 4	
66.0 ± 0.2			49 ± 5
66.5 ± 0.4			73 ± 8
68.5 ± 0.4			51 ± 6
70.5 ± 0.4			56 ± 6
72.4 ± 0.3			53 ± 6
74.5 ± 0.3			55 ± 6
76.5 ± 0.3			45 ± 5
78.5 ± 0.3			28 ± 3
80.4 ± 0.2			41 ± 5
82.3 ± 0.2			16 ± 2
84.2 ± 0.2			22 ± 2

Table 3. Measured cross sections for the formation of ^{80m}Br, utilising the ^{80}Se$(p, n)^{80m}$Br reaction.

Proton energy (MeV)	Cross section (mb)
7.4 ± 0.4	203 ± 31
8.7 ± 0.4	320 ± 48
10.1 ± 0.4	384 ± 58
11.3 ± 0.3	356 ± 53
11.7 ± 0.3	431 ± 65
13.1 ± 0.3	253 ± 38
13.3 ± 0.3	306 ± 46
14.4 ± 0.3	172 ± 26
15.2 ± 0.3	99 ± 15
15.7 ± 0.3	147 ± 22
16.8 ± 0.3	66 ± 10
18.5 ± 0.3	72 ± 11

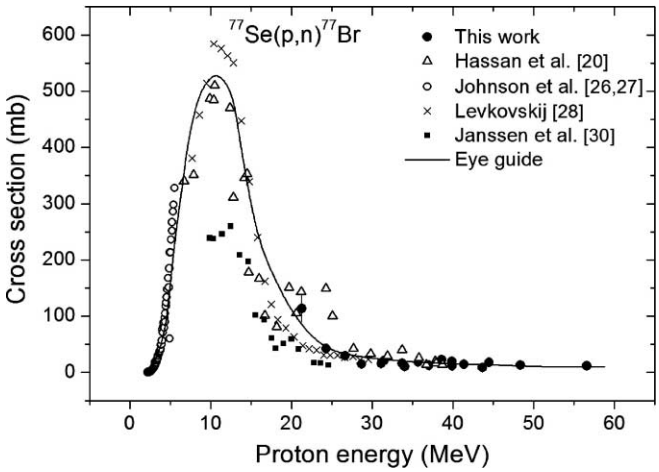

Fig. 1. Experimentally determined reaction cross sections for the formation of ^{77}Br using enriched ^{77}Se target material together with data from the literature. The data of Levkovskij [28] have been adjusted by 20% (see text).

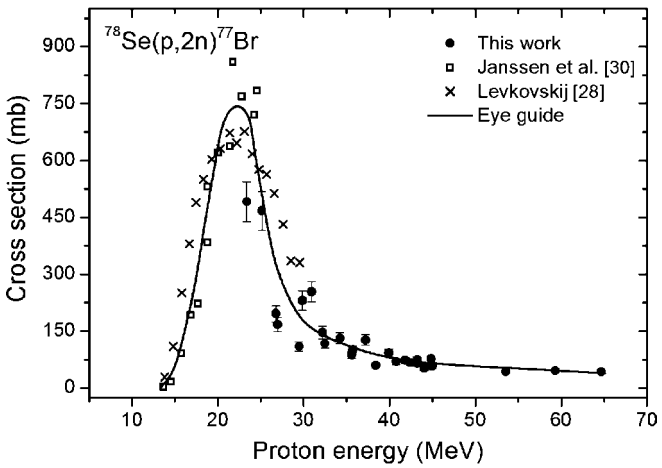

Fig. 2. Experimentally determined reaction cross sections for the formation of ^{77}Br using enriched ^{78}Se target material together with data from the literature. The data of Levkovskij [28] have been adjusted by 20% (see text).

data, in Figs. 1–4. The cross section data given in [25] are not included in Figs. 1–3, as those are based on the irradiation of natural target material and thus represent averaged

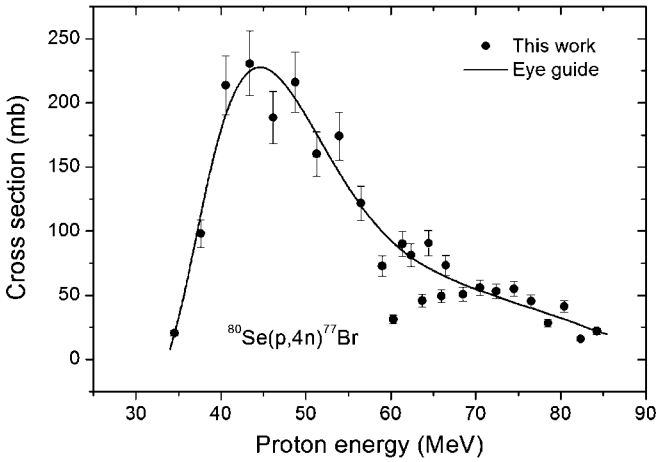

Fig. 3. Experimentally determined reaction cross sections for the formation of ^{77}Br using enriched ^{80}Se target material.

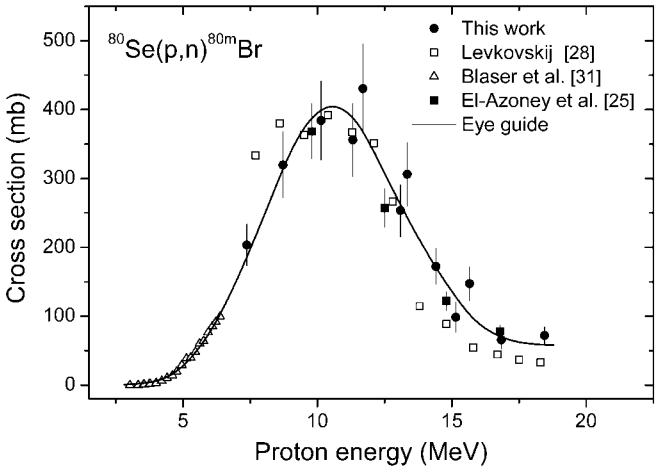

Fig. 4. Experimentally determined reaction cross sections for the formation of ^{80m}Br using enriched ^{80}Se target material together with data from the literature. The data of Levkovskij [28] have been adjusted by 20% (see text).

results of competing reaction channels, which cannot easily be compared with the other data. In Fig. 4, however, the data are shown corrected for the isotope abundance of ^{80}Se.

3.1.1 ^{77}Se$(p, n)^{77}$Br reaction

The measured cross sections for the formation of ^{77}Br *via* the (p, n) process using enriched ^{77}Se are depicted in Fig. 1 together with an eye-guided fit curve. This reaction has been investigated previously by different researchers. In the low-energy range, Johnson *et al.* [26, 27] reported data up to 5 MeV. In addition to the data published by Levkovskij [28], the excitation function was investigated by Hassan *et al.* [20] in the energy range between 5 and 40 MeV. The Levkovskij data were adjusted downwards by 20% according to the study of Takács *et al.* [29], who showed that those results were based on incorrect cross sections of the used Mo monitor foils. Nevertheless, there are some discrepancies concerning the maximum of the excitation function at about 11 MeV. The present measurements extend the data to about 57 MeV. It appears that our data suggest a broader shape of the excitation function than the results of Levkovskij and

Janssen *et al.* [30]. The data by Hassan *et al.* [20] showed an increase in the cross section at energies between 20 and 25 MeV due to an isotopic impurity of ^{78}Se (4.7%) in the sample. Combined with the older data of Johnson *et al.* [26, 27], in this work, a complete excitation function of the ^{77}Se(p, n)^{77}Br reaction has been developed.

3.1.2 ^{78}Se(p, 2n)^{77}Br reaction

The newly measured cross section data on the ^{78}Se(p, 2n)^{77}Br reaction are shown in Fig. 2. For this reaction, two data sets existed in the literature [28, 30], covering the proton energy range from 14 up to 25 and 30 MeV, respectively. Our data provide the first experimental cross sections above 30 MeV. The rather slow decrease in cross section at higher proton energies implies that the (p, 2n) process on ^{78}Se may be useful for the production of ^{77}Br. However, in this energy region production of the PET radionuclide ^{76}Br *via* the ^{78}Se(p, 3n)^{76}Br reaction would also occur, thereby reducing the radioisotopic purity of ^{77}Br (*cf*. [5]). This aspect will be discussed in detail in Sect. 3.2.1.

3.1.3 ^{80}Se(p, 4n)^{77}Br reaction

Whereas the proton induced formation of ^{77}Br using natural selenium target material was studied earlier by Hassan *et al.* [20], Nozaki *et al.* [12] and El-Azony *et al.* [25], our work provides the first specific cross section measurements concerning the ^{80}Se(p, 4n)^{77}Br reaction channel. The data are shown in Fig. 3. In the energy region 59–66 MeV, our data show rather strong and unexpected scatter. In particular, some points appear to be too low compared with the other data. Due to that and with regard to the fact that the data shown are the results of repeated irradiation experiments, using the same set of samples, the most likely reason for the scatter is damage in one or two of the sediment samples. As mentioned in Sect. 2.1, those samples are rather fragile and some may have developed cracks or partial flattening during the preparation setup. Nevertheless, the remaining data points are sufficient to show the trend of the excitation function. A rather broad maximum can be observed at about 43 MeV, maintaining a significant magnitude up to 75 MeV and beyond. Although the cross section values are significantly lower than those of the (p, n) and (p, 2n) reactions, the width of the excitation function and the higher proton energy applied indicate that the (p, 4n) reaction may be useful for the production of ^{77}Br. However, the possibility of co-producing isotopic impurities has to be analysed, which is discussed in detail below. There is, however, a clear disagreement between our data and the results given by El-Azony *et al.* Our measurements result in a cross section maximum at 40–45 MeV of about 220 mb using 99.90% enriched ^{80}Se, whereas the maximum given by El-Azony *et al.* [25] obtained from irradiation of natural Se (49.6% ^{80}Se) is about 270 mb at the same proton energy. In comparison with the (p, n) and (p, 2n) reaction cross section maxima, the data for this reaction given in this work appear to be more realistic, because they agree better with the proportional trend of the excitation functions of those reaction channels. However, additional work on the determination of the maximum cross section of the excitation function may be necessary.

3.1.4 ^{80}Se(p, n)^{80m}Br reaction

The cross section of the ^{80}Se(p, n)^{80m}Br reaction, systematically measured up to 18 MeV, is shown in Fig. 4 as a function of proton energy. In the low energy range some old cross section data on this nuclear process can be found [28, 31]; the newest, however, are the data reported by Levkovskij in 1991, which are shown in Fig. 4 after downward adjustment as described in Sect. 3.1.1. In fact, no measurement detail has been given in that work, so that the authenticity of data cannot be ascertained. Our cross section values, nonetheless, agree rather well with Levkovskij's data: only a slight deviation at higher energies is observed. The data of El-Azoney *et al.* [25], which were obtained using natural target material, also agree with our new measurements if normalised to a theoretical 100% enrichment. A possible contribution resulting from the (p, 3n) reaction on ^{82}Se (9.4%) can be neglected within the investigated energy range. In the low energy range up to about 6.5 MeV the data of Blaser *et al.* [31], obtained using a Geiger-counter, show a remarkably good agreement with our results. Our results on enriched ^{80}Se, if normalised to ^{nat}Se as target, agree well with the recently published measurement of El-Azony *et al.* [25] on the ^{nat}Se(p, n)^{80m}Br reaction.

3.2 Integral yield and radionuclidic purity

Based on the new and better defined excitation functions presented in this work, the integral yields for the production of ^{77}Br and ^{80m}Br using enriched Se targets were calculated. In Fig. 5, the calculated integral yields for the four nuclear reactions investigated in this work are shown as a function of projectile energy. For production purposes the proton induced reactions on Se are more effective than the reported alternative irradiations of As, Br and Kr (*cf*. [9, 11, 15]). For medical application, however, the radionuclidic purity of the product is also of crucial importance. In Table 4 the possible thick target yields are given for the production of ^{80m}Br, ^{77}Br and the previously studied ^{76}Br together with potential radionuclidic impurities.

Although the production of ^{80m}Br and ^{77}Br for medical application has been investigated earlier, the produc-

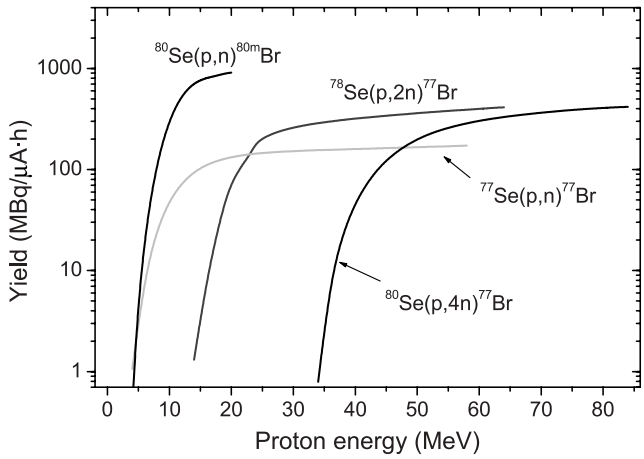

Fig. 5. Calculated integral yields of ^{77}Br and ^{80m}Br based on the determined excitation functions (eye guide) of proton induced nuclear reactions presented in this work using enriched selenium target material.

Table 4. Comparison of calculated production yields of ^{76}Br, ^{77}Br and ^{80m}Br using different production energy ranges together with the corresponding radionuclidic impurities at the end of bombardment.

	Energy range (MeV)	Calc. yield (MBq μA^{-1} h^{-1})	Impurity
^{77}Se(p, 2n)^{76}Br	66 → 14	1320	^{77}Br (10%)
	66 → 22	1033	^{77}Br (6%)
^{78}Se(p, 2n)^{77}Br	26 → 14	219	–
^{80}Se(p, 4n)^{77}Br	86 → 34	422	^{76}Br (127%)
	66 → 34	343	^{76}Br (91%)
	50 → 34	199	^{76}Br (8%)
^{80}Se(p, n)^{80m}Br	16 → 2	803	–

tion routes involving proton induced reactions on selenium did not receive much attention in the past. In 1979, Madhusudhan *et al.* [32] reported a thick target yield of about 66.5 MBq μA^{-1} h^{-1} for ^{77}Br, using the ^{78}Se(p, 2n) reaction. In 1982, Dimitriev *et al.* [33] reported thick target yields of about 46 and 51 MBq μA^{-1} h^{-1}, respectively, for the production of ^{77}Br *via* proton and deuteron induced reactions on ^{nat}Se in the energy range up to 22 MeV. A recent publication by El-Azony *et al.* [25] gives a calculated thick target yield of about 350 MBq μA^{-1} h^{-1} for ^{77}Br produced by proton induced reactions on natural Se at 60 MeV, which is in agreement with the data given by Nozaki *et al.* [12]. An extrapolation of our data to that target composition and energy range leads to about 300 MBq of ^{77}Br. For ^{80m}Br, El-Azony *et al.* calculated a production yield of about 450 MBq μA^{-1} h^{-1} in the energy range of up to 15 MeV. By extrapolating the yield from ^{nat}Se to 100% ^{80}Se, this value agrees with the ^{80}Se(p, n)^{80m}Br reaction yield obtained in this work using enriched target material.

3.2.1 Production of ^{77}Br with high radionuclidic purity

Whereas all three investigated nuclear reactions allow the production of ^{77}Br in yields larger than 100 MBq μA^{-1} h^{-1}, the (p, 4n) reaction on ^{80}Se causes an increased formation of radioactive co-products, especially ^{76}Br (*cf*. Table 4). The application of an incident proton energy of 50 MeV for the irradiation of ^{80}Se leads to a reduction of ^{76}Br to about 8%. The ^{78}Se(p, 2n)^{77}Br reaction, which shows the highest integral yield, appears to be the most promising nuclear process for the production of ^{77}Br. In Fig. 6, the calculated integral yield of this reaction is shown together with the yield curves for the formation of ^{75}Br and ^{76}Br, which was discussed in detail in the preceding paper [5]. The comparison indicates that the production of pure ^{77}Br using enriched ^{78}Se as target material is possible in the energy range $E_p = 26 \rightarrow 14$ MeV, leading to a yield of about 219 MBq μA^{-1} h^{-1}. The application of higher incident proton energies will lead to higher yields up to 400 MBq. However, this would also increase the amount of ^{76}Br in the target, due to the initiation of the ^{78}Se(p, 3n)^{76}Br process.

3.2.2 Production of ^{80m}Br in high radionuclidic purity

Concerning the production of ^{80m}Br, only the ^{80}Se(p, n) process was investigated, which proves to be highly effective for the production of this therapeutic radionuclide. The possible radionuclide yield amounts to about 800 MBq μA^{-1} h^{-1} using an incident proton energy of 16 MeV. Furthermore, the measurements have shown that this nuclear reaction constitutes a very good application of small cyclotrons, which by now can be found in many medical facilities; thus allowing an efficient production of this promising radionuclide. If enriched ^{80}Se is used as target material, no relevant radioactive co-products are produced *via* this production route.

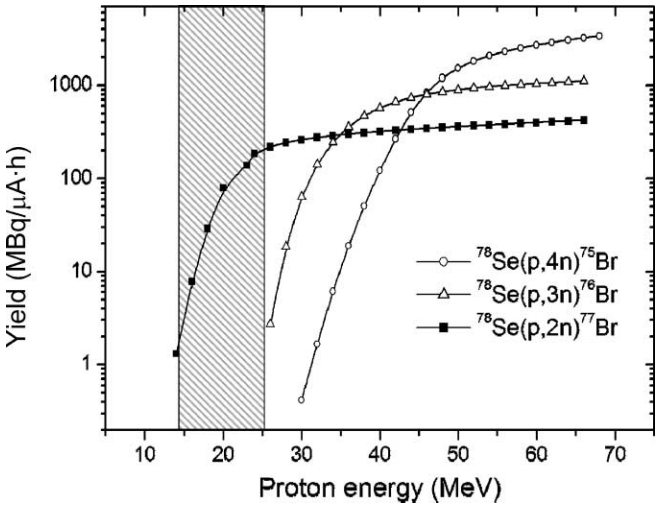

Fig. 6. Integral yield of ^{77}Br calculated from the fitted excitation function (eye guide) of the ^{78}Se(p, 2n)^{77}Br reaction in comparison with yield curves for the formation of ^{75}Br and ^{76}Br. The shaded area gives the optimum energy range for the production of ^{77}Br.

4. Conclusion

Nuclear reaction cross section data for the production of the medically interesting radionuclides ^{77}Br and ^{80m}Br were experimentally determined, in the case of a few reactions for the first time. Based on the extended data, full excitation functions of the ^{77}Se(p, n)^{77}Br, ^{78}Se(p, 2n)^{77}Br, ^{80}Se(p, 4n)^{77}Br and ^{80}Se(p, n)^{80m}Br reactions could be developed. Possible radionuclide yields and associated isotopic impurities were calculated. With respect to the production of ^{77}Br, the ^{78}Se(p, 2n) reaction appears to be the most advantageous, although the choice of production energy range proved to be critical to obtain a high radionuclidic purity. The production of ^{80m}Br *via* the ^{80}Se(p, n) process can be done with good efficiency and high purity at a small cyclotron. Regarding both the discussed bromine isotopes, the use of enriched target material is mandatory to achieve good yield and purity.

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