Upgrade of recommended nuclear cross section data base for production of therapeutic radionuclides

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Received: 27 July 2021 / Accepted: 2 January 2022 / Published online: 20 February 2022
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Abstract

The IAEA Nuclear Data Section has coordinated several actions to setup and improve a database for recommended cross sections and nuclear decay data for various charged-particle reactions that can be used for medical radionuclide production. Some of the earlier evaluations did not provide uncertainties for the recommended cross sections. Updated evaluations with uncertainty quantification for 25 reactions relevant for production of ^{67}Cu , ^{103}Pd , $^{102\text{m}}\text{Rh}$, $^{114\text{m}}\text{In}$, ^{125}I , ^{169}Yb , $^{177\text{g}}\text{Lu}$, ^{186}Re , ^{192}Ir and $^{210,211}\text{At}$ therapeutic radioisotopes are presented. Recommended cross-section data and their uncertainties for production of therapeutic radionuclides are available on the Web page of the IAEA Nuclear Data Section at <https://nds.iaea.org/radionuclides> and also at the IAEA medical portal <https://nds.iaea.org/medportal>.

Keywords Nuclear data · Radionuclide production · Medical radioisotopes · Nuclear reaction modelling · Accelerator production

Introduction

Optimization of radionuclide production for those isotopes of interest in medical applications are of considerable interest to IAEA. The IAEA Nuclear Data Section has hence coordinated several actions to set up a database for recommended cross-sections and associated nuclear decay data for various charged-particle reactions used for medical radionuclides production over the last 25 years. The results of these evaluations were published in webpages of the IAEA-NDS and documented in [1–7] and at numerous conferences. For most of the reactions studied these evaluations resulted in recommended cross section data with uncertainties and production yield data. For few earlier evaluations the uncertainties of the recommended cross section data are missing. Over the last 2 years an upgrade of these evaluations to

include an uncertainty quantification was carried out. The results are presented in this work for 25 reactions relevant for production of ^{67}Cu , ^{103}Pd , $^{102\text{m}}\text{Rh}$, $^{114\text{m}}\text{In}$, ^{125}I , ^{169}Yb , $^{177\text{m}}\text{Lu}$, ^{186}Re , ^{192}Ir and $^{210,211}\text{At}$ therapeutic isotopes.

Methods of compilation, correction, selection and data fitting

The main steps of this upgrading evaluation process are:

- Survey of new or missing literature for experimental data of studied production routes.
- Correction of the published datasets for up-to-date monitor cross sections or nuclear decay characteristics.
- Selection of the data sets for fitting of all available corrected datasets considering the earlier evaluations and the results of model calculations.
- Fit of the selected experimental data using Padé approach (approximant by rational function) [8, 9].
- Deducing recommended data with uncertainties.
- Calculation of integral production yields based on recommended cross-section data.

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Some additional, important comments should be repeated related to above mentioned steps:

- The experimental circumstances and the nuclear decay data used are often not documented properly in the original publications. In those cases, corrections for nuclear data are practically impossible, when the only information available is the year of publication to estimate the values of the used decay data.
- Without detailed experimental description decay data can only be corrected for the linearly contributing parameters (intensities) and correction for half-life is, in most cases, impossible.
- Systematic differences of cross sections often exist between the different publications. One of the main reasons is an improper estimation of the number of incident particles that can be determined by direct measurement of collected charge (or secondary particles) or indirectly by using monitor reactions. The proper technical base and equipment for direct charge measurement are available only at a limited number of experimental sites. To determine the beam intensity by using monitor reactions requires in principle exact knowledge of the incident energy on the monitor foils. In most cases the energy of the extracted beams is not well defined and by using only one monitor foil, especially in an energy region where the excitation function is rapidly changing, improper estimation of the beam intensity can be obtained.
- It is a well-known experimental fact that cross section data deduced from spectra measured at different times and different sample-detector distances may be systematically different (within usual 3–4% uncertainties), due to uncertainties in the efficiency of the detector and different dead-time corrections during measurements. To reduce uncertainties hence in principle the monitor and target foils should be measured practically simultaneously, which in most cases is not possible.
- The estimation of the target thickness and hence number of target atoms present, is also improper in many cases, especially for targets made by sedimentation, pressing, electro-deposition etc. Improper target preparation can result in systematic errors of the measured data, but also can be the source of scattering of the obtained data.
- An important factor in data selection is the experience of the research group in data measurement and data evaluation. Some laboratories have a proper technical background and large expertise in data measurement and reporting, proved by several earlier publications. Usually, more weight is given to results measured in these laboratories when only limited number of discrepant data points are available.
- In the evaluations the weight of each experiment is determined by the reported uncertainties, which hence deserve

special attention. In reported data uncertainties difference by a factor of two are seen for laboratories having the same level of technical background and expertise. Evaluations based only on original data, without critically considering uncertainties, will often result in erroneous recommended data.

- Theoretical data and systematics can be helpful for selection of experimental data especially for decisions on very outlying data points, on overall shape of the excitation function and for systematic energy shifts. This is especially true near the threshold of the reaction as the theoretical calculations are reliable and depend only on the well-measured masses. During the data selections, these outlying data points are mostly neglected, and systematic energy shift can be only partly corrected when the data set covers a large energy range.
- The fitting process requires often additional de-selection of outlying data points, or to introduce additional “guessed” points in energy ranges not covered or represented by the reported experimental results.
- Uncertainties in the fitted results were estimated via a least-squares method with an addition of a 4% systematic uncertainty which is an expert estimate of overall unrecognized uncertainties as discussed in Ref. [10].

Detailed information on the method of collection and selection of experimental data including extensive discussion of the Padé fitting methodology and obtaining uncertainties of the fit, can be found in the introductory chapters of the IAEA related publications: [1–7].

Evaluated nuclear reactions

The summary of the evaluated reactions in the present report is collected in the Table 1 that contains the list of reactions, the number of available experimental data sets, the maximal energy of the experimental data, the number of selected data series and the parameters of the final Padé fit. The main decay data used in the evaluation of the reported radionuclides and the parameters showing their applicability in nuclear medicine are collected in Table 2.

For each radionuclide of interest, we mention shortly the possible medical applications in separate subsections. They were discussed in detail in the IAEA TRS 473 [2] and specially dedicated paper [6]. After presentation of the decay data of the reaction product the evaluation and the results for each of the reactions studied (multiple reactions possible for one medical radioisotope) are illustrated in two figures: the first figure shows all available experimental data (corrected if necessary), the second figure contains only the selected experimental data with their uncertainties and the

Table 1 List of evaluated nuclear reactions for radionuclide production

Product	Reaction	Exp. serie	Max. energy (MeV)	Selected-exp. serie	Padé parameters
^{67}Cu	$^{68}\text{Zn}(p,2p)^{67}\text{Cu}$	10	430	8	Padé 8, $N=80$, $\chi^2=1.50$
	$^{70}\text{Zn}(p,\alpha)^{67}\text{Cu}$	3	39.6	2	Padé 7 cc, $N=41$, $\chi^2=0.88$
	$^{\text{nat}}\text{Zn}(p,x)^{67}\text{Cu}$	4	140.5	3	Padé 9, $N=36$, $\chi^2=0.74$
	$^{\text{nat}}\text{Zn}(d,x)^{67}\text{Cu}$	2	48.3	2	Padé 9, $N=30$, $\chi^2=0.85$
^{103}Pd	$^{103}\text{Rh}(p,n)^{103}\text{Pd}$	9	39.65	8	Padé 13, $N=156$, $\chi^2=2.00$
	$^{103}\text{Rh}(d,2n)^{103}\text{Pd}$	2	39.9	2	Padé 9, $N=53$, $\chi^2=0.52$
$^{102\text{m}}\text{Rh}$	$^{103}\text{Rh}(p,x)^{102\text{m}}\text{Rh}$	2	63.86	2	Padé 7, $N=46$, $\chi^2=1.47$
	$^{103}\text{Rh}(d,x)^{102\text{m}}\text{Rh}$	3	49.8	3	Padé 14, $N=122$, $\chi^2=2.14$
$^{102\text{g}}\text{Rh}$	$^{103}\text{Rh}(p,x)^{102\text{g}}\text{Rh}$	2	53.74	2	Padé 7, $N=36$, $\chi^2=1.15$
	$^{103}\text{Rh}(d,x)^{102\text{g}}\text{Rh}$	3	39.6	3	Padé 9, $N=49$, $\chi^2=0.87$
$^{114\text{m}}\text{In}$	$^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$	17	400	12	Padé 11, $N=122$, $\chi^2=2.41$
	$^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$	5	20.7	4	Padé 10, $N=61$, $\chi^2=1.42$
	$^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$	3	400	3	Padé 17, $N=49$, $\chi^2=0.92$
^{125}I	$^{125}\text{Te}(p,n)^{125}\text{I}$	5	105	4	Padé 10, $N=33$, $\chi^2=0.89$
	$^{124}\text{Te}(d,n)^{125}\text{I}$	1	14.1	1	Padé 8, $N=23$, $\chi^2=0.994$
$^{169\text{g}}\text{Yb}$	$^{169}\text{Tm}(p,n)^{169}\text{Yb}$	4	44.9	4	Padé 8, $N=55$, $\chi^2=1.76$
	$^{169}\text{Tm}(d,2n)^{169}\text{Yb}$	4	49.8	4	Padé 7, $N=35$, $\chi^2=0.95$
$^{177\text{g}}\text{Lu}$	$^{176}\text{Yb}(d,p)^{177}\text{Lu}$	3	25.2	3	Padé 11, $N=54$, $\chi^2=0.87$
	$^{176}\text{Yb}(d,x)^{177\text{g}}\text{Lu}$	5	39.2	5	Padé 18, $N=51$, $\chi^2=0.452$
$^{186\text{g}}\text{Re}$	$^{186}\text{W}(p,n)^{186\text{g}}\text{Re}$	11	68.9	9	Padé 12, $N=115$, $\chi^2=2.68$
	$^{186}\text{W}(d,2n)^{186\text{g}}\text{Re}$	11	49.2	8	Padé 10, $N=130$, $\chi^2=3.31$
$^{192\text{g}}\text{Ir}$	$^{192}\text{Os}(p,n)^{192\text{m}1+\text{g}}\text{Ir}$	3	66.5	3	Padé 10, $N=66$, $\chi^2=1.12$
	$^{192}\text{Os}(d,2n)^{192\text{m}1+\text{g}}\text{Ir}$	2	49.8	2	Padé 17, $N=32$, $\chi^2=0.99$
^{211}At	$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$	6	89.14	6	Padé 9, $N=150$, $\chi^2=1.59$
^{210}At	$^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$	10	90	10	Padé 9, $N=101$, $\chi^2=1.84$

Padé fit that defines the recommended cross sections for the evaluated reaction. The uncertainties defined for the recommended cross sections are expressed as percentages on the secondary axis of the figure. The theoretical predictions taken from the TENDL 2017 [11] and TENDL 2019 libraries [12], based on TALYS-model code calculations, are also shown for comparison in the first figure. Integral yields for every reaction (integrated yield for a given incident energy down to the reaction threshold) are calculated from the recommended cross section data, as shown in a separate figure at the end of each subsection. The results represent the physical yields (obtained in an instantaneous irradiation time) [13, 14].

^{67}Cu production

^{67}Cu is the longest-lived radioisotope of copper, is ideally suited for both radionuclide therapy and imaging. Along with 100% β^- emission, ^{67}Cu emits gamma photons of 92 and 184 keV that are suitable for gamma scintigraphy (Fig. 1).

The $^{68}\text{Zn}(p,2p)^{67}\text{Cu}$, $^{70}\text{Zn}(p,\alpha)^{67}\text{Cu}$, $^{\text{nat}}\text{Zn}(p,x)^{67}\text{Cu}$ and $^{\text{nat}}\text{Zn}(d,x)^{67}\text{Cu}$ production routes were evaluated.

Cross sections for production of ^{67}Cu

$^{68}\text{Zn}(p,2p)^{67}\text{Cu}$ reaction

A total of 10 data sets were found in literature: [18–29] (Fig. 2). Out of them two [28, 29] are new and were not included in the previous evaluation [2].

Only one data point at 200 MeV was reported in Mirzadeh et al [22] that was not considered in the evaluation process. The data of McGee [21] were adjusted in order to account for improved IAEA monitor data. Data of Levkovskij [23] were corrected by 0.8 to adjust to the new monitor data. No correction was done for the small contribution of the reactions on ^{70}Zn for data measured on $^{\text{nat}}\text{Zn}$.

Two data sets were deselected. Cohen [18] data were rejected because the authors state a very high uncertainty for their ^{67}Cu cross-sections; Schwarzbach [28] published relative data that showed a very large scatter. Twelve data points in the energy range 35–45 MeV of Stoll [24] were

Table 2 Decay data of investigated reaction products taken from ENSDF [15]. ENSDF nuclear structure and decay data can be easily extracted, understood and studied in an attractive user-friendly manner by means of LiveChart of Nuclides [16] and NuDat [17]

Product or isomer, excitation energy, isomer spin J^π	Half life and decay mode (%)	$E_{\alpha, \max}$ (keV)	$\langle E_{\beta^-} \rangle$ or $\langle E_{\beta^+} \rangle$ (keV)	Main electrons auger (AE), conversion (CE) E_c (keV) and I_c (%) in parentheses	Main gamma lines E_γ (keV) and I_γ (%) in parentheses X-ray are indicated
^{67}Cu	61.83 h β^- 100		β^- 141	AE K 7.03 (1.9), CE K 90.9 (3.4)	91.266 (7.0), 93.311 (16.1), 184.577 (48.7)
^{103}Pd	16.991 d ϵ 100 (to $^{103\text{m}}\text{Rh}$)			AE L 2.39 (168), AE K 17 (18.2), CE K 16.528 (9.521), CE L 36.336 (71.237), CE M 39.121 (14.377)	39.748 (0.0683), 357.45 (0.0221), 20.074 (22.4) X-ray K_α 20.216 (42.5) X-ray K_α
$^{103\text{m}}\text{Rh}$ 39.75 keV ($J^\pi = 7/2+$)	56.114 min IT 100			CE L 36.343 (70), CE M 39.128 (14.3)	
$^{102\text{m}}\text{Rh}$ 140.7 keV ($J^\pi = 6+$)	3.742 y IT 0.233 ϵ 99.767			AE K 16.2 (17.7)	475.06 (95), 631.29 (56.0), 697.49 (44.0), 766.84 (34.0), 1046.59 (34.0), 1112.84 (19.0)
$^{102\text{g}}\text{Rh}$	207.3 d ϵ 78 β^+ 14.7 β^- 22		β^+ 520 β^- 390	AE K 16.2 (10.7)	475.06 (46)
$^{114\text{m}}\text{In}$ 190.27 keV ($J^\pi = 5+$)	49.51 d IT 96.75 ϵ 3.25			AE L 2.94 (65), AE K 20.1 (5.98), CE 189.44 (6.71)	190.27 (15.56)
$^{114\text{g}}\text{In}$	71.9 s β^- 99.5 ϵ 0.5 β^+ 0.0034		β^- 777.9 β^+ 200	AE L 2.72 (0.43), AE K 19.3 (0.067)	1299.83 (0.139)
^{125}I	59.407 d ϵ 100			AE L 3.19 (156.5), AE K 22.7 (19.8), CE K 3.6787 (78.1), CE L 30.5533 (10.7)	35.492 (6.68) 27.472 (73.1) X-ray K_α 27.202 (39.6) X-ray K_α
$^{169\text{g}}\text{Yb}$	32.018 d ϵ 100			AE L 5.67 (161.8), AE K 40.9 (10.6), CE K 50.3896 (34.3), CE L 53.0047 (7.03), CE K 71.133 (6.16), CE L 99.663 (5.46), CE K 117.8235 (10.9), CE K 138.527 (12.86)	49.773 (52.5) X-ray K_α 50.742 (91.6) X-ray K_α 63.120 (43.6) X-ray K_β
$^{177\text{g}}\text{Yb}$	1.911 h β^- 100		β^- 423	CE K 58.31 (4.6) CE K 75.30 (1.43) CE K 87.08 (1.8)	121.62 (3.05), 150.40 (18.0), 1080.20 (5.08)
$^{177\text{g}}\text{Lu}$	6.6443 d β^- 100		β^- 148.8	AU L 11.23 (8.64) CE K 47.6 (5.02) CE L 103.38 (6.76) CE M 111.28 (1.68) CE K 143.016 (0.57)	71.6418 (0.164), 112.9498 (6.23), 136.7245 (0.0465), 208.3662 (10.41), 249.6742 (0.1997), 321.3159 (0.2186)

Table 2 (continued)

Product or isomer, excitation energy, isomer spin J^π	Half life and decay mode (%)	$E_{\alpha, \max}$ (keV)	$\langle E_{\beta^-} \rangle$ or $\langle E_{\beta^+} \rangle$ (keV)	Main electrons auger (AE), conversion (CE) E_c (keV) and I_c (%) in parentheses	Main gamma lines E_γ (keV) and I_γ (%) in parentheses X-ray are indicated
^{177m}Lu 970.176 keV ($J^\pi = 23/2^-$)	160.4 d IT 22.7 β^- 77.3		β^- 40.39	AE L 6.180 (126.1) AE K 44.80 (5.9) CE K 40.00 (33.9) CE K 47.60 (17.2) CE K 63.15 (24.4) CE K 87.93 (15.2) CE L 101.68 (23.2) CE M 102.76 (1.64) CE N 112.41 (1.34) CE L 117.23 (4.67) CE K 138.75 (5.61) CE L 142.01 (2.78) CE K 149.08 (2.36) CE K 163.13 (4.15) CE L 217.21 (1.91)	105.3589 (12.68), 112.9498 (21.4), 128.5027 (16.04), 153.2842 (16.54), 174.3988 (12.47), 204.1050 (13.51), 208.3662 (55.4), 228.4838 (35.9), 281.7868 (13.97), 327.6829 (18.43), 378.5036 (29.40), 418.5388 (21.72)
^{186g}Re	3.7186 d β^- 92.53 ϵ 7.47		β^- 346.7		137.16 (9.47)
^{192g}Ir	73.829 d β^- 95.24		β^- 178.9		295.96 (28.71), 308.45 (29.70), 316.51 (82.86), 468.07 (47.84), 604.41 (8.216), 612.46 (5.34), 884.54 (0.29)
^{210}At	8.1 h α 0.175 ϵ 99.825	5524.0			245.3 (79), 1181.4 (99), 1436.7 (29.0), 1483.3 (46.5), 1599.5 (13.4)
^{210}Po	138.376 d α 100	5304.3			803.06 (0.00103)
^{211}At	7.214 h α 41.80 ϵ 58.20	5869.5			669.78 (0.0037), 742.72 (0.001)
^{211m}Po 1462 keV ($J^\pi = 25/2^+$)	25.3 s α 99.984 IT 0.016	8883			363.0 (0.016), 1064.9 (0.015)
^{211}Po	0.516 s α 100	7450.3			569.65 (0.535), 897.8 (0.551)

Fig. 1 ^{67}Cu decay scheme

excluded due to systematic errors in that energy range (information from authors). The selected data vs the Padé fit are shown in Fig. 3.

$^{70}\text{Zn}(p,\alpha)^{67}\text{Cu}$ reaction

A total of 3 data sets were found in literature: [23, 28, 30] (Fig. 4). None of these sets are new and were already evaluated in TRS 473 [2]. The data in Schwarzbach [28] are only relative and were normalized at low energies, but as the resulting values are very different from the TENDL predictions they were excluded.

Fig. 2 $^{68}\text{Zn}(p,2p)^{67}\text{Cu}$ reaction: all experimental data and TENDL predictions

Fig. 3 $^{68}\text{Zn}(p,2p)^{67}\text{Cu}$ reaction: selected experimental works and Padé fit (solid line) with total derived uncertainties, including 4% systematic uncertainty (dashed line, right hand scale)

Fig. 4 $^{70}\text{Zn}(p,\alpha)^{67}\text{Cu}$ reaction: all experimental data and TENDL predictions

Fig. 5 $^{70}\text{Zn}(p,\alpha)^{67}\text{Cu}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

The two last, discrepant, points of Kastleiner et al [30] were excluded (large difference from TENDL predictions showing rising cross sections at this energy) as shown in Fig. 5. Fit made till 30 MeV.

$^{\text{nat}}\text{Zn}(p,x)^{67}\text{Cu}$ reaction

This reaction on natural targets was not evaluated earlier. A total of four data sets can be derived from literature: [23, 25, 28, 30] and are compared with TENDL evaluations in Fig. 6.

Schwarzbach [28] data (see remark on normalisation above) were deselected as they are scattered and contradicting the Bonardi [25] data.

Levkovskij [23] and Kastleiner [30] data, measured on ^{70}Zn , were normalised to $^{\text{nat}}\text{Zn}$ below the $(p,2p)$ threshold and were included. Levkovskij [23] data were corrected due to outdated monitor reaction data. The selected and corrected data vs the Padé fit are shown in Fig. 7.

Fig. 6 $^{\text{nat}}\text{Zn}(p,x)^{67}\text{Cu}$ reaction: all experimental data and TENDL predictions

Fig. 7 $^{\text{nat}}\text{Zn}(p,x)^{67}\text{Cu}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale).

Fig. 8 $^{\text{nat}}\text{Zn}(d,x)^{67}\text{Cu}$ reaction: all experimental data and TENDL predictions

Fig. 9 $^{\text{nat}}\text{Zn}(d,x)^{67}\text{Cu}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 10 Yield calculated from the recommended cross sections for ^{67}Cu production

Fig. 11 The ^{103}Pd and $^{103\text{m}}\text{Rh}$ decay scheme

Fig. 12 The $^{102\text{m}}\text{Rh}$ and $^{102\text{g}}\text{Rh}$ decay scheme

$^{nat}\text{Zn}(d,x)^{67}\text{Cu}$ reaction

A total of 2 data sets were found in literature: Tárkányi [31] and Khandaker [32] and are compared with TENDL evaluations in Fig. 8. Both sets were selected and fitted (Fig. 9). This reaction was not evaluated earlier.

Integral yields for production of ^{67}Cu

The integral yields calculated on the basis of fitted cross-sections for production of ^{67}Cu are collected in Fig. 10.

^{103}Pd and ^{102}Rh production

Palladium-103 ($T_{1/2} = 16.991$ d) decaying 100% by electron capture, accompanied by emission of Auger electrons and low energy X-rays, is extensively used in the treatment of prostate cancer and ocular melanoma. Applied mostly in brachytherapy form.

Rhodium-102 (metastable and ground state) is an important radioisotopic impurity generated during production of ^{103}Pd .

The simplified decay schemes of ^{103}Pd and $^{103\text{m}}\text{Rh}$ are shown in Fig. 11, and those for the co-produced $^{102\text{m}}\text{Rh}$ and $^{102\text{g}}\text{Rh}$ in Fig. 12.

The $^{103}\text{Rh}(p,n)^{103}\text{Pd}$, $^{103}\text{Rh}(d,2n)^{103}\text{Pd}$, $^{103}\text{Rh}(p,x)^{102\text{m}}\text{Rh}$, $^{102\text{g}}\text{Rh}$, $^{103}\text{Rh}(d,x)^{102\text{m}}\text{Rh}$, $^{102\text{g}}\text{Rh}$ production routes were evaluated.

Cross sections for production of ^{103}Pd and $^{102\text{m}}\text{Rh}$

$^{103}\text{Rh}(p,n)^{103}\text{Pd}$ reaction

A total of 9 data sets were found in literature: [33–41], which are compared to TENDL evaluations in Fig. 13. The work by Bramblett [36] is to be considered new as it was not included in the previous evaluation.

The set of Mukhammedov [39] was de-selected because of the differences in shape compared with all other excitation functions just above the threshold energy.

The highest energy point of Albert [34] is outlying and was not considered for the fitting.

It was mentioned in an earlier publication [2] that a systematic difference in cross sections was found depending on if X-lines, or γ -lines were used for the activity measurement. This discrepancy could not be explained by a recent unpublished review of ^{103}Pd decay data although for X-lines absolute intensities are calculated, while γ -ray abundances are measured. For the present report we used cross sections derived from X-ray measurement, except for the datasets of [34, 35, 38] that rely on neutron measurements.

The uncertainty for data of Sudar [41] was increased up to 10% (selected data vs. Padé fit are shown in Fig. 14).

$^{103}\text{Rh}(p,x)^{102\text{m}}\text{Rh}$ reaction

For formation of the ground and metastable state of ^{102}Rh by proton induced reactions on ^{103}Rh , the two data sets found in literature were used for fitting: [40, 42]. The data

Fig. 13 $^{103}\text{Rh}(p,n)^{103}\text{Pd}$ reaction: all experimental data and TENDL predictions

Fig. 14 $^{103}\text{Rh}(p,n)^{103}\text{Pd}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 15 $^{103}\text{Rh}(p,x)^{102m}\text{Rh}$ reaction: all experimental data and TENDL predictions

by Tárkányi [42], both for production of ^{102m}Rh and ^{102g}Rh , are new. All data and the fitted data vs the Padé fit are shown in Figs. 15 and 16, respectively.

$^{103}\text{Rh}(p,x)^{102g}\text{Rh}$ reaction

Two data sets were found in the literature published by [40] and are compared with TENDL evaluations in Fig. 17. Tárkányi 40 data have large uncertainties in the overlapping high energy region and were normalized to Hermanne [42] data by a factor of 0.7 before the fit was undertaken. Corrected data are shown in Fig. 18 versus the Padé fit.

$^{103}\text{Rh}(d,2n)^{103}\text{Pd}$ reaction

For formation of ^{103}Pd by deuteron induced reactions on ^{103}Rh , the two data sets found in literature were used for fitting: [43–45] (Fig. 19). The set of Tárkányi [45] is new and was not considered in the earlier evaluation. The data reported in Ditrói [46] are identical to those in Tárkányi [45] and were excluded from the compilation. In the earlier evaluation the X-ray data were selected. In the last unpublished review of decay data, a small change was made for γ -ray probability. The Tárkányi data [45] relying on γ -measurements are systematically lower than the

Fig. 16 $^{103}\text{Rh}(p,x)^{102m}\text{Rh}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 17 $^{103}\text{Rh}(p,x)^{102g}\text{Rh}$ reaction: all experimental data and TENDL predictions

Hermanne [43, 44] values based on X-ray measurements and were hence multiplied by 1.2 according to ratio shown in case of protons for the $^{103}\text{Rh}(p,n)^{103}\text{Pd}$ reaction.

Hermanne [43, 44] X-ray data and the Tárkányi [45] corrected gamma data were selected and used for fitting as shown in Fig. 20.

$^{103}\text{Rh}(d,x)^{102m}\text{Rh}, ^{102g}\text{Rh}$ reactions

A total of 3 data sets were found in literature for formation of the ground and metastable state of ^{102}Rh by deuteron

irradiation of ^{103}Rh : [43, 44, 46, 47]. The values reported in Hermanne [47] and Ditrói [46] data are new.

A few low energy points of Ditrói [46] below the threshold were deselected.

The collected and the selected data vs the Padé fit for production of ^{102m}Rh are shown in Figs. 21 and 22, and for production of ^{102g}Rh in Figs. 23 and 24, respectively.

Fig. 18 $^{103}\text{Rh}(p,x)^{102g}\text{Rh}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 19 $^{103}\text{Rh}(d,2n)^{103}\text{Pd}$ reaction: all experimental data and TENDL predictions

Integral yields for production of ^{103}Pd , ^{102m}Rh and ^{102g}Rh

The deduced integral yields for the (p,n) and $(d,2n)$ reactions leading to ^{103}Pd are shown in Fig. 25.

Four calculated integral yields of the $^{103}\text{Rh}(p,x)^{102g}\text{Rh}$, $^{103}\text{Rh}(p,x)^{102m}\text{Rh}$, $^{103}\text{Rh}(d,x)^{102m}\text{Rh}$ and $^{103}\text{Rh}(d,x)^{102g}\text{Rh}$ reactions are shown in Fig. 26.

^{114m}In production

The radionuclide ^{114m}In ($T_{1/2}=49.51$ d), being a longer-lived analogue of ^{111}In , is of potential interest in Auger and conversion electron therapy for longer lasting therapeutic studies with use of its compounds of appropriately slow kinetics.

The decay scheme and the decay data are shown in Fig. 27 and Table 2.

Fig. 20 $^{103}\text{Rh}(d,2n)^{103}\text{Pd}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 21 $^{103}\text{Rh}(d,x)^{102\text{m}}\text{Rh}$ reaction: all experimental data and TENDL predictions

Evaluated nuclear reactions

The $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$, $^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ and $^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$ reactions were evaluated.

$^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$ reaction

A total of 17 data sets were found in literature: [48–62] (Fig. 28). Two sets are new as they were not included in the previous evaluation: Hermanne [57] and Zarubin [62].

Five datasets were de-selected: Zaitseva [55] (obtained on $^{\text{nat}}\text{Cd}$ target, shows a systematic shift to the higher energies),

Fig. 22 $^{103}\text{Rh}(d,x)^{102\text{m}}\text{Rh}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 23 $^{103}\text{Rh}(d,x)^{102\text{g}}\text{Rh}$ reaction: all experimental data and TENDL predictions

Abramovich [53] (refer to sum of metastable + ground state cross sections), Nieckarz [51] (high energy measurements), Mirzaei [56] (data are theoretical results obtained from ALICE code, no experimental data for $^{114\text{m}}\text{In}$), and Said [59] (measured on enriched target, the large deviation from other sets is probably caused by an unreliable target thickness determination).

The collected and the selected data vs the Padé fit for the $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$ reaction are shown in Figs. 28 and 29, respectively.

$^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ reaction

A total of 5 data sets were found in literature: [56, 63–65] (Fig. 30). No new data were found since the last evaluation. The set of Tárkányi [65] was corrected by a factor of 0.9 after re-analysing and using the Cu + d monitor reactions instead of the Fe + d reactions. The data of Mirzaei [56] were deselected. The absolute cross-section values are too small comparing to Tárkányi [65] and to Nassiff [63]. The absolute cross-section values are also too small for the simultaneously measured ^{111}In . Two data points of Nassiff [63] above 17 MeV were deselected.

Fig. 24 $^{103}\text{Rh}(d,x)^{102g}\text{Rh}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 25 Yields calculated from the recommended cross sections for ^{103}Pd production

The data measured on $^{\text{nat}}\text{Cd}$ target of Tárkányi [60] contains the contribution from the $^{113}\text{Cd}(d,n)^{114\text{m}}\text{In}$ reaction. According to the Alice IPPE calculation this contribution can be neglected (estimated $^{113}\text{Cd}(d,n)^{114\text{m}+g}\text{In}$ is around 5–10% in the important low energy range, for $^{114\text{m}}\text{In}$ alone is even smaller). No correction was done for this contribution considering that the data measured on ^{114}Cd targets and

derived from $^{\text{nat}}\text{Cd}$ targets show excellent agreement and the uncertainty on the absolute values is in both cases in the 12–15% range.

As the threshold for $^{116}\text{Cd}(d,4n)^{114}\text{In}$ is 19.6 MeV, we used normalized data obtained on $^{\text{nat}}\text{Cd}$ up to 20.7 MeV. The collected and the selected data vs the Padé fit for the

Fig. 26 Yield calculated from the recommended cross sections for $^{103}\text{Rh}(p,x)^{102\text{m,g}}\text{Rh}$ and $^{103}\text{Rh}(d,x)^{102\text{m,g}}\text{Rh}$ reactions

Fig. 27 $^{114\text{m}}\text{In}$ decay scheme

Fig. 28 $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$ reaction: all experimental data and TENDL predictions

Fig. 29 $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 30 $^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ reaction: all experimental data and TENDL predictions

$^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ reaction are shown in Figs. 30 and 31, respectively.

$^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$ reaction

A total of 3 data sets were found in literature: [51, 64, 66]. The sets of Nieckarz [51] and Hermanne [66] are new and were not used in the previous evaluation as shown in Fig. 32. All data were selected and fitted and are shown vs the Padé fit in Fig. 33.

$^{114\text{m}}\text{In}$ yields

Calculated integral yields of the $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$, $^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ and $^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$ reactions are shown in Fig. 34.

^{125}I production

The long-lived iodine isotope ^{125}I ($T_{1/2} = 59.41$ d) is an intense Auger electron emitter. It is commonly used in radio-immunoassay.

Fig. 31 $^{114}\text{Cd}(d,2n)^{114m}\text{In}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 32 $^{116}\text{Cd}(p,3n)^{114m}\text{In}$ reaction: all experimental data and TENDL predictions

Fig. 33 $^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 34 Yield calculated from the recommended cross sections for $^{114}\text{Cd}(p,n)^{114\text{m}}\text{In}$, $^{114}\text{Cd}(d,2n)^{114\text{m}}\text{In}$ and $^{116}\text{Cd}(p,3n)^{114\text{m}}\text{In}$ reactions

The decay scheme and the decay data are shown in Fig. 35 and Table 2.

The $^{125}\text{Te}(p,n)^{125}\text{I}$ and $^{124}\text{Te}(d,n)^{125}\text{I}$ production routes were evaluated.

$^{125}\text{Te}(p,n)^{125}\text{I}$ reaction

A total of five data sets were found in literature: [67–71] (see Fig. 36).

Three datasets are new and were not used in the previous evaluation [2]: [68–70].

The single discrepant data point of Zweit [68] was deselected due to its low cross-section value.

The lowest energy outlying data point of Al-Azony [70] was removed. The selected data and the Padé fit are shown in Fig. 37.

Fig. 35 ^{125}I decay scheme **Fig. 36** $^{125}\text{Te}(p,n)^{125}\text{I}$ reaction: all experimental data and TENDL predictions

$^{124}\text{Te}(d,n)^{125}\text{I}$ reaction

Three data sets measured by Bastian [72] on highly enriched ^{124}Te and by Zaidi [73] and Hermanne [74] on tellurium target with natural isotopic composition were found in literature (Fig. 38). Zaidi [73] and Hermanne [74] data were not considered relevant here due to the low threshold (3.2 MeV) of the contaminating $^{125}\text{Te}(d,2n)^{125}\text{I}$ reaction, so those data are not shown in Fig. 38. Selected data are shown vs the Padé fit in Fig. 39.

Integral yields for production of ^{125}I

Calculated integral yields of the $^{125}\text{Te}(p,n)^{125}\text{I}$ and $^{124}\text{Te}(d,n)^{125}\text{I}$ reactions are shown in Fig. 40.

^{169}Yb production

^{169}Yb emits a low-energy photon spectrum, evaluated for use in high dose rate brachytherapy.

The decay scheme and the decay data are shown in Fig. 41 and Table 2.

The $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ and $^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reactions were evaluated.

Cross sections for production of ^{169}Yb

$^{169}\text{Tm}(p,n)^{169}\text{Yb}$ reaction

Four data sets measured by [75–78] were found in literature. Two of them are new and were not considered in the

Fig. 37 $^{125}\text{Te}(p,n)^{125}\text{I}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 38 $^{124}\text{Te}(d,n)^{125}\text{I}$ reaction: all experimental data and TENDL predictions

previous evaluation: [77, 78]. All data sets were selected and compared with TENDL predictions in Fig. 42.

The data in Spahn [76] were normalized considering the systematic trend of the other selected datasets. Two outlying data points of Birattari [75] near the maximum were excluded from the figure and uncertainties were increased up to 10%. The fitted data versus the Padé fit are shown in Fig. 43.

$^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reaction

A total of four data sets were found in literature: [79–83] and are compared to TENDL libraries in Fig. 44. The results of [80–83] are new as they were not considered in the earlier evaluation. All data sets were selected for fitting without changes and are shown vs the Padé fit in Fig. 45.

Fig. 39 $^{124}\text{Te}(d,n)^{125}\text{I}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 40 Yield calculated from the recommended cross sections for $^{125}\text{Te}(p,n)^{125}\text{I}$ and $^{124}\text{Te}(d,n)^{125}\text{I}$ reactions

Integral yields for production of ^{169}Yb

Calculated integral yields of the $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ and $^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reactions are shown in Fig. 46.

^{177g}Lu production

The ground state of ^{177}Lu is one of the most important novel therapeutic β^- emitters that also emits low energy gammas for imaging and localization with gamma cameras (a

Fig. 41 ^{169}gYb decay scheme **Fig. 42** $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ reaction: all experimental data and TENDL predictions **Fig. 43** $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 44 $^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reaction: all experimental data and TENDL predictions

Fig. 45 $^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

theranostic radioisotope).

The simplified decay scheme and the decay data are shown in Fig. 47 and collected in Table 2.

The $^{176}\text{Yb}(d,p)^{177}\text{Yb} \rightarrow ^{177g}\text{Lu}$ and $^{176}\text{Yb}(d,n)^{177g}\text{Lu}$ reactions were evaluated.

$^{176}\text{Yb}(d,p)^{177}\text{Yb}$ reaction

A total of 4 data sets were found in literature for formation of the parent radionuclide ^{177}Yb : [84–87] and are compared to TENDL evaluations in Fig. 48. The data sets of

Tárkányi [85] and Khandaker [87] are new. All data series were selected for fitting and are compared versus the Padé fit in Fig. 49.

$^{176}\text{Yb}(d,x)^{177g}\text{Lu}$ reaction

A total of 5 data sets were found in literature: [84, 85, 87–89]. The results by [85–88] are new as they were published after the earlier evaluation. All available data are compared to TENDL libraries in Fig. 50.

Fig. 46 Yield calculated from the recommended cross sections for $^{169}\text{Tm}(p,n)^{169}\text{Yb}$ and $^{169}\text{Tm}(d,2n)^{169}\text{Yb}$ reactions

Fig. 47 ^{177}Yb , $^{177\text{m}}\text{Lu}$ and $^{177\text{g}}\text{Lu}$ decay schemes

The data sets of Tarkanyi [85, 86] are deselected as they are significantly different within the uncertainty limits of the three other datasets that agree very well. The selected data are compared with the Padé fit in Fig. 51.

Integral yields for production of ^{177}Yb and $^{177\text{g}}\text{Lu}$

Calculated integral yields of the $^{176}\text{Yb}(d,p)^{177}\text{Yb}$ and $^{176}\text{Yb}(d,x)^{177\text{g}}\text{Lu}$ reactions are shown in Fig. 52.

Fig. 48 $^{176}\text{Yb}(d,p)^{177}\text{Yb}$ reaction: all experimental data and TENDL predictions

Fig. 49 $^{176}\text{Yb}(d,p)^{177}\text{Yb}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

^{186g}Re production

The radionuclide ^{186g}Re provides both high-abundance β^- particle emissions to deliver high doses, and low-energy

γ -rays suitable for imaging.

The simplified decay scheme and the decay data are presented on Fig. 53 and Table 2.

The $^{186}\text{W}(p,n)^{186g}\text{Re}$ and $^{186}\text{W}(d,2n)^{186g}\text{Re}$ reactions were evaluated.

Fig. 50 $^{176}\text{Yb}(d,x)^{177g}\text{Lu}$ reaction: all experimental data and TENDL predictions

Fig. 51 $^{176}\text{Yb}(d,x)^{177g}\text{Lu}$ reaction selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

$^{186}\text{W}(p,n)^{186g}\text{Re}$ reaction

A total of 11 data sets were found in literature: [90–102] and are compared with TENDL libraries in Fig. 54.

Four sets are new and were reported after the last evaluation: [98–101].

The reason of large systematic disagreements was not found during detailed investigation of the reported experimental methods and data evaluation methods. Systematic behavior of the excitation functions in the same atomic mass range was also studied. The data by Shigeta [90], Zhang [92], Khandaker [98], and Tarkanyi [94] were deselected as they show too high or too low cross-section values, respectively. Lapi data [97] were normalized at the maximum to

get more data points to fit near the maximum. Selected data vs the Padé fit are compared in Fig. 55.

$^{186}\text{W}(d,2n)^{186g}\text{Re}$ reaction

A total of 11 data sets were found in literature: [103–114] which are compared with TENDL evaluations in Fig. 56.

Three datasets are new since the last evaluation: [112–114].

Three sets were deselected: Manenti [104] and Duchemin [106] (unusual shape, too high cross-section values) and Alekseev [110] (shifted in energy).

The too low cross-section point at 15.7 MeV of Zhenlan [105] was not taken into account for fitting. The selected data and the Padé fit are shown in Fig. 57.

Fig. 52 Yield calculated from the recommended cross sections for $^{176}\text{Yb}(d,p)^{177}\text{Yb}$ and $^{176}\text{Yb}(d,x)^{177}\text{Lu}$ reactions

Fig. 53 $^{186\text{m,g}}\text{Re}$ decay scheme

Integral yields for production of ^{186}Re

Calculated integral yields of the $^{186}\text{W}(p,n)^{186\text{g}}\text{Re}$ and $^{186}\text{W}(d,2n)^{186\text{g}}\text{Re}$ reactions are shown in Fig. 58.

^{192}Ir production

The ^{192}Ir has good decay properties for therapy (high intensity beta radiation and long half-life), but it emits undesirable high-energy gammas difficult for shielding. It is commonly used in brachytherapy. The simplified decay scheme and the decay data are presented in Fig. 59 and Table 2.

The reactions $^{192}\text{Os}(p,n)^{192\text{m1+g}}\text{Ir}$ and $^{192}\text{Os}(d,2n)^{192\text{m1+g}}\text{Ir}$ were evaluated.

Cross sections for production of $^{192\text{m1+g}}\text{Ir}$

$^{192}\text{Os}(p,n)^{192\text{m1+g}}\text{Ir}$ reaction

A total of four data sets were found in literature: [115–118] and were compared with TENDL evaluations in Fig. 60. The two sets by Szelecsenyi and Hermanne [117, 118] are new since the last evaluation. All data sets were selected and fitted and are compared vs the Padé fit in Fig. 61.

Fig. 54 $^{186}\text{W}(p,n)^{186g}\text{Re}$ reaction: all experimental data and TENDL predictions

Fig. 55 $^{186}\text{W}(p,n)^{186g}\text{Re}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 56 $^{186}\text{W}(d,2n)^{186g}\text{Re}$ reaction: all experimental data and TENDL predictions

Fig. 57 $^{186}\text{W}(d,2n)^{186g}\text{Re}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 58 Yield calculated from the recommended cross sections for $^{186}\text{W}(p,n)^{186}\text{Re}$ and $^{186}\text{W}(d,2n)^{186}\text{Re}$ reactions

Fig. 59. $^{192\text{m}}\text{Ir}$ and $^{192\text{g}}\text{Ir}$ decay scheme

$^{192}\text{Os}(d,2n)^{192\text{m}1+\text{g}}\text{Ir}$ reaction

Two experimental data sets were published and compared to TENDL evaluations in Fig. 62. Both datasets were selected for fitting: [119, 120] Fitted data versus the Padé fit are shown in Fig. 63.

The data series of Hermanne [120] is new and was not included into the earlier evaluation.

Integral yields for production of $^{192\text{m}1+\text{g}}\text{Ir}$

Calculated integral yields of the $^{192}\text{Os}(p,n)^{192\text{m}1+\text{g}}\text{Ir}$ and $^{192}\text{Os}(d,2n)^{192\text{m}1+\text{g}}\text{Ir}$ reactions are shown in Fig. 64.

Fig. 60 $^{192}\text{Os}(p,n)^{192\text{m}1+\text{g}}\text{Ir}$ reaction: all experimental data and TENDL predictions

Fig. 61 $^{192}\text{Os}(p,n)^{192\text{m}1+\text{g}}\text{Ir}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

^{211}At production

^{211}At is one of the most promising α -particle emitting radionuclides for targeted radionuclide therapy using short penetration, high linear energy transfer and great biological effectiveness of the α -particles. ^{210}At is an impurity that

leads to production of radio-toxic ^{210}Po . The decay schemes of ^{211}At and ^{210}At are shown in Figs. 65 and 66 and their decay data are collected in Table 2.

The $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ and $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reactions were evaluated.

Fig. 62 $^{192}\text{Os}(d,2n)^{192\text{m}1+\text{g}}\text{Ir}$ reaction: all experimental data and TENDL predictions

Fig. 63 $^{192}\text{Os}(d,2n)^{192\text{m}1+\text{g}}\text{Ir}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Cross sections for production of $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ and $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$

$^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ reaction

A total of seven data sets were found in literature: [121–127] (in Refs. [126] and [127] two data sets were reported: by direct measurement and through decay of ^{211}Po). Comparison of available data versus TENDL evaluations is shown in Fig. 67. No new data were reported since the last evaluation in [2]. The data by Stickler [124] were deselected, due to

significantly lower cross-section values. Fitted data versus the Padé fit are shown in Fig. 68.

$^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reaction

A total of 13 data sets were found in literature: [121–132] (two data sets were reported in [126, 127]: by direct measurement and through decay of ^{210}Po). Available data are compared with TENDL evaluations in Fig. 69. No new data were published since the last evaluation. The data by Rattan [128] were deselected because they show significantly lower cross-section values, similarly data above 38 MeV of incident α -energy from Rizvi [130] were also deselected due

Fig. 64 Yield calculated from the recommended cross sections for $^{192}\text{Os}(p,n)^{192}\text{Ir}$ and $^{192}\text{Os}(d,2n)^{192}\text{Ir}$ reactions

Fig. 65 Decay scheme of ^{211}At , $^{211\text{m}}\text{Po}$ and ^{211}Po

Fig. 66 Decay scheme of ^{210}At and ^{210}Po **Fig. 67** $^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$ reaction: all experimental data and TENDL predictions

to too low and scattered cross-section values. The selected data were fitted and are compared vs the Padé fit in Fig. 70.

Integral yields for production of ^{211}At and ^{210}At

Calculated integral yields of the $^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$ and $^{209}\text{Bi}(\alpha, 3n)^{210}\text{At}$ reactions are shown in Fig. 71.

Summary

New evaluations were performed on 25 reactions for production of ^{67}Cu , ^{103}Pd , $^{102\text{m}}\text{Rh}$, $^{114\text{m}}\text{In}$, ^{125}I , ^{169}Yb , $^{177\text{g}}\text{Lu}$, ^{186}Re , ^{192}Ir and $^{210,211}\text{At}$ therapeutic radioisotopes by upgrading the compilations with new experimental data and to get uncertainties of the recommended data. The experimental data were compared with theoretical predictions taken from the TENDL-2017 and TENDL-2019 libraries. A Padé fitting method was applied for the selected evaluated datasets to deduce recommended data and their uncertainties. Based on recommended production data integral yields were calculated. Recommended cross-section data and their

Fig. 68 $^{209}\text{Bi}(\alpha, 2n)^{211}\text{At}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 69 $^{209}\text{Bi}(\alpha, 3n)^{210}\text{At}$ reaction: all experimental data and TENDL predictions

Fig. 70 $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reaction: selected experimental works (with uncertainties) and Padé fit with derived uncertainties (dashed line, right hand scale)

Fig. 71 Yield calculated from the recommended cross sections for $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ and $^{209}\text{Bi}(\alpha,3n)^{210}\text{At}$ reactions

uncertainties for production of therapeutic radionuclides are available on the Web page of the IAEA Nuclear Data Section at <https://nds.iaea.org/radionuclides> and also at the IAEA medical portal <https://nds.iaea.org/medportal>. These data have importance for radionuclide production and can be used to validate nuclear reaction models.

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