NEW DEVELOPMENTS IN THE EXPERIMENTAL DATA FOR CHARGED PARTICLE PRODUCTION OF MEDICAL RADIOISOTOPES

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Abstract The goal of the present work is to give a review of developments achieved experimentally in the field of nuclear data for medically important radioisotopes in the last three years. The availability and precision of production related nuclear data is continuously improved mainly experimentally. This review emphasizes a couple of larger fields: the Mo/Tc generator problem and the generator isotopes in general, heavy alpha-emitters and the rare-earth elements. Other results in the field of medical radioisotope production are also listed.

Keywords: charged particle induced nuclear reactions; medical radio-isotopes; review

1 Introduction

Nuclear data play an important role in the production and the application of medical radioisotopes. Out of the basic nuclear data, the activation cross sections and the related production yields are also requested. These data can be obtained experimentally and/or by using nuclear reaction codes. The significance of the experimental data is twofold: they give direct information for the production and they also contribute to the development of nuclear reaction model codes. During the previous dedicated and satellite investigations, large amount

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of activation data were measured. In spite of the large experimental databases and the significant progress in the reaction theory, the importance of collection of reliable experimental data has not decreased. New candidate radioisotopes appear for diagnostics and therapy, the radioisotope impurities became more important, new experimental techniques appear to measure low radio-activities, weak performance of nuclear theory was recognized for some type of nuclear reactions and for the metastable states, preparation of recommended databases require re-measurement of mostly used reactions due to contradicting data. Application of highenergy accelerators, usefulness of deuteron induced reactions, broader application of numerous low energy cyclotrons all require further data measurements and improvements. Nuclear data for medical applications are mainly used in the following fields: production of radioisotopes (medical), dosimetry calculations (staff, patients), radiotherapy planning, diagnostics and economy (planning of the production, distribution, treatment, etc.). The necessary nuclear data can be divided into two larger groups: i.e. structure and decay data, which are mainly interesting for fundamental research but also used for medical physics, and the excitation functions and production yields, which are rather application related data. The sources of stored nuclear data are manifold, if one is interested in the source publications, then turns to such publication databases as the WoS (Web of Science) [1]. If more precise compiled data are necessary then the source is the EXFOR (Experimental Nuclear Reaction Data) [2] database, and evaluated data can be found in the newest version of the ENDF (Evaluated Nuclear Data Library) [3] libraries.

2 Experimental data

The most important medically related radioisotopes and their basic nuclear data are listed in different literature sources [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14] and summarized in Table 1. These sources might not contain the new emerging radioisotopes under investigation, which are referred in the following sections. If really reliable production related data are needed, one can search in the experimental databases. The experimental groups perform their measurements by using: activation method, sometimes followed by chemical separation, on solid or gas targets. Single target, rotating wheel or stacked targets are used. The activity is measured by using γ -, X-ray and α -spectrometry or mass spectrometry. The most frequent goals of these studies are: new isotopes for medical, industrial and other purposes; new production routes of important isotopes; side reactions and impurities; clarification of disagreements between previous measurements. According to our experiences, the published results are not always free of problems. These problems can be summarized as follows:

- The available poor technology in some laboratories (beam intensity, beam energy measurement, target preparation, chemical separation)
- Missing basic knowledge on data measurement, data evaluation, definitions, etc.
- Too optimistic uncertainties
- The reports are not detailed enough for data corrections and for production of covariance matrices

Some groups, especially those participating in coordinated research programs try to address these problems in the recent publications. In addition, people responsible for database inputs pay more attention to the above problems when evaluating a new work. Out of medical applications, the published results can also be used for basic nuclear physics research, development of theoretical models, improvement of computer codes based on these models, industrial applications, energy related and safety/security related applications. According to the last IAEA recommendations [4] particular data improvements are needed at the following areas:

- Monitor reactions (induced by light ions in the used energy ranges)
- Diagnostic and the rapeutic $\gamma\text{-emitters}\;(^{123,121}\text{I},\,^{123}\text{Cs},$ ¹²³Xe, ⁵¹Cr, ^{186,188}Re, ^{99m,g}Tc, ^{90m,g}Y, ⁹⁹Mo)
- Positron emitters (52 Fe, 55 Co, 61 Cu, 66,68 Ga, 90 Nb, ⁸⁹Zr, ⁷³Se, ⁷⁶Br, ⁸⁶Y, ⁸⁹Zr, ^{94m}Tc, ^{110m}In, ¹²⁰I)
- Generators (⁶²Zn/⁶²Cu, ⁶⁸Ge/⁶⁸Ga, ⁷²Se/⁷²As, ${}^{82}Sr/{}^{82}Rb)$
- Therapeutic α -emitters (²²⁵Ra, ^{225,227}Ac, ²³⁰U, ²²⁷Th)

Out of these recommendations also the ¹¹¹In, ²⁰¹Tl, ¹¹⁹Sb, ⁹⁷Ru therapeutic electron and X-ray emitters require further data improvements. The recently emerged theranostic approach in nuclear medicine, which consists of performing imaging of the bio-distribution and therapy in the same time, by using the same isotope or different isotopes of the same element or isotopes of two elements with similar chemical behavior, opened a new field in nuclear data experiments and renewed the interest for some radionuclides. In the last 3-4 years, developments have been achieved in the field of experimental production data in the following four areas.

2.1 Production of $^{99}Mo/^{99m}Tc$ generator

Shutdown and decommissioning of several nuclear reactors responsible for the large-scale production of ⁹⁹Mo caused (or will cause in the near future) a shortage on the market of the ${}^{99}Mo/{}^{99m}Tc$ generator system. Several attempts have been made to elaborate methods to substitute the reactor HEU (highly enriched uranium) production route by LEU (low enriched uranium target), fast neutron [15,16], high energy photon [17] and charged particle irradiation, both for ⁹⁹Mo production [18, 19] and direct ^{99m}Tc production [20]. Fig. 1 shows results on charged particle production routes for proton, deuteron and α -particle induced reactions on natural and enriched molybdenum targets. From Fig. 1, one can see that if there are more than one published experimental datasets for a reaction type (e.g. (d,x) reaction by Chodash [18] and Tárkányi [6]), the agreement between the independent experiments is very good. If the results on enriched targets are normalized to be compared with natural targets, the agreement is also good except for the lower energy part of the measured excitation functions. Fig. 1 also shows that the alternative production route of ⁹⁹Mo can be the deuteron activation, but the availability of higher energy deuterons (E_d 15 MeV), by the commercial medical accelerators, is limited. Moreover, deuterons have a shorter range in matter than protons, which gives a lower thick target yield for equivalent cross section values, thats why the proton production route is also competitive [21].

2.2 Heavy α -emitters

 α -emitter isotopes have a promising future in the field of targeted radio-therapy. The emitted α -particles are relatively heavy projectiles, having different energies with short range in human tissues. Thats why they can easily induce the medically required double-strand - Therapeutic electron and X-ray emitters (¹³¹Cs, ¹⁷⁸Ta) DNA break in the tumor cells without damaging the



Fig. 1 Recent results on 99 Mo production by charged particle activation on natural Mo [6,7,18,19] and 100 Mo enriched targets [20]

surrounding healthy cells. New results have been published for the α -particle and proton induced production of ²¹¹At [22] and ²²⁵Ac [23,24] respectively. The actinide radioisotope 225 Ac has a half-life of 10 days, emits four alpha particles in its decay chain, and has recently gained importance for application in future treatment of metastatic cancer via targeted α -immunotherapy [25]. 225 Ac can also be used as a generator for 213 Bi, another shorter-lived α -emitter ($T_{1/2} = 45.6 \text{ min}$) considered for targeted alpha therapy. Up till now, the widespread use of 225 Ac and 213 Bi in radiotherapy has been restricted by the limited availability of ²²⁵Ac. Presently, ²²⁵Ac is almost exclusively supplied by separating the isotope radio-chemically from only two ²²⁹Th sources, one located at Oak Ridge National Laboratory (ORNL), USA [26] and the other at the Institute for Transuranium Elements in Karlsruhe (ITU), Germany [27]. The ²²⁹Th, available at both sites was recovered from 233 U, which was in long-term storage at ORNL. This ²³³U was produced in kilogram quantities in the 1960s by neutron irradiation of 232 Th in molten salt breeder reactors [28]. Another radionuclide of interest, ²²³Ra, has a half-life of 11.4 days and also emits four alpha particles in its decay chain. It is a promising candidate for the treatment of bone cancer [29]. It can also be used as a generator for the production of ²¹¹Pb [30]. Proton induced production of more than 80 isotopes on thorium was measured at high and low proton energies [31,32]. New results on production of ²²³Ra, ²²⁵Ac [24] and ²²⁷Th [23,24] were published recently. As an example, in Fig. 2, recent results (2012) for proton-induced reaction cross section of ²²⁵Ac on a thorium target are shown. Two groups measured this excitation function in overlapping energy ranges. The agreement in the medium energy region is not so good.



Fig. 2 New results on the production of $^{225}\mathrm{Ac}$ by high energy proton irradiation of $^{232}\mathrm{Th}$

2.3 Rare earth elements

As there are a lot of emerging medical radioisotopes between the rare earth elements, most of the new results have been published in this field. Out of the rare earth radioisotopes, also new data for other important radioproducts (side products) were determined. New experimental data were published for proton induced production of Hf, Lu and Ta radioisotopes on natural Hf target [33], proton induced production of Ho radioisotopes on Dy target [34], Zr, Y, Sr, Rb radioisotope production on natural yttrium by proton irradiation [35], measurement of the excitation functions of Pm, Nd, Pr and Ce radioisotopes on natural Nd target with deuteron activation [36], production of Yb and Tm radioisotopes on thulium target by proton activation [37]. As an example, the new production cross section of the medically interesting therapeutic ¹⁶¹Ho radio-lanthanide, which is an Auger-electron emitter, is presented in Fig. 3. This cross section has not been measured before, thats why the results were compared with the output of the different theoretical nuclear reaction model codes (such as TALYS, ALICE and EMPIRE [38, 39, 40]). These codes give good trend but different and incorrect quantitative estimation for the cross section.

2.4 Generators

Radioisotope generators are very important in the everyday medical practice, because they make possible the access to short-lived radioisotopes without the presence of a medical accelerator in the vicinity of the hospital. The most important generator/daughter pair is the 99 Mo/ 99m Tc, which was discussed in detail in a previous section. As an example for this part, the new



Fig. 3 Excitation function of the medically important 161 Ho radioisotope by proton bombardment of natural dysprosium and comparison with the results of the different nuclear reaction model codes



Fig. 4 Latest results on production cross sections for 62 Zn with proton (Jost, Khandaker, Siiskonen, Uddin [32,41,42, 43]) and deuteron (Simeckova [44]) irradiation of copper targets

results on 62 Zn for 62 Cu generator is shown in Fig. 4. It contains both proton [32, 41, 42, 43] and deuteron [44] induced routes. From the results presented in Fig. 4, only the data of Jost [32] for proton irradiation and the data of Simeckova [44] for deuteron irradiation are new (from the last three years), the others are presented for comparison. The figure shows that the newest 62 Zn data for proton irradiation support the previous results and also confirm that the proton induced route is preferable than the deuteron one for its production. New results have also been published for 178 W production (generator for 178 Ta) [45, 46], for 44 Ti production (generator for 149 Pm (generator of 149 Pm (generator of 149 Pm (36].

2.5 Other new results

New results on other medically interesting nuclear data have also been published in the last three years:

- Production cross section of ^{110m,110g,111g,114m}In on natural cadmium with α-particle irradiation and many side reactions producing In, Cd and Sn radioisotopes
 [49] (PET, electron emitter respectively).
- Production cross section of ^{186g}Re with deuteron [50] and proton [45] irradiation on natural tungsten target and side products (therapy).
- Production cross section of ^{203,201}Pb and ²⁰¹Tl on natural thallium with proton irradiation and many side products [51] (SPECT).
- Production parameters of ¹⁰⁵Rh by proton irradiation of natural palladium [52] (therapy).
- Production cross section of ¹⁶⁷Tm and many side thulium and ytterbium products by proton irradiation of natural thulium [37] (therapy).
- Production cross section of 66,67,68 Ga by proton irradiation of 68 Zn and α -particle irradiation of natural copper [53] (SPECT, PET).
- Production cross section of ^{90,95g}Nb and ⁸⁸Y with side products by proton irradiation of natural zirconium [54] (PET).
- Production cross section of ¹¹C, ¹⁵O and ¹³N isotopes by proton irradiation of the corresponding target elements [55] (PET).
- Production of ⁶⁷Cu by deuteron irradiation of natural zinc [56] (therapy).
- Production cross section ¹²³Cs by proton irradiation of ¹²⁴Xe [57] (SPECT).
- Production cross section of ¹²³Xe by α-particle [58] and proton irradiation of ¹²⁰Te and ¹²⁴Xe targets [57] respectively (SPECT).
- Production cross section of ⁵¹Cr by proton irradiation of natural chromium, ⁵⁶Fe [59], natural nickel, ⁹³Nb [60], ⁵⁵Mn [61] and ⁵⁹Co [62] as well as by deuteron irradiation of natural iron [63,64], natural vanadium [65], ⁵⁵Mn [66], natural chromium [67] and natural nickel [68,69], production of ⁵²Mn by proton irradiation of natural chromium [70] (SPECT, PET).
- Production cross section of ⁹⁰Nb by proton induced reactions of natural zirconium [54], ⁹³Nb [60,5] and natural molybdenum [19], deuteron [6] and α-particle [7] induced reaction on natural molybdenum (PET).
- Production cross sections of ^{147,149}Gd by proton and deuteron induced reactions on natural europium [71] (SPECT).

3 Conclusions

The status of the nuclear reaction databases for medical applications has been significantly improved. Further developments are important in both the reaction and decay fields. It requires new, dedicated experiments, reliable (proved) experimental technique, new evaluation technique and proper reporting of the experimental data. Some isotopes are emerging, especially in the field of theranostic applications. It requires further measurements for these new isotopes and also remeasurements of isotopes having renewed interest. The results provided by the nuclear reaction model codes are not always satisfactory, thats why further and closer co-operation is necessary between the code developers and experimental groups. The huge amount of new data on medical radioisotopes confirms the large potential of experimental groups behind the work. The IAEA NDS is only one organization trying to promote and improve the co-operation in the nuclear data, especially the medical nuclear data field. Independent groups also provided important contribution to the experimental nuclear data for the medical radioisotopes (see in the section Other new results).

Table 1 List of important and emerging medically interesting radioisotopes, for which charged particle production route exist and/or measured recently [1,2,3,4] (new measurements marked with *)

Radionuclide	Half-life	Decay mode	Reaction (main routes)	Application
¹¹ C*	20.4 min	β^{+} (100%)	$^{14}N(p,\alpha)^{11}C$	Positron emitter
¹³ N	10 min	β^{+} (100%)	$^{16}O(p,\alpha); {}^{12}C(d,n)$	Radiotracer, PET, labelling
¹⁵ O*	2.03 min	EC $(0.1\%); \beta^+$ (99.9%)	¹⁵ N(p,n); ¹⁴ N(d,n); ¹⁶ O(p,pn); ¹² C(α ,n)	Labelling, flow measurement
¹⁸ F*	109.8 min	EC (3%); β^+ (97%)	$\frac{18}{18}O(p,n); \frac{nat}{18}Ne(d,x)^{18}F$	PET
²² Na*	2.6 a	EC (9.6%); β^+ (90.6%)	$^{22}Ne(p,n); ^{22}Ne(d,2n), ^{24}Mg(d,\alpha)$	PET calibration
^{34m} Cl	32 min	IT (44.6%); β^+ (54.3%)	$nat Cl(p,pxn); {}^{34}S(p,n); {}^{34}S(d,2n)$	PET
³⁸ K*	7.636 min	EC $(0.47\%); \beta^+ (99.53\%)$	$\frac{35}{\mathrm{Cl}(\alpha,\mathbf{n})}, \frac{38}{3}\mathrm{Ar}(\mathbf{p},\mathbf{n})$	PET
⁴³ K*	22.3 h	$\beta = 100 \%$	$40 \operatorname{Ar}(\alpha, p)^{43} \mathrm{K}$	biology
^{44}Sc	3.97 h	EC (5.73%); β^+ (94.27%)	44 Ca(p,n) 44 Sc; 44 Ca(d,2n) 44 Sc;	PET
44 77: 44 0-*	50.1 - / 2.07h	- (100%)	45 Sc(p,2n) 44 Ti; 45 Sc(d,3n) 44 Ti	
51 C=*	39.1 a/ 3.97fi	ε (100%) = (100%)	$nat_{\mathcal{M}(n-1)}$, $nat_{\mathcal{M}(n-2)}$, $nat_{\mathcal{M}(n-2)}$	i
CF	27.701 d	£ (100%)	v(p,n); v(a,2n); n(a,x)	γ -emitter
$52m_{Mn}$	21.1 min	EC $(3.25\%); \beta^+ (95.0\%);$	$^{55}Mn(p,4n)^{52}Fe;$ $^{nat}Ni(p,x)^{52}Fe;$	PET
50 50m		IT (1.75%)	${}^{52}\mathrm{Cr}({}^{3}\mathrm{He},3\mathrm{n}){}^{52}\mathrm{Fe}$	
52 Fe/52 m Mn*	8.275 h	(100%)		
55 0 *	15.01	ε: (100%) EG (20%) α [±] (77%)	56 m(2) $54 m(1)$ $58 m(2)$ $nat m(2)$	DET
61 C *	17.0 h	EC (23%); B (77%)	$fe(p,2n); fe(d,n); fi(p,\alpha), fe(p,x)$	PET
62 Cu	0.67 min	EC $(39\%); \beta \cdot (01\%)$ EC $(2.17\%); \beta \pm (07.82.\%)$	$63_{Cu(p,2n)}62_{Zn}$ $63_{Cu(d,2n)}62_{Zn}$	PET
- Cu	9.67 mm	EC (2.17%); p · (97.85 %)	$60_{\rm Ni}(-2\pi)$	FE1
$62 Z_n / 62 Cu^*$	9.193 h/ 9.67 min	ε (100%)	$NI(\alpha, 2\pi)$	
64				
04Cu*	12.7 h	EC (44%); $\beta^+(17\%)$; β^- (39%)	$^{04}Ni(p,n); ^{04}Ni(d,2n); ^{08}Zn(p,\alpha n); ^{00}Zn(d,\alpha)$	PET, therapy, Cu metabolism
07 Cu*	62 h	β^{-} (100%)	$^{04}Ni(\alpha,p);$ $^{08}Zn(p,2p);$ $^{70}Zn(p,\alpha)$	Therapy
⁶³ Zn	38 min	EC (7%); β ⁺ (93%)	63Cu(p,n)	PET biomarker for Zn
⁶⁶ Ga*	9.49 h	EC (43%); β^+ (57 %)	$\frac{^{66}\operatorname{Zn}(p,n);}{^{63}\operatorname{Cu}(\alpha,n)}$	PET
⁶⁷ Ga*	3.26 d	EC (100%)	67 Zn(p,n); 68 Zn(p,2n)	SPECT
$^{68}Ga^{*}$	68 min	EC (11%); β^+ (89%)	⁶⁸ Zn(p,n)	PET imaging, PET calibration
72 Ge/ Ga*	270.8 d/68 min	ε (100%)	$\frac{nat}{2n(\alpha, \mathbf{x})}; \frac{nat}{72} \operatorname{Ga}(\mathbf{p}, \mathbf{x}); \frac{n9}{9} \operatorname{Ga}(\mathbf{p}, 2\mathbf{n})$	
$72^{4} As^{*}$	26.0 h	EC (12.2%); β^+ (87.8%)	75 72 72 72 72	PET
Se/ As	6.40 a/20.0 h	E (100%)	$^{\prime o}As(p,4n)^{\prime 2}Se; {}^{\mu a \nu}Br(p,x)^{\prime 2}Se$	
73 As*	8.3 d	ε (100%)	$nat \operatorname{Ge}(\mathbf{p}; \alpha, \mathbf{x})$	PET and labelling
74 As*	17.8 d	ε (100%)	14 Ge(d;p,xn); nat Ga(α ,x)	PET (cancer diagnostics)
/3 _{Se*}	39.8 min	EC (79.6%); β^+ (20.4%)	75 As(p,3n), 72 Ge(α ,3n)	PET
⁷⁵ Br*	97 min	β^+ (75%) EC (25%)	tx Se(p;d; ³ He; α ,X); t8 Kr(p, α)	PET
⁷⁶ Br*	16.2 h	β^+ (54%) EC (46%)	76 Se(p,n); 77 Se(p,2n); 75 As(α ,3n),	PET
			$nat \operatorname{Se}(\mathbf{p}, \mathbf{xn});$ $nat \operatorname{Br}(\mathbf{p}, \mathbf{xn});$ $nat \operatorname{Br}(\mathbf{d}, \mathbf{xn}),$	
			$^{18}\mathrm{Kr}(\mathrm{d},\alpha)$	
¹ ¹ Br	57 h	EC (99.3%) $\beta^+(0.73\%)$	$nat \operatorname{Se}(\mathbf{p},\mathbf{xn}); T^{3}\operatorname{As}(\alpha,2\mathbf{n})$	SPECT, therapy
81 pt 81m V-*	13 s	IT (99.9975%)	82-r (-) 80-r ()	Pulmonology, SPECT
82-1	4.0 II/13 S		Kr(p,2n); Kr(d,n)	
82 gn /82 ph *	1.3 min	EC (4.57%); β^{+} (95.43%)	62 Sr daughter	PET
517 110	25 0/1.5 mm	2 (100%)	$82 \operatorname{Kb}(p,4n);$ $82 \operatorname{Kb}(p,xn);$ $82 \operatorname{Kr}(\alpha,4n),$	
86.1/*	14.77.1	EG (00%) 0± (04%)	86 $($ $)$ 88 $($ a $)$ nat $($ $)$ $($ $)$	
	14.7 h	EC (66%); <i>b</i> · (34%)	$\operatorname{Sr}(p,n); \operatorname{Sr}(p,3n); \operatorname{Sr}(d,x)$	agent
90 _{Nb*}	14.60 h	EC (48.8%): β^{\pm} (51.2%)	$90_{Zr(p,n)}$, $90_{Zr(d,2n)}$	PET
88 Y	106 d	£ (100%)	$\frac{88}{\mathrm{Sr}(\mathrm{p},\mathrm{n})} \frac{88}{\mathrm{Sr}(\mathrm{p},\mathrm{n})} 88$	Tracing of ⁹⁰ Y
⁸⁸ Zr/ ⁸⁸ Y*	83.4 d/106 d	ε (100%)	89 Y(p,2n); 89 Y(d,3n)	
⁸⁹ Zr*	3.3 d	EC (77%); β^+ (23%)	$^{89}Y(p,n); ^{89}Y(d,2n)$	PET, labelling
94m _{Tc}	52 min	EC (28%); β^+ (72%)	$nat_{Mo(p,n)}$; $nat_{Mo(\alpha,x)}$ also on enriched	PET imaging, ^{99m} Tc replacement
		- (targets	
99m Tc*	6.0067 h	IT (99.9963%); β^{-} (0.0037%)	$100 Mo(p,2n)^{99m} Tc; 100 Mo(d,3n)^{99m} Tc$	SPECT
99 _{Mo} /99m _{Tc*}	65.976 /6.0067 h	β^{-} (100%)	$100 Mo(p,pn)^{99} Mo; 100 Mo(d,p2n)^{99} Mo$	
¹⁰³ Pd*	17 d	ε (100%)	103 Rh(p,n); 103 Rh (d,2n)	Brachytherapy
¹¹¹ Ag*	7.45 d	β^{-} (100%)	$^{110}Pd(d,n)$	Therapy
$^{109}Cd^{*}$	461.4 d	EC (100%)	$^{109}Ag(p,n); ^{107}Ag(\alpha,x)$	¹⁰⁹ Cd/ ^{109m} Ag biomedical genera-
110m - *			110 ~ · · · · 110 ~ · · · ·	tor
$110m_{In*}$ $110c_{-}/110m_{I-*}$	69 min	EC (99%); β^{+} (0.008%)	nat nat nat nat nat nat nat	PET analogue of 1111n; labelling
1111 - *	2.92.4	EC (100%)	$\frac{111}{10} (p,x); \frac{112}{112} Cl(-P,x); \frac{100}{10} Cl(-p,x) Cl(-P,x); \frac{100}{10} Cl(-p,x); $	ODECT dias (
113m T-*	2.83 G	EC (100%)	$nat_{Cd(p,n)} \xrightarrow{\text{rec}} Cd(p,2n); \xrightarrow{\text{rec}} Ag(\alpha,2n)$	SFECT, diagnostics
in the	59.470 min	11 (100%)	$114 Cd(d 2n) 113 m_{In}$	51 EQ1, radio-tracer, therapy
$113 \frac{Sn}{113m} \frac{113m}{In^*}$	115.09 d	EC (100%)	$nat_{C_1(3)}$ $nat_{C_2(3)}$ $nat_{C_2(2)}$ $nat_{C_2(2)}$ $nat_{C_2(2)}$	
			$nat_{\text{CP}}(d_{\text{re}})^{113}$ $nat_{\text{CP}}(d_{\text{re}})^{113}$ $nat_{\text{CP}}(d_{\text{re}})^{113}$	
			113_{T} ()113 c nat_{T} ()113 c	
			$113_{I_{p}}(d_{p})$ $113_{C_{p}}(nat_{I_{p}}(d_{p}))$ $113_{C_{p}}(d_{p})$	
			$111_{G_1(d,x)}$ $113_{G_2(d,x)}$ $113_{G_2(d,x)}$ $113_{G_2(d,x)}$	
114m _{In*}	49.5.d	IT (96 75%); e (2 25%)	114Cd(p,p), 116Cd(p,2p), 114Cd(d,2p)	therapy radio-tracer
120g T	1 35 h	EC (31.8%), 6 ⁺ (69.9%)	$nat_{Te(p, xp)}$	PET
-1 117m _{Sn*}	14 00 d	IT (100%)	$116 Cd(\alpha 3n)$. $116 Cd(3 He 2n)$	therapy
121 _I	2.12 h	EC $(91.4\%) \cdot \beta^{\pm} (10.6\%)$	122 Te(p, 2p)	SPECT
1221*	3.63 min	EC (22%)· 6 ⁺ (78%)	122Te(d 2n)	PET analogue of 123,125,131
122 Xe/122 I*	20.1 h/3.63 min	ε (100%)	$127_{I(p,6n)}$; $127_{I(d,7n)}$; $124_{Xe(p,x)}$	
123 _{I*}	13.2 h	EC (100%)	$123 \operatorname{Te}(p,n);$ $124 \operatorname{Te}(p,2n);$ $122 \operatorname{Te}(d,n);$	Thyroid SPECT diagnostics
	-	×/	124 Xe(p,x)	
124 _{I*}	4.2 d	EC (78.3%); β ⁺ (22.7%)	$123 \operatorname{Te}(d,n);$ $124 \operatorname{Te}(p,n);$ $124 \operatorname{Te}(d,2n).$	PET, diagnostic and therapy
			121 Sb(α ,n)	````````
¹²⁷ Xe	34.4 d	EC (100%)	127 _{I(p,n)}	SPECT
¹²⁸ Cs	3.62 min	EC (31.1%); β^+ (68.9%)	133 Cs(p,5n) $128 Ba$	PET analogue of ¹³¹ Cs
$^{128}Ba^{/128}Cs^{*}$	2.43 d/3.62 min	ε (100%)		Potassium analogue
¹³¹ Cs* 131 p. (131 m. *	9.689 d	EC (100%)	¹³¹ Xe(p,n)	Brachytherapy
145	11.50 d/9.689 d	ε (100%)	$133 \text{Cs}(p,3n)^{131} \text{Ba} \rightarrow 131 \text{Cs}$	
145 Sm* 145 Fm /145 g *	340 d	ε (100%)	144 Sm(d,x) 145 Sm	Brachytherapy
Eu/ Sm *	0.93 d	EC (98.099%); β^+ (1.91%)	nu Sm(p,x) ¹⁴⁰ Eu \rightarrow ¹⁴⁰ Sm	1 nerapy

Table 1 cont.

Radionuclide	Half-life	Decay mode	Reaction (main routes)	Application
¹⁵³ Sm*	46.50 h	β^{-} (100%)	$152_{Sm(d,p)}$	Therapy
149 Pm	53.08	β^{-} : (100%)	148 Nd(d,x); 150 Nd(d,x); 150 Nd(p,x)	Therapy
140 Nd/ 140 Pr*	3.37 d	ε (100%)	$^{141}Pr(p,2n);$ $^{141}Pr(d,2n);$ $^{nat}Nd(d,x),$	¹⁴⁰ Pr therapy, ¹⁴⁰ Nd PET
	3.39 min	EC (49%); β^+ (51.0%)	nat _{Nd(p,x)}	
¹⁶¹ Tb*	6.89 d	β^{-} (100%)	$^{160}Gd(d,n)$	Therapy
¹⁶¹ Ho*	2.48 h	ε (100%)	161 Dy(p,n) 161 Ho, 162 Dy (p,2n); 161 Dy(d,2n)	Therapy
165 _{Er} *	10.36 h	ε (100%)	165 Ho(p,n); 165 Ho(d,2n); nat Er(p,x) 165 Tm	Therapy
			\rightarrow^{165} Er, nat Er(d,x) ¹⁶⁵ Tm \rightarrow^{165} Er	
¹⁶⁷ Tm*	9.25 d	ε (100 %)	165 Ho(α ,2n); 167 Er(p,n); 167 Er(d,2n);	Therapy, SPECT
			$^{nat}_{Yb(p,xn)}^{167}_{Lu}^{167}_{Yb}^{167}_{Tm}$	
¹⁶⁹ Yb*	32.018 d	ε (100 %)	169 Tm(p,n); 169Tm (d,2n); 168 Er(α ,2n)	Therapy
¹⁷⁷ Lu*	6.71 d	β^{-} (100%)	176Yb(d,x)	Therapy
178 _{Ta*}	2.36 h	EC (100%)	nat Hf(p,x) ¹⁷⁸ Ta	Therapy (e ⁻ , X-ray)
$178 W/178 Ta^*$	21.6 d/2.36 h	ε (100%)	$nat_{\mathrm{Ta}(\mathbf{p},\mathbf{x})}^{178}\mathrm{W};$ $nat_{\mathrm{Ta}(\mathbf{d},\mathbf{x})}^{178}\mathrm{W};$	
			$178_{\rm Hf}(\alpha,2n)^{178}{\rm W}$	
100			100	
¹⁸⁶ Re*	3.72 d	β^{-} (92.53%), ε (7.47%)	$^{186}W(d,2n); ^{186}W(p,n)$	Therapy
¹⁹² Ir *	73.829 d	β^{-} (95.24%), ε (4.76 %)	$^{192}Os(p,n); ^{192}Os(d,2n)$	Brachytherapy
¹⁹¹ Pt*	2.802 d	EC (100%)	193 Pt(p,3n)	Diagnostic for therapy
¹⁹⁸ Au*	2.6947 d	β^{-} (100%)	$198_{Pt(p,n)}$	Brachytherapy
¹⁹⁹ Au*	3.139 d	β^{-} (100%)	198 Pt(d,n)	Therapy
195 Au	30.5 s	IT (100%)	¹⁹⁷ Au(p,3n); ^{nat} Pt(α ,x)	Angiocardiography
$195m_{Hg}/195m_{Au^*}$	41 h/30.5 s	EC (45.8%); IT (54.2%)		
201 T1 201 201	73.1 h	EC (100%)	²⁰³ Tl(p,3n) ²⁰¹ Pb ²⁰¹ Tl	SPECT, myocardia
201 Pb/201 Tl*	0.22 h	$EC(00.026\%), \beta^{\pm}(0.064\%)$		
203 _{Pb}	51.9 h	s (100%)	$nat_{T1(p,x)}$, 205 _{T1(p,3p)}	In vivo in vitro studies
225 A	10.0 1/60 55	$e^{-(07.8\%)} = (2.2\%)$	$226 p_{-}(-2r) 225 A_{-} 232 Th (-2r) 225 A_{-}$	- improve the statics
229 Th -223 Ba	10.0 4/60.55 mm	β (91.8%), a (2.2%)	$\operatorname{Ra}(p,2n)$ $\operatorname{Rc}(p,x)$ $\operatorname{Rc}(p,x)$ $\operatorname{Rc}(p,x)$	α -immunotherapy α targeted therapy
decay chain				8F)
$^{233}U(\alpha)$				
229 Th $(\alpha)^{225}$ Ra (β^{-})				
$^{225}Ac(\alpha)$ $^{221}Fr(\alpha)$				
$217_{At(\alpha)}^{213}_{Bi(\beta^{-})}$				
$213_{PO}(\alpha)^{209}Pb(\beta^{-})$				
209 Bi(stable)				
()				
²¹¹ At	7.2 h	EC (59%), a (41%)	209 Bi $(\alpha, 2n)$	α targeted therapy
²²⁷ Th- ²²³ Ra de-	18.68 d/11.43 d	α (100%)	$nat_{Th(p,x)}$	α targeted therapy
cay chain		α (100%)		
227 Th $(\alpha)^{223}$ Ra (α)				
219 Rn(α)				
215 Po(α)				
$^{211}Pb(\beta^{-})$				
$^{211} Bi^{207} Tl(\beta^{-})$				
²⁰⁷ Pb(stable)				
²³⁰ U- ²²⁶ Th decay	20.8 d/ 30.57 min	α (100%)	231 Pa(p,2n) 230 U	α targeted therapy
chain		α (100%)		
$\int_{-200}^{-200} U(\alpha)^{220} Th(\alpha)$				
222 Ra $(\alpha)^{218}$ Rn (α)				
$^{214}Po(\alpha)^{210}Pb(\beta^{-})$				
$ ^{210}\text{Bi}(\beta^{-})^{210}\text{Po}(\alpha)$				
²⁰⁶ Pb(stable)				

References

- 1. Thomson-Reuters. Web of science (wos) http://http://apps.webofknowledge.com (2014)
- 2. IAEA. Experimental nuclear reaction data (exfor) https://www-nds.iaea.org/exfor/exfor.htm (2014)
- 3. IAEA. Evaluated nuclear data file (endf) https://www-nds.iaea.org/exfor/endf.htm (2014)
- 4. D. Paraskevi. Nuclear data development and dissemination at iaea (2013)
- G.F. Steyn, C. Vermeulen, F. Szelecsenyi, Z. Kovacs, K. Suzuki, T. Fukumura, K. Nagatsu, Journal of the Korean Physical Society 59, 1991 (2011)
- F. Tárkányi, F. Ditrói, S. Takács, B. Király, A. Hermanne, M. Sonck, M. Baba, A.V. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B 274, 1 (2012)
- F. Ditrói, A. Hermanne, F. Tárkányi, S. Takács, A. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms 285, 125 (2012)
- S.M. Qaim, Journal of the Korean Physical Society 59(2), 1965 (2011)
- 9. S.M. Qaim, Radiochimica Acta 99(10), 611 (2011)
- 10. S.M. Qaim, Radiochimica Acta **100**(8-9), 635 (2012)
- 11. S.M. Qaim, Radiochimica Acta $\mathbf{89}(4\text{-}5),\,189$ (2001)
- 12. S.M. Qaim, Radiochimica Acta $\mathbf{89}(4\text{-}5),\,223$ (2001)
- R. Capote Noy, F.M. Nortier, in *Summary report*, vol. INDC(NDS)-0591, ed. by IAEA (IAEA, Vienna, 2011)
- A.L. Nichols, S.M. Qaim, R. Capote-Noy, Summary report of the technical meeting on intermediate-term nuclear data needs for medical applications: Cross sections and decay data. Tech. rep., IAEA (2011)
- 15. Y. Nagai, EPJ Web of Conferences ${\bf 66},\,10007$ (2014)
- Y. Nagai, K. Hashimoto, Y. Hatsukawa, H. Saeki, S. Motoishi, N. Sato, M. Kawabata, H. Harada, T. Kin, K. Tsukada, T.K. Sato, F. Minato, O. Iwamoto, N. Iwamoto, Y. Seki, K. Yokoyama, T. Shiina, A. Ohta, N. Takeuchi, Y. Kawauchi, N. Sato, H. Yamabayashi, Y. Adachi, Y. Kikuchi, T. Mitsumoto, T. Igarashi, Journal of the Physical Society of Japan 82(6) (2013)
- A.V. Sabelnikov, O. Maslov, L. Molokanova, M. Gustova, S.E. Dmitriev, Radiochemistry 48(2), 191 (2006)
- P. Chodash, C.T. Angell, J. Benitez, E.B. Norman, M. Pedretti, H. Shugart, E. Swanberg, R. Yee, Applied Radiation and Isotopes 69(10), 1447 (2011)
- F. Tárkányi, F. Ditrói, A. Hermanne, S. Takács, A.V. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B 280, 45 (2012)
- B. Király, F. Tárkányi, A. Hermanne, S. Takács, M. Sonck, Z. Sz["] ucs, A.V. Ignatyuk, Applied Radiation and Isotopes **69**(1), 18 (2011)
- S.M. Qaim, S. Sudár, B. Scholten, A.J. Koning, H.H. Coenen, Applied Radiation and Isotopes 85(0), 101 (2014)
- K. Gyehong, C. Kwonsoo, P. Sung Ho, K. Byungil, Physics in Medicine and Biology 59(11), 2849 (2014)
- S.V. Ermolaev, B.L. Zhuikov, V.M. Kokhanyuk, V.L. Matushko, S.N. Kalmykov, R.A. Aliev, I.G. Tananaev, B.F. Myasoedov, Radiochimica Acta 100, 223 (2012)
- J.W. Weidner, S.G. Mashnik, K.D. John, F. Hemez, B. Ballard, H. Bach, E.R. Birnbaum, L.J. Bitteker, A. Couture, D. Dry, M.E. Fassbender, M.S. Gulley, K.R. Jackman, J.L. Ullmann, L.E. Wolfsberg, F.M. Nortier, Applied Radiation and isotopes : 70, 2602 (2012)
- M. Miederer, D.A. Scheinberg, M.R. McDevitt, Advanced Drug Delivery Reviews 60(12), 1371 (2008)

- R.A. Boll, D. Malkemus, S. Mirzadeh, Applied Radiation and Isotopes 62(5), 667 (2005)
- C. Apostolidis, R. Carlos-Marquez, W. Janssens, R. Molinet, T. Nikula, A. Ouadi, Nuclear News 44, 29 (2001)
- W.R. Grimes, Chemical research and development for molten-salt breeder reactors ornl-tm-1853. Tech. rep., Oak Ridge, Tennessee, USA (1967)
- O.S. Bruland, S. Nilsson, D.R. Fisher, R.H. Larsen, Clinical Cancer Research 12(20), 6250s (2006)
- L.I. Guseva, Journal of Radioanalytical and Nuclear Chemistry 281(3), 577 (2009)
- J.W. Engle, S.G. Mashnik, J.W. Weidner, L.E. Wolfsberg, M.E. Fassbender, K. Jackman, A. Couture, L.J. Bitteker, J.L. Ullmann, M.S. Gulley, C. Pillai, K.D. John, E.R. Birnbaum, F.M. Nortier, Physical Review C 88(1), 014604 (2013). PRC
- C.U. Jost, J.R. Griswold, S.H. Bruffey, S. Mirzadeh, D.W. Stracener, C.L. Williams, in *AIP Conference Pro*ceedings, vol. 1525 (2013), vol. 1525, pp. 520–524
- M. Shahid, K. Kim, H. Naik, G. Kim, Nuclear Instruments and Methods in Physics Research, Section B 322, 13 (2014). Export Date: 7 July 2014
- F. Tárkányi, F. Ditrói, A. Hermanne, S. Takács, A.V. Ignatyuk, Journal of Radioanalytical and Nuclear Chemistry 298, 277 (2013)
- M.U. Khandaker, K. Kim, M.W. Lee, K.S. Kim, G. Kim, N. Otuka, Nuclear Instruments and Methods in Physics Research, Section B 271, 72 (2012)
- 36. F. Tárkányi, S. Takács, F. Ditrói, A. Hermanne, H. Yamazaki, M. Baba, A. Mohammadi, A.V. Ignatyuk, Nuclear Instruments and Methods in Physics Research Section B **325**(0), 15 (2014)
- F. Tárkányi, A. Hermanne, S. Takács, F. Ditrói, I. Spahn, A.V. Ignatyuk, Applied Radiation and Isotopes 70(1), 309 (2012)
- A.J. Koning, D. Rochman, Nuclear Data Sheets 113, 2841 (2012)
- A.I. Dityuk, A.Y. Konobeyev, V.P. Lunev, Y.N. Shubin, New version of the advanced computer code alice-ippe. Tech. rep., IAEA (1998)
- M. Herman, R. Capote, B.V. Carlson, P. Oblozinsky, M. Sin, A. Trkov, H. Wienke, V. Zerkin, Nuclear Data Sheets 108(12), 2655 (2007)
- M.U. Khandaker, M.S. Uddin, K.S. Kim, Y.S. Lee, G.N. Kim, Nuclear Instruments & Methods in Physics Research B 262, 171 (2007)
- T. Siiskonen, J. Huikari, T. Haavisto, J. Bergman, S.J. Heselius, J.O. Lill, T. Lonnroth, K. Perajarvi, Applied Radiation and Isotopes 67, 2037 (2009)
- M.S. Uddin, M.U. Khandaker, K.S. Kim, Y.S. Lee, G.N. Kim, Nuclear Instruments & Methods in Physics Research B 258, 313 (2007)
- 44. E. Simeckova, P. Bem, M. Honusek, M. Stefanik, U. Fischer, S.P. Simakov, R.A. Forrest, A.J. Koning, J.C. Sublet, M. Avrigeanu, F.L. Roman, V. Avrigeanu, Nuclear Physics 84, 14605 (2011)
- 45. Y.E. Titarenko, V.F. Batyaev, A.Y. Titarenko, M.A. Butko, K.V. Pavlov, S.N. Florya, R.S. Tikhonov, V.M. Zhivun, A.V. Ignatyuk, S.G. Mashnik, S. Leray, A. Boudard, J. Cugnon, D. Mancusi, Y. Yariv, K. Nishihara, N. Matsuda, H. Kumawat, G. Mank, W. Gudowski, Physics of Atomic Nuclei **74**, 551 (2011)
- 46. F. Tárkányi, S. Takács, F. Ditrói, A. Hermanne, A.V. Ignatyuk, M.S. Uddin, Applied Radiation and Isotopes 91, 114 (2014)
- 47. A. Hermanne, R.A. Rebeles, F. Tárkányi, S. Takács, M.P. Takács, J. Csikai, A. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B 270, 106 (2012)

- O. Lebeda, V. Lozza, P. Schrock, J. Stursa, K. Zuber, Physical Review C 85, 14602 (2012)
- M.U. Khandaker, K. Kim, M. Lee, G. Kim, Nuclear Instruments and Methods in Physics Research, Section B 333, 80 (2014). Export Date: 7 July 2014
- A. Guertin, C. Duchemin, F. Haddad, N. Michel, V. Mtivier, Nuclear Medicine and Biology 41, Supplement(0), e16 (2014)
- F. Tárkányi, F. Ditrói, A. Hermanne, S. Takács, R. Adam-Rebeles, N. Walravens, O. Cichelli, A.V. Ignatyuk, Applied Radiation and Isotopes 74, 109 (2013)
- M.U. Khandaker, K. Kim, G. Kim, Pramana Journal of Physics 79(2), 243 (2012)
- 53. F. Szelecsényi, Z. Kovács, K. Nagatsu, K. Fukumura, K. Suzuki, K. Mukai, Radiochimica Acta **100**(1), 5 (2012)
- M. Al-Abyad, A.S. Abdel-Hamid, F. Tárkányi, F. Ditrói, S. Takács, U. Seddik, I.I. Bashter, Applied Radiation and Isotopes **70**(1), 257 (2012)
- T. Akagi, M. Yagi, T. Yamashita, M. Murakami, Y. Yamakawa, K. Kitamura, K. Ogura, K. Kondo, S. Kawanishi, Radiation Measurements 59, 262 (2013)
- J. Kozempel, K. Abbas, F. Simonelli, A. Bulgheroni, U. Holzwarth, N. Gibson, Radiochimica Acta 100(419), 419 (2012)
- 57. A. Hermanne, F. Tárkányi, S. Takács, R. Adam Rebeles, A. Ignatyuk, S. Spellerberg, H. Schweikert, Applied Radiation and Isotopes 69, 358 (2011)
- A. Palumbo, W.P. Tan, J. Gorres, M. Wiescher, N. Ozkan, R.T. Guray, C. Yalcin, Physical Review C 85, 028801 (2012)
- Y.E. Titarenko, V.F. Batyaev, A.Y. Titarenko, M. Butko, K.V. Pavlov, S.N. Florya, R.S. Tikhonov, V.M. Zhivun, A.V. Ignatyuk, S.G. Mashnik, S. Leray, A. Boudard, J. Cugnon, D. Mancusi, Y. Yariv, K. Nishihara, N. Matsuda, H. Kumawat, G. Mank, W. Gudowski, Physics of Atomic Nuclei **74**, 523 (2011)
- y.E. Titarenko, V.F. Batyaev, A.Y. Titarenko, M.A. Butko, K.V. Pavlov, S.N. Florya, R.S. Tikhonov, V.M. Zhivun, A.V. Ignatyuk, S.G. Mashnik, S. Leray, A. Boudard, J. Cugnon, D. Mancusi, Y. Yariv, K. Nishihara, N. Matsuda, H. Kumawat, G. Mank, W. Gudowski, Physics of Atomic Nuclei **74**, 537 (2011)
- F. Ditrói, F. Tárkányi, S. Takács, A. Hermanne, H. Yamazaki, M. Baba, A. Mohammadi, Nuclear Instruments & Methods in Physics Research B **308**, 34 (2013)
- 62. F. Ditrói, F. Tárkányi, S. Takács, A. Hermanne, H. Yamazaki, M. Baba, A. Mohammadi, Journal of Radioanalytical and Nuclear Chemistry **298**, 853 (2013)
- L. Zavorka, E. Simeckova, M. Honusek, K. Katovsky, Journal of the Korean Physical Society 59, 1961 (2011)
- M.U. Khandaker, H. Haba, J. Kanaya, N. Otuka, Nuclear Instruments & Methods in Physics Research B 316, 33 (2013)
- 65. F. Tárkányi, F. Ditrói, S. Takács, A. Hermanne, M. Baba, A.V. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B 269(15), 1792 (2011)
- 66. F. Ditrói, F. Tárkányi, S. Takács, A. Hermanne, H. Yamazaki, M. Baba, A. Mohammadi, A.V. Ignatyuk, Nuclear Instruments & Methods in Physics Research Section B 269(17), 1878 (2011)
- A. Hermanne, R. Adam Rebeles, F. Tárkányi, S. Takács, M. Takács, A.V. Ignatyuk, Nuclear Instruments & Methods in Physics Research B 269, 2563 (2011)
- A. Hermanne, S. Takács, R. Adam-Rebeles, F. Tárkányi, M.P. Takács, Nuclear Instruments & Methods in Physics Research B 299, 8 (2013)

- N. Amjed, F. Tárkányi, F. Ditrói, S. Takács, H. Yuki, Applied Radiation and Isotopes 82, 87 (2013)
- M. Buchholz, I. Spahn, B. Scholten, H.H. Coenen, Radiochimica Acta 101(8), 491 (2013)
- M. Buchholz, I. Spahn, H.H. Coenen, Applied Radiation and Isotopes 91, 8 (2014)