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RADIONUCLIDE PRODUCTION BY PROTONS, DEUTERONS AND α - PARTICLES IN THE ENERGY RANGE 6 - 70 MeV

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Radionuclide production by protons, deuterons and α-particles in the energy range 6 - 70 MeV

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Abstract

The *Progetto Adroterapia* financed by the Italian National Institute of Nuclear Physics is a feasibility study for a hospital-based hadron-therapy facility for Italy. This report discusses the possibility of producing radionuclides of biomedical interest as a complementary activity to be carried out at the accelerator complex of the facility. The paper provides a compilation of data on the production of radionuclides of biomedical interest, for present and future uses, by employing beams of protons, deuterons and α-particles from the injector. The aim is to give sufficient information in order that one can determine what radionuclides can be produced, and in what amount, having a given accelerator available. In particular, the energies considered are 5 MeV, 11 MeV, 30 MeV, 55 MeV and 70 MeV for protons, 6 MeV and 15 MeV for deuterons, 30 MeV and 55 MeV for α-particles. Some basic relationships relevant to radioisotope production are given in the Appendix.

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1. Introduction

The TERA project financed by the Italian National Institute of Nuclear Physics (Istituto Nazionale di Fisica Nucleare, INFN) is a feasibility study for a hospital-based hadron-therapy facility for Italy (Progetto Adroterapia) [1]. The term *hadrons* is used to collectively indicate protons and light ions (typically up to neon) to be used in cancer radiation therapy and possibly thermal and epithermal neutrons to be employed in boron neutron capture therapy (BNCT). The feasibility study, which should be completed by summer 1994, aims at designing a flexible facility, starting radiation therapy with proton beams but subsequently upgradable to light ions with only minor modifications to the accelerators. These will consist of a radiofrequency quadrupole (RFQ), a drift tube linear accelerator (linac) and a synchrotron [2, 3, 4]. Acceleration of light ions will be achieved in the same ring by addition of a second injector. The production of neutrons will also be implemented if experimental or clinical results will definitely indicate BNCT as a promising therapeutic technique. The facility should be a "centre of excellence" and is therefore appropriate to evaluate other activities of medical interest which could be carried out at the centre using the available equipment. In particular, it is believed that providing the hospital with an advanced diagnostic tool such as positron emission tomography (PET) justifies the addition of a little complexity to the whole facility by including the capability of production and radiochemical processing of positron emitters. In fact the recent development of positron emission tomography has boosted the hospital installation of large number of low energy proton and deuteron cyclotrons, mainly dedicated to the on-line production of ^{11}C, ^{13}N, ^{15}O and ^{18}F. The capability of producing large amounts of other medically interesting radionuclides should be carefully evaluated versus the overall increase in cost and complexity. The requirement which should always be born in mind is that such additional activities should not interfere with the main use of the machine, i.e. radiation therapy.

This paper deals with the possibility of producing radionuclides of biomedical interest as a complementary activity to be carried out at the accelerator complex of the hadron-therapy facility. Radionuclide production requires relatively low beam energies, compared to the maximum figure of 200 MeV necessary for the treatment of deep seated tumours, and high beam currents (of the order of tens of microAmpères versus typical values of a few nanoAmpères required for therapy). The obvious candidate for carrying out radionuclide production in significant amounts is the injector (RFQ and linac). According to the output energy of the injector (i.e., the injection energy into the synchrotron) different radionuclides can be produced. It is generally recognised that the minimum energy recommended for injection into a proton synchrotron is about 4 MeV. The accelerator studied for the hadron-therapy facility is a H^- synchrotron which should be upgraded, at a later stage, to accelerate light ions [3, 4] and a somewhat higher injection energy (11 MeV) is presently considered. Higher energy values are beneficial from the point of view of synchrotron operation and increase the radionuclide production capability, but the linac obviously becomes larger and more expensive.

As an example, the radio frequency linear accelerator system model PL-11 marketed by AccSys Technology, Inc. (Pleasanton, California, U.S.A.) can accelerate hydrogen ions (protons or H^-) to a final energy of 11 MeV. According to the characteristics quoted by the producer, this system works with a pulse repetition rate variable between 1 and 120 Hz, a beam pulse width of 35-215 μsec and a peak output current of 25-40 mA, which in turn means an average beam current of 1-1000 μA. Since a synchrotron typically works at a repetition rate of a few Hertz (2 Hz in our case), the linac needs to inject into the ring only a few (two in our case) pulses per second and most of the beam can be used elsewhere in parallel

with the operation of the synchrotron. By operating the linac at 15 Hz, with a beam pulse width of 100 μsec and a peak current of 30 mA, an average beam current of 45 μA is obtained, sufficient to carry out radionuclide production in fairly large amounts, and still maintaining the linac operation well below its maximum specifications.

According to the energy available from the injector, a number of other activities could also be implemented. Besides generation of neutrons for BNCT (the available neutron flux is also a function of the energy and the beam current available from the linac), we shall here just mention the fact that proton beams can be used for elemental analysis of samples of biomedical, environmental and industrial interest, by making use of different methods such as particle induced x-ray emission (PIXE), nuclear reaction analysis (NRA), Rutherford backscattering (RBS), activation analysis or the technique of PIXE-induced XRF. Some of these subjects are dealt with in another report of this series [5].

The aim of this report is to provide a compilation of data on the production of radionuclides of biomedical interest (for present and future uses) by proton, deuteron and α-particle beams in the energy range 6 - 70 MeV. Deuteron and α-particles are included because of the foreseen capability of light ion acceleration at our facility. The data presented here are taken from the literature and an extensive reference list is enclosed. This review is certainly not exhaustive: each of the radionuclides listed in the tables given below, and even each production route leading to any given radioisotope, can be the object of a dedicated experimental investigation or literature review. This report only wants to act as a guide and provide basic data which should then be investigated more deeply whenever necessary. In particular, this report focuses itself on production data and no information are given about the medical use of each radionuclide. The purpose is that of providing sufficient information in order that one can assess what radionuclides can be produced, and roughly in what amount, with a given accelerator.

The following energies will be considered: 5 MeV, 11 MeV, 30 MeV, 55 MeV and 70 MeV for protons, 6 MeV and 15 MeV for deuterons, 30 MeV and 55 MeV for α-particles. In principle, a linac can be designed which is optimized for ion acceleration and which would also accelerate protons using lower fields: in order to achieve this, the ions travel in the linac with half the proton velocity and are then accelerated to a final kinetic energy per nucleon which is equal to 1/4 of the proton kinetic energy [6]. Therefore a linac can possibly be designed to provide proton beams with energy E_p, deuteron beams with energy $E_d=E_p/2$ and α-particle beams with energy $E_\alpha=E_p$. However, it appears that it is better not to try to combine proton and other ion acceleration in the same linac [4]. Two separate injectors seem a better solution in terms of simplicity and reliability of operation, flexibility and cost. In addition, since therapy with light ions will be implemented only a few years after beginning of proton treatments, there is little justification in building a complex and expensive injector which is initially not required for operating the facility with protons.

The optimum injection energy for light ion acceleration in the synchrotron is presently being investigated [4]. If fully stripped light ions are injected into the ring with an energy per nucleon equal to 1/4 of the proton kinetic energy, their magnetic rigidity is the same and the same injection line can be used. In fact, an energy of about 3 MeV/nucleon seems sufficient. We can then consider the assumption above for the energy of deuterons and α-particles as still valid.

2. Radionuclide production for medical uses

Radionuclides employed in medicine to label radiopharmaceuticals must meet a number of requirements: high specific activity, organ selectivity of labelled compounds, suitable radioactive emission (either γ, β^+,β^-, EC) according to the intended use, mimimum dose imparted to the patient if employed in diagnostics or, alternatively, maximum dose imparted to the target volume if employed in therapy; in addition, they must be ready available at the hospital. For diagnostic use, short-lived radionuclides are obviously preferred, either positron emitters (for PET) or γ-emitters with energy in the range 140-300 keV (for SPECT, single photon emission computerised tomography). There is an extensive literature (see, for example refs [7 - 25]) on the production and use of radionuclides for medical purposes.

In choosing the production route, i.e., nuclear reaction, energy range and target material (isotopic composition and chemical purity), one has to be careful in order to minimize the level of contaminants produced. While non-isotopic contaminants can in principle be removed by chemical processing, this is not possible with isotopic impurities. Radioactive contaminants have two adverse effects: they can worsen image quality in diagnostics (if high energy γ-emitters) and increase the total dose to the patient.

The level of contaminants can be reduced by properly choosing (see ref [7], page 106) the beam parameters (intensity, beam profile, low energy spread), the incident energy and energy loss in the target, the irradiation time, the interval between the end of bombardment and the beginning of the radiochemical processing or utilization of the radiopharmaceutical, the isotopic composition and chemical purity of the target. Most of the above parameters can be properly selected from a knowledge of the excitation function of the nuclear reaction for the production both of the main radionuclide and its radioisotopic impurities. As an example, figure 1 shows the excitation functions for (p,xn) reactions on a selenium target with 96.5% ^{76}Se enrichment for the production of ^{75}Br. It is not possible to obtain "pure" ^{75}Br via the reaction ^{76}Se(p,2n)^{75}Br because of the competing reaction ^{76}Se(p,n)^{76}Br. ^{76}Br has a longer half-life than ^{75}Br (16 h and 1.6 h, respectively). With an incident energy of 24 MeV and an energy loss in the target of 2.5 MeV, the level of the contaminant is 2% at the EOB (end of bombardment, see Appendix).

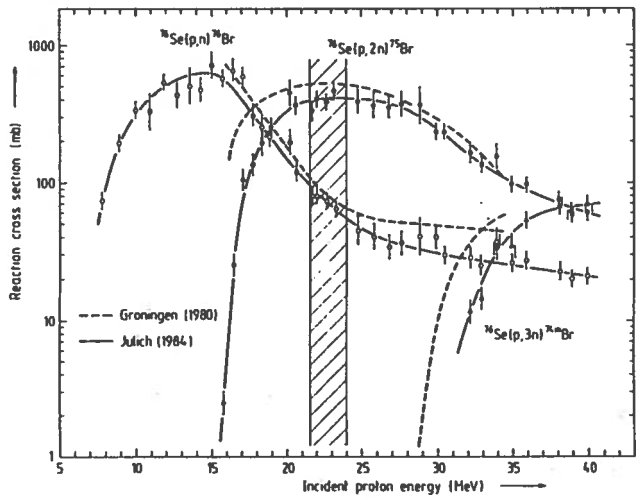


Fig. 1: Excitation functions of (p , xn) reactions on 96.5 % enriched ^{76}Se

Radionuclides for medical uses can be classified, somewhat arbitrarily, in the following seven groups (see ref [7], page 25]:

1) "physiological" β^+ emitters (^{11}C, ^{13}N, ^{15}O);
2) other β^+ emitters (^{68}Ga, ^{73}Se, ^{77}Kr,...);
3) halogens (^{18}F, $^{75,77}Br$, ^{123}I,...);
4) inert gases (^{77}Kr, ^{81m}Kr,...);
5) generators ($^{68}Ge/^{68}Ga$, $^{81}Rb/^{81m}Kr$,...);
6) "inorganic" (^{52}Fe,^{67}Ga,^{111}In, ^{201}Tl,...);
7) for therapy (^{125}I, ^{186}Re, ^{211}At,...).

There is only a very limited number of "physiological" radionuclides that can directly substitute the corresponding stable nuclide in a biomolecule (^{30}P and ^{34m}Cl in addition to the above mentioned positron emitters), but many other radionuclides possess features that make them suitable for medical applications. In particular, the large use of radiohalogens is justified by their ability to create covalent bonds with carbon atoms and therefore to produce structural analogs of diagnostic interest. Radiohalogens are mainly used for labelling organic compounds but can also be directly employed in ionic form. Inert gases are instead used in lung ventilation and blood flow studies. The production and distribution of generators make the use of radionuclides of relatively short half-life possible at centres not provided with production capabilities. A few radionuclides decaying β^-, EC or α are used or being tested in radiotherapy. These nuclides can in principle produce a large ionization over a short range in tissue, but their therapeutic use is still limited.

In the following tables, 38 radionuclides of medical interest are reviewed. In addition to nuclear reactions induced by protons, deuterons and α-particles, ^3He ions are also considered as bombarding particles. The tables are organised as follows:

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
1	2	3	4	5	6	7	8

1) nuclear reaction (in order of importance in the case of main radionuclides);
2) natural isotopic abundance of the target nuclide;
3) Q-value of the nuclear reaction;
4) energy range of the cross section measurements reported in the next two columns;
5) energy of maximum of cross section;
6) maximum value of cross section in the energy range investigated;
7) literature reference from which the previous cross section data are taken, followed by a reference code which identifies the data in the EXFOR library;
8) the energy range or upper energy limit in which the thick target yield (TTY, see Appendix) data have been investigated is given in round brackets, followed by a literature reference in which these data can be found and by a reference code identifying the data in the EXFOR library.

The EXFOR data are collected, processed and updated at four research centres, according to their origin:

1) NEA-DATA BANK in Paris, for Western Europe;
2) NNDC-BNL at Upton, New York, for the Unites States and Canada;
3) OBNINSK in Russia, for the Republics formerly USSR and Eastern European countries;
4) IAEA in Vienna for all other countries.

These centres exchange data among each other and are in charge of their distribution in the geographical areas of competence. The EXFOR data are distributed free of charge to research centres, universities and industrial parties. Italy obviously falls under the area covered by the NEA-DATA BANK in Paris: at present requests should be addressed to Dr. Clas Nordborg.

3. List of radionuclides

1) ^{11}C
2) ^{13}N
3) ^{15}O
4) ^{18}F
5) ^{30}P
6) ^{34m}Cl
7) ^{38}K
8) ^{43}K
9) $^{44}Ti/^{44}Sc$
10) ^{51}Cr
11) ^{52}Fe
12) $^{52}Fe/^{52m}Mn$
13) $^{62}Zn/^{62}Cu$
14) ^{67}Ga
15) $^{68}Ge/^{68}Ga$
16) ^{73}Se
17) ^{75}Se
18) ^{75}Br
19) ^{77}Br
20) ^{77}Kr
21) $^{81}Rb/^{81m}Kr$
22) $^{82}Sr/^{82}Rb$
23) $^{87}Y/^{87m}Sr$
24) $^{89m,g}Zr$
25) ^{111}In
26) $^{113}Sn/^{113m}In$
27) $^{118}Te/^{118}Sb$
28) $^{122}Xe/^{122}I$
29) ^{123}I
30) ^{124}I
31) $^{127m,g}Xe$
32) $^{128}Ba/^{128}Cs$
33) $^{169m,g}Yb$
34) $^{178}W/^{178}Ta$
35) ^{186}Re
36) $^{195m,g}Hg/^{195m}Au$
37) ^{201}Tl
38) ^{211}At

CARBON-11

Half-life: 20.38 min.
Decay: β^+(99.76%), EC(0.24%). Maximum positron energy 0.96 MeV, range in water of about 4 mm. No γ emissions.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{14}N(p,\alpha)^{11}C$	99.63	-2.9221	3.81-13.96 5-22 4.65-14.72 5.08-13.6	7.49 7.6 7.4 6.9	176 253 243 146	41 R0026 42 R0025 43 R0010 44 A0286	(22) 225 A0195 (4.49-22.36) 226 A0259 (5.83-17.2) 44 A0286
$^{10}B(d,n)^{11}C$	20.0	6.4667	1.5-12 0.5-3.2 2.93-11 7-16.01	5.3 2.3 <2.93 9.2	175 270 139 101	45 46 D0026 47 A0166 37 A0330	
$^{11}B(p,n)^{11}C$	80.0	-2.7647	2.5-400 0.2-98.6 4.7-15 2.9-5.51	10 9.3 9 3.69 >5.5	100 100 300 62.3 102	33 34 B0076 35 P0045 36 P0001	(22) 225 A0195
$^{12}C(p,pn)^{11}C$	98.90	-18.7219	8.5-104 20.7-50.5 27.6-41.8 15.9-32	46 33 34 >32	100 92 89 89	34 B0076 39 B0095 40 P0051 38 B0077	
$^{12}C(^3He,\alpha)^{11}C$	98.90	1.8566	4.5-24 2.4-9.5 1.56-5.78	8.9 8.9 2.7 4.3 4.85 5.6	340 350 165 255 281 293	48 49 50 P0108	
$^{10}B(p,\gamma)^{11}C$	20.0	8.6913	0.6-2.6 2.6-17	1.2 4 7 8.7	0.0075 0.0099 0.0111 0.0114	31 32	

NITROGEN-13

Half-life: 9.965 min.
Decay: β^+(99.8%), EC(0.2%). Maximum positron energy 1.19 MeV, range in water of about 5 mm. No γ emissions.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{16}O(p, \alpha)^{13}N$	99.76	-5.2182	6.22-15.6	8.5	40	40 P0051	(22) 225 A0195
				11.4	50		(6.18-22.66) 228 A0260
				14.6	40		
			6.66-15.77	8	51.3	61 C0202	(6.66-15.77) 61 C0202
				11.04	53.6		
				14.73	30.5		
			9.7-15	10.9	79	35 P0045	
				12.5	41		
				14.7	50		
			6.7-9.27	7.99	139	56 B0157	
			6.51-7.71	>7.71	13.8	57	
$^{12}C(d, n)^{13}N$	98.9	-0.2812	2-20	5	110	58	
			0.4-3	>3	260	62	
			1.96-4.5	2.30	200	63 P0130	
				3.98	153		
				>4.5	162		
$^{13}C(p, n)^{13}N$	1.1	-3.003	3.2-6.8	6.8	200	33	(22) 225 A0195
			3.24-4.25	3.9925	130	55 C0070	(4.08-23.12) 228 A0260
			3.88-5.25	3.990	83	36 P0001	
				4.520	79		
				5.030	94		
			3.2-12.9	4.0	120	59	
				5.05	170		
				6.7	275		
			5-13.5	6.7	230	60	
$^{10}B(\alpha, n)^{13}N$	20.0	1.0598	2.55-4.83	2.98	27.3	36 P0001	
				4.69	106		
$^{12}C(p, \gamma)^{13}N$	98.9	1.9435	0.195-0.448	>0.448	0.065	51	(0.407-1.996) 227 A0144
			0.128-0.202	>0.202	$2 \cdot 10^{-5}$	52	
			0.085-0.130	>0.130	$8 \cdot 10^{-7}$	53 P0050	
			5,11		2.5 , 1.8	54 B0047	

OXYGEN-15

Half-life: 2.037 min.
Decay: β^+(99.9%), EC(0.1%). Maximum positron energy 1.72 MeV, range in water of about 8 mm. No γ emissions.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{14}N(d, n)^{15}O$	99.63	5.0673	2-5	3.68	28	68	
			0.9-5.3	2.7	25	69	
			0.6-14.35	4.3	210	70 B0125	
			1.08-12.28	4.02	227	71 A0316	(1.08-12.28) 71 A0316
			0.5-3.2	>3.2	300	46 D0026	
$^{15}N(p, n)^{15}O$	0.37	-3.5417	5.5-13.5	6.6	230	60	
			3.95-9	6.5	190	64	
			5.8-8.6	6.45	182	65	
			3.72-16.58	6.41	142	66 A0313	(4-16) 66 A0313
			5.53-9.26	6.31	207	67 A0334	
$^{12}C(\alpha, n)^{15}O$	98.90	-8.5078	15-19	15.5	9.4	72	(3.6-9.9) 229 D0047
				16.6	9.2		
				17.3	10.5		
				18.5	9.7		
			11.4-22.7	14.5	26	73 P0133	
				22.4	22.8		
$^{16}O(p, pn)^{15}O$	99.76	-15.7	16.7-32.8	76.10	32.8		
$^{16}O(^3He, \alpha)^{15}O$	99.76	4.9090	2.9-8.9	6.6	169	49	

FLUORINE-18

Half-life: 1.8295 h.
Decay: β^+(96.9%), EC(3.1%). Maximum positron energy 0.96 MeV, range in water of about 3 mm. No γ emissions.

^{18}F can be produced either via direct reaction or as daughter of ^{18}Ne $\left[^{18}\text{Ne} \xrightarrow{\beta^+\ 1.672s} {}^{18}\text{F}\right]$.

Nuclar reaction	%	Q [MeV]	Range.ind. [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
^{20}Ne(d , α)^{18}F	90.51	2.7968	24.7-76	<24.7	11.6	79 A0175	(16.5) 231 B0176
^{18}O(p , n)^{18}F	0.20	-2.4378	6-13 2.5-3.9 2.3-14.7 7-13.5	7 2.64 3.02 3.37 3.86 5.2 <7	40 140 220 190 280 630 95	74 75 76 A0235 77	(22) 225 A0195 (3.76-22.37) 228 A0260
^{16}O(^{3}He , p)^{18}F	99.76	2.0330	2.9-9.5 1.5-4.5 13.9-40.3	6.3 >4.5 <13.9	436 139 135.9	49 82 83 B0151	 (7.7-40.0) 83 B0151
^{16}O(α , pn)^{18}F	99.76	-18.5455	21-40	≥40	250	84 P0121	(55) 236 A0183
^{20}Ne(d , p3n)^{18}Ne	90.51	-30.73	40-76	57.5	23	79 A0175	
^{20}Ne(^{3}He, αn)^{18}Ne	90.51	-15.517	18.44-30.9	30.9	2.7	79 A0175	
^{19}F(d , t)^{18}F	100	-4.1731	5.8-15.2	≥15.2	290	78	(22) 230 A0194
^{16}O(t , n)^{18}F	99.76	1.2692	0.68-2.13 0.5-3	>2.1 >3	100 820	80 81	

PHOSPHORUS-30

Half-life: 2.498 min.
Decay: β^+(99.9 %), EC (0.1 %). Maximum positron energy 3.25 MeV, range in water of about 16 mm. Principal γ-rays: 1262.9 keV, 3769.4 keV.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{32}S(d, \alpha)^{30}P$	95.02	4.091	4.86-13.05	10.1	41	87 A0318	
$^{28}Si(^3He, p)^{30}P$	92.23	6.8667	12.91-34.59	15.6	65	87 A0318	
$^{27}Al(\alpha, n)^{30}P$	100	-2.6378	5.2-11.0 10-27 0-34.4	9.8 15 8.8/15.8	350 400 480	88 P0070 85 A0181 89 A0171	(3.61-9.95) 229 D0047 (3.7-9.9) 229 D0048 (4.0-5.5) 332 D2001
$^{28}Si(\alpha, d)^{30}P$	92.23	-11.9985	0-34.4	25.5/34	150	89 A0171	
$^{31}P(p, p\,n)^{30}P$	100	-12.3073	19.9-34.4 21.5	26 21.5	260 240	85 A0181 86 B0049	

CHLORINE-34 m

Half-life: 32.23 min.
Decay: IT (44.5 %); principal γ-ray emissions: 144.34 keV (40.5 %), 1174.1 keV (14.11 %), 2127.4 keV (42.9 %), 3303.6 keV (12.31 %). β^+ (54 %), maximum positron energy 4.5 MeV, no γ. EC (1.5 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{32}S(^3He, p)^{34m}Cl$	95.02	6.0666	3.8-22.1	8	37	91 A0240	
$^{31}P(\alpha, n)^{34m}Cl$	100	-5.6479	6.5-7	>7	28	92	
$^{35}Cl(p, p\,n)^{34m}Cl$	75.77	-12.6463	10-45 21.5-45		120	90 86 B0049	

POTASSIUM-38

Half-life: 7.636 min.
Decay: β^+(100 %). Maximum positron energy 2.68 MeV, range in water of about 13 mm. Principal γ-ray emissions: 1768.2 keV (0.0094 %), 2167.68 keV (99.858 %), 3935.8 keV (0.124 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{40}Ar(p, 3n)^{38}K$	99.6	-23.6744					(32) 256
$^{35}Cl(\alpha, n)^{38}K$	75.77	-5.868	7-26	17.5	200	94	(7-26) 94 (9-24.5) 233
$^{40}Ca(d, \alpha)^{38}K$	96.94	4.657	1.9-5.5	>5.5	4.77	93	258
$^{37}Cl(^3He, 2n)^{38}K$	24.23	-4.182	7.3-20.2	14.7/15	23	91 A0240	
$^{40}Ca(^3He, \alpha p)^{38}K$	96.94	0.837	8.1-20.2	>20.2	76.6	91 A0240	

POTASSIUM-43

Half-life: 22.3 h.
Decay: β^-(100 %); maximum β^- energy 0.8 MeV, 1.8 MeV. Principal γ-ray emissions: 372.81 keV (86.7 %), 396.93 keV (11.36 %), 593.39 keV (11.0 %), 617.51 keV (80.0 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{40}Ar(\alpha, p)^{43}K$	99.6	-3.322	11.6-36.7	18	68	95 P0125	
$^{nat}V(p, \textit{spall})^{43}K$			590 800		3.8 5.4	96	

GENERATOR $^{44}Ti/^{44}Sc$

^{44}Ti Half-life: 47.3 y.
Decay: EC
^{44}Sc Half-life: 3.927 h.
Decay: β^+(94 %), EC (6 %).Maximum positron energy 1.5 MeV. Principal γ-ray: 1157 keV (99.9 %)

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{45}Sc(p , 2n)^{44}Ti$	100	-12.369	15-85	32	65	97 B0053	(14.5-22.3) 234 A0021 (22) 235 A0168 (22) 225 A0195
$^{45}Sc(d , 3n)^{44}Ti$	100	-14.594					(17-22.6) 234 A0021 (22) 230 A0194
$^{51}V(p , spall)^{44}Ti$	99.75	-70.4	200			29	29 , 26
$^{nat}Ti(\alpha , 2p\ xn)^{44}Ti$			43-171	>171	3.3	98	

CHROMIUM-51

Half-life: 27.704 d
Decay: EC (100 %), principal γ-ray: 320.084 keV (9.83 %).

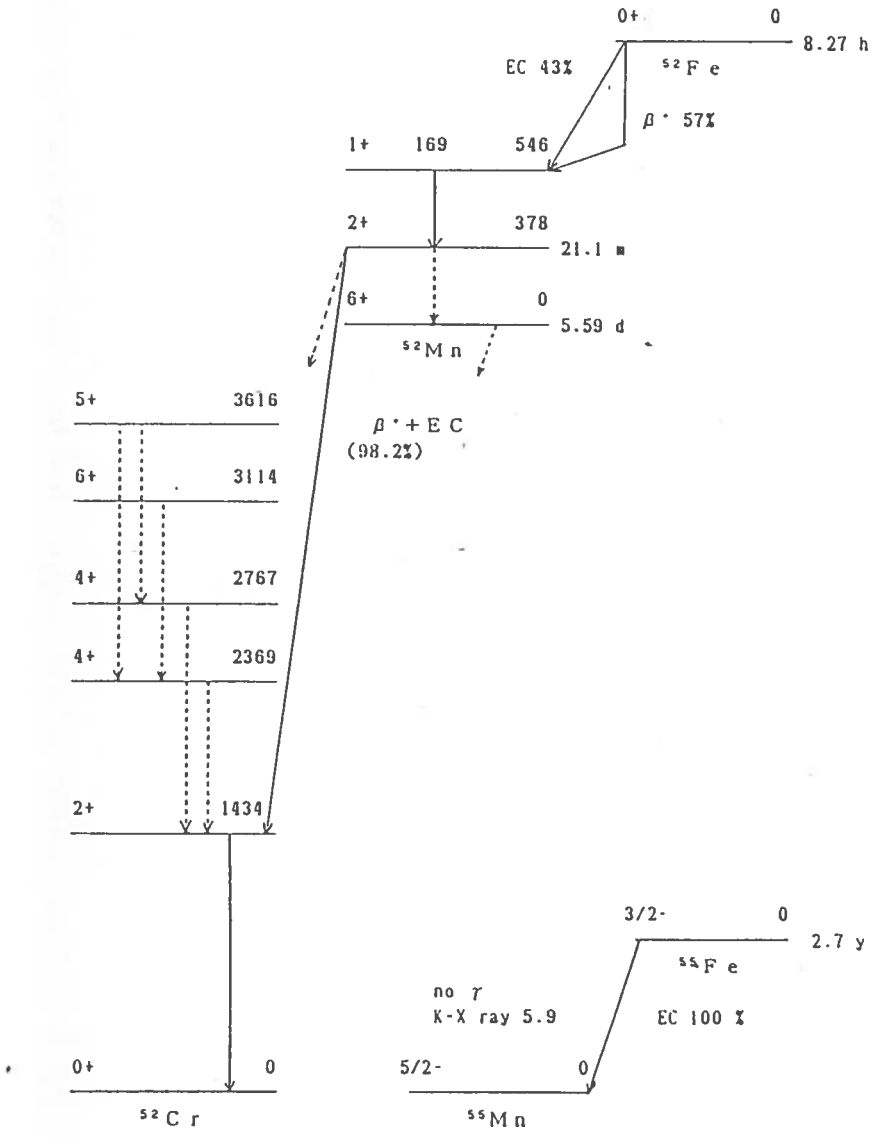
Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{51}V(p , n)^{51}Cr$	99.75	-1.5338	6.7-13.3 3.1-10.4 11.3-44.7 5-11 7-15 3.6-8.1 1.572-5.42 4.38-6.61	10 10.4 11.3 11 11 >8.1 >5.42 >6.61	540 645 834 595 729 485 365 385	101 B0043 102 B0065 103 B0027 104 B0066 105 P0021 106 B0093 107 B0068 108 B0051	(22) 225 A0195
$^{51}V(d , 2n)^{51}Cr$	99.75	-3.7585	5.58-90.5	17.2	678	100 A0169	(6-12) 237 A0211
$^{nat}Ti(^3He , xn)^{51}Cr$			9.74-135.4	17	23	100 A0169	
$^{nat}Ti(\alpha , xn)^{51}Cr$			8.98-171.5	16	590	100 A0169	

IRON-52

Half-life: 8.257 h.
Decay: β^+(56 %), EC(44 %). Principal γ-ray emissions: 168.684 keV (99.2 %), 377.738 keV (1.68 %).

GENERATOR $^{52}Fe/^{52m}Mn$

Decay and half-life, see figure.



Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{55}Mn(p , 4n)^{52}Fe$	100	-34.8855	40-73	54	1.4	7 pag 182	
$^{50}Cr(\alpha , 2n)^{52}Fe$	4.345	-15.641	18-44	30	20	117 , 119	(20-44) 117
$^{52}Cr(^{3}He , 3n)^{52}Fe$	83.79	-16.365	10-45	34	5	117 , 118	(15-45) 117
$^{59}Co(d , 2p\ 7n)^{52}Fe$	100	-71.847	68.9-84.7	>84.7	0.116	116 A0209	
$^{nat}Ni(p , \textit{spall})^{52}Fe$			800		1.54	122	
$^{75}As(p , \textit{spall})^{52}Fe$	100		590		0.04	121	
$^{nat}Cu(^{3}He,\textit{spall})^{52}Fe$			258-.910		0.2 / 0.4	120	

GENERATOR $^{62}Zn/^{62}Cu$

^{62}Zn Half-life: 9.26 h.
Decay: EC (91.6 %), β^+(8.4 %).

^{62}Cu Half-life: 9.74 m.
Decay: β^+(97 %), EC (3 %). Maximum positron energy 2.93 MeV, range in water of about 14.9 mm.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{63}Cu(p, 2n)^{62}Zn$	69.17	-13.327	17-99.2 16-33 15.2-31.8 16.1-69.8 14-32.4 21.5 400 1500-11500	27 27 26.2 24 24 <1500	140 95 218 64 66 100 0.8 0.23	123 B0054 130 B0074 131 B0017 133 134 A0333 111 B0050 113 B0071 132 B0031	(22) 225 A0195
$^{60}Ni(\alpha, 2n)^{62}Zn$	26.10	-17.083	20-39 18.3-38.1 23.3-37.7	33 31 33	230 120 134	131 B0017 127 P0037 123 B0128	(12.8-31.9) 239 B0164
$^{nat}Ni(\alpha, xn)^{62}Zn$			16-37 17-122	31 29	29 36.6	123 89	
$^{63}Cu(d, 3n)^{62}Zn$	69.17	-15.551	17.3-38.3	33	73	135 B0121	(22) 230 A0194
$Rb+Br(p, spall)^{62}Zn$			800		2	136	
$^{nat}Rb(p, spall)^{62}Zn$			593		0.31	121	
$^{nat}Br(p, spall)^{62}Zn$			593		0.69	121	
$^{75}As(p, spall)^{62}Zn$	100		593		1.17	121	
$^{nat}Cu(^3He, spall)^{62}Zn$			285-910		1.2 / 2.7	120	

GALLIUM-67

Half-life: 3.261 d.
Decay: EC (100 %). Principal γ-ray emissions: 91.257 keV (2.95 %), 93.317 keV (37.0 %), 184.578 keV (20.4 %), 208.951 keV (2.33 %), 300.218 keV (16.3 %), 394.594 keV (4.64 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{68}Zn(p, 2n)^{67}Ga$	18.8	-11.9823	15-85 21.5 400	20	430 780 2.34	97 B0053 111 B0050 138 B0024	(22) 225 A0195
$^{67}Zn(p, n)^{67}Ga$	4.1	-1.783	2.34-6.37 1.845-5.34	>6.37 >5.34	420 130	133 B0048 109 B0068	
$^{65}Cu(\alpha, 2n)^{67}Ga$	30.83	-14.107	16.4-36.6 15.2-40.1 11.3-26.5 18.4-60	27 28.5 ≥26.5 26.7	520 630 967 897	141 128 B0156 139 B0079 145 B0040	
$^{nat}Zn(\alpha, X)^{67}Ga$			8.8-96.5 12.7-36	44.5 19.2	202.6 277	146 B0097 144 B0135	(8.8-96.5) 146 B0097 (12.7-36) 144 B0135
$^{66}Zn(d, n)^{67}Ga$	27.9	3.0463	1.5-15.5 4.5-11.3	8 8.8	450 221	126 115 A0202	(7-12) 237 A0211
$^{65}Cu(^{3}He, n)^{67}Ga$	30.83	6.471	8.4-23.7 8.1-69.4	12 11.8	13 7.63	139 B0079 140 B0039	
$^{64}Zn(\alpha, p)^{67}Ga$	48.6	-3.995	13.4-39.6 9.1-36.9	18.5 18-20	515 452	142 P0073 143	
$^{nat}As(p, \textit{spall})^{67}Ga$			800		28.4	96	
$Rb+Br(p, \textit{spall})^{67}Ga$			800		41	96	

GENERATOR $^{68}Ge/^{68}Ga$

^{68}Ge Half-life: 270.8 d.
Decay: EC (100 %)

^{68}Ga Half-life: 1.135 h.
Decay: β^+(89 %), EC (11 %). Maximum positron energy 1.9 MeV, range in water of about 9 mm. Principal γ-ray emission: 1077.29 keV.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σmax [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{69}Ga(p, 2n)^{68}Ge$	60.1	-11.479	13-55 21.5	22	490 360	125 P0014 111 B0050	(22) 225 A0195 (19.5) 240 R0034
$^{71}Ga(p, 4n)^{68}Ge$	39.9	-32.703	37-55	42.4	134	125 P0014	
$^{69}Ga(d, 3n)^{68}Ge$	60.1	-13.704	14-32	28	550	257	(22) 230 A0194
$^{nat}Zn(\alpha, xn)^{68}Ge$			20-38	31	150	144	
$^{67}Zn(^3He, 2n)^{68}Ge$	4.1	-2.4					
$^{68}Zn(^3He, 3n)^{68}Ge$	18.8	-12.6					
$Ge(p, pxn)^{68}Ge$			24-64	37	100	147	
$Rb+Br(p, spall)^{68}Ge$			800		19	136	
$^{89}Y(p, spall)^{68}Ge$	100		593		6.75	121	
$^{nat}Rb(p, spall)^{68}Ge$			593		7.80	121	
$^{nat}Br(p, spall)^{68}Ge$			593		11.1	121	
$^{75}As(p, spall)^{68}Ge$	100		593		10.7	121	

SELENIUM-73

Half-life: 7.15 h.
Decay: β^+(66 %), EC (34 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{75}As(p , 3n)^{73}Se$	100	-21.742	25-50 25-45 400 540 , 593	35 33-35	350 300 4.32 2.8 ,2.67	148 150 , 151 138 B0024 121 D0029	(24.5-44.5) 150
$^{70}Ge(\alpha , n)^{73}Se$	20.5	-7.993	13-31.5 10-28	23.5 20	504 900	149 B0152 151	
$^{72}Ge(\alpha , 3n)^{73}Se$	24.7	-26.157	31.5-39.5	>39.5	435	149 B0152	
$^{75}As(d , 4n)^{73}Se$	100	-23.966	27.4-51.3 26-55.5	41.2 41	77 200	152 150	(26.5-55.5) 150
$^{72}Ge(^3He , 2n)^{73}Se$	24.7	-5.579	16.5-36.5	22.5	309	149 B0152	
$^{73}Ge(^3He , 3n)^{73}Se$	7.8	-12.363	32.5-36.5	>36.5	1498	149 B0152	
$^{nat}Ge(^3He , xn)^{73}Se$			10-40	20	106	148	
$^{nat}Ge(\alpha , xn)^{73}Se$			10-40	21	180	148	(10.8-44) 242 A0006

SELENIUM-75

Half-life: 119.77 d.
Decay: EC (100 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{75}As(p , n)^{75}Se$	100	-1.647	1.7-5.7	>5.7	251	107 , 109 B0068	(6.5-21.7) 241 A0022
			3.6-8.1	7-8	447	106 B0093	(10.4) 238 A0287
			400		1.40	138 B0024	(22) 225 A0195
			540,593		1.88,1.9	121 D0029	(22) 235 A0168
			3-45	12	800	150 , 151	(6.5-44.5) 150
$^{75}As(d , 2n)^{75}Se$	100	-3.8718	10.2-49.4	16.8	523	152	(9.1-23) 241 A0022
			5.5-55.5	18-19	700	150	(9-55.5) 150
							(22) 230 A0194
$^{76}Se(^{3}He , \alpha)^{75}Se$	9.0	9.4176	10.2-35.1	>35.1	88.9	154 A0154	
$^{77}Se(^{3}He , \alpha n)^{75}Se$	7.6	1.9987	15-35.4	22.65	98.9	154 A0154	
$^{nat}Br(p , X)^{75}Se$			593		31.9	121 D0029	
$^{nat}Rb(p , X)^{75}Se$			593		24.6	121 D0029	
$^{89}Y(p , X)^{75}Se$	100		540 , 593		17.8,18.7	121 D0029	
$^{90}Zr(p , X)^{75}Se$	51.54		1000		23.9	153 A0041	
$^{91}Zr(p , X)^{75}Se$	11.32		1000		22.8	153 A0041	
$^{94}Zr(p , X)^{75}Se$	17.28		1000		20.5	153 A0041	

BROMINE-75

Half-life: 1.62 h.
Decay: β^+(75.5 %), EC (24.5 %). Maximum positron energy 1.7 MeV. Principal γ-ray emissions: 112.22 keV (1.75 %), 141.30 keV (6.9 %), 286.56 keV (92 %), 292.97 keV (2.79 %), 377.44 keV (4.1 %), 427.28 keV (4.5 %), 431.72 keV (4.0 %), 573.01 keV (2.08 %), 608.96 keV (1.76 %), 734.02 keV (1.61 %), 912.17 keV (1.06 %), 952.27 keV (1.74 keV).

^{75}Br can be produced either via direct reaction or as daughter of ^{75}Kr $\left[{}^{75}\text{Kr} \xrightarrow{\beta^+ \text{ EC } 4.3 \text{ min}} {}^{75}\text{Br}\right]$.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
^{76}Se(p , 2n)^{75}Br	9	-14.954	16.5-34.5	21.4	520	155 A0253	(16-35) 245
^{76}Se(d , 3n)^{75}Br	9	-19.78	21.8-44.27	30.7	370	155 A0253	
^{75}As(^{3}He , 3n)^{75}Br	100	-13.158	15.77-41.39 17.9-35.7 15.2-62.2	25 31 28.5	203 186 352	155 A0253 156 A0160 157 A0232	(25-36) 243 R0032 (36) 244 R0033 (17-35) 245
^{75}As(α , 4n)^{75}Br	100	-33.737	40.3-71.7 42.6-106	55 53.8	186 268	155 A0253 157 A0232	
^{nat}Br(d , xn)^{75}Kr→			60-80	76	4	158	
^{78}Kr(p , α)^{75}Br							
^{74}Se(p , γ)^{75}Br	0.9	4.231	1.6-3	>3	2.3	110 A0048	

BROMINE-77

Half-life: 2.37650 d.
Decay: EC (99.26 %), β^+(0.74 %). Principal γ-ray emissions: 238.97 keV (23.9 %), 520.61 keV (23.1 %).

^{77}Br can be either produced via direct reaction or as daughter of ^{77}Kr $\left[{}^{77}\text{Kr} \xrightarrow{\beta^+ \text{ EC } 1.24\text{ h}} {}^{77}\text{Br}\right]$.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
^{78}Se(p , 2n)^{77}Br	23.6	-12.644	13.68-24.58	22	800	160 A0255	
^{75}As(α , 2n)^{77}Br	100	-13.5112	15-27.5 13.8-28.1 26.1-125.1 20-40	21.76 26.3 ≤26.1 25	850 803 690 950	162 A0346 161 A0243 157 A0232 159 A0184	(15-29) 162 A0346 (28) 243 R0032 (28) 244 R0033 (20-40) 159 A0184 (22.3-43.8) 246 A0122
^{75}As(^{3}He , n)^{77}Br							
^{77}Se(p , n)^{77}Br	7.6	-2.147	2.19-5.54 9.9-24.6 400	>5.54 <9.9	328 232 2	107 , 109 B0068 160 A0255 113 B0071	
^{nat}Se(p , xn)^{77}Br			10-50	20 45	238 174	159 A0184	(10-50) 159 A0184 (22) 235 A0168

KRYPTON-77

Half-life: 1.24 h.
Decay: β^+(87 %), EC (13 %). Maximum positron energy 1.9 MeV. Principal γ-ray emissions: 129.75 keV (80 %), 146.40 keV (37.6 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{79}Br(p, 3n)^{77}Kr$	50.69	-22.763	24.6-64.7 23-51 25-85	35.7 36 35	178 150 260	163 A0187 159 164 B0171	(65) 247 R0030
$^{81}Br(p, 5n)^{77}Kr$	49.31	-40.806	45-85	60	41	164 B0171	
$^{79,81}Br(d, xn)^{77}Kr$			20-90	43	58	165	
$^{76}Se(^3He, 2n)^{77}Kr$	9.0	-6.229	13.15-35	≈22	370	154 A0154	
$^{77}Se(^3He, 3n)^{77}Kr$	7.6	-13.648	18.06-35.72	31	356	154 A0154	

GENERATOR $^{81}Rb/^{81m}Kr$

^{81}Rb: Half-life: 4.58 h.
Decay: β^+(31 %), EC (69 %)
^{81m}Kr: Half-life: 13 s.
Decay: IT (100 %). Principal γ-ray emission: 190.4 keV (67 %).

^{81}Rb can be produced either via direct reaction or as daughter of ^{81}Sr $\left[^{81}Sr \xrightarrow{\beta^+\ 22.15\ min} {}^{81}Rb\right]$.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{nat}Kr(p, xn)^{81}Rb$			12-45	27			(16-32) 248 A0186 (10-43) 249
$^{79}Br(\alpha, 2n)^{81}Rb$	50.69	-14.37	13-38	30	380	168 R0029	(40) 168 R0029
$^{nat}Br(^3He, xn)^{81}Rb$			12-37	27	350	168 R0029	(30-40) 234 R0029
$^{85}Rb(p, 5n)^{81}Sr\rightarrow$	72.17	-43.61	49-69.9	68	28	167 B0111	(48.6-70.7) 167 B0111
$^{85}Rb(p, p4n)^{81}Rb$	72.17	-39.03	46.6-69.9	69.9	200	167 B0111	(45.3-70.5) 167 B0111

GENERATOR $^{82}Sr/^{82}Rb$

^{82}Sr: Half-life: 25.55 d.
Decay: EC (100 %).
^{82}Rb: Half-life: 1.273 min.
Decay: β^+(95 %), EC (5 %). Maximum positron energy 0.8 MeV. Principal γ-ray emission: 776.62 keV (13.4 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{85}Rb(p, 4n)^{82}Sr$	72.17	-31.56	33.7-69.9	50	230	167 B0111	(37-70.8) 167 B0111
$^{82}Kr(^3He, 3n)^{82}Sr$	11.6	-14.6	15-36				245
$^{80}Kr(\alpha, 2n)^{82}Sr$	2.25	-16.3					
$^{nat}Kr(^3He, xn)^{82}Sr$			11-33	>33	42	169, 151	(11-33) 169
$^{nat}Kr(\alpha, xn)^{82}Sr$			17.2-24.5	>24.5	60	169	(17-24) 169
Rb,Mo(p, *spall*)^{82}Sr			800 800		2.1 24.5	136 170	
$^{nat}Rb(p, spall)^{82}Sr$			593		19.7	121	
$^{89}Y(p, spall)^{82}Sr$	100		593		2.59	121	
$^{nat}Mo(p, spall)^{82}Sr$			590, 800		15, 24.5	96	

GENERATOR $^{87}Y/^{87m}Sr$

^{87}Y: Half-life: 3.346 d.
Decay: EC (99.8 %), β^+(0.2 %).
^{87m}Sr Half-life: 2.795 h.
Decay: IT (99.7 %), EC (0.3 %). Principal γ-ray emission: 388.40 keV (82.3 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{87}Sr(p, n)^{87}Y$	7.00	-2.664	2.6-6.8	>6.8	324	124 P0033	
$^{88}Sr(p, 2n)^{87}Y$	82.58	-13.778	15-33	25	1210	171 B0069	(22) 225 A0195
$^{86}Sr(d, n)^{87}Y$	9.86	3.539					(4-12) 237 A0211
$^{87}Rb(^3He,3n)^{87m}Y$	27.835	-11.2	12-37	25	30	173 A0284	
$^{85}Rb(\alpha, 2n)^{87m}Y$	72.165	-12.2	15-40 15-38	29 25	700 450	173 A0284 174 P0064	
$^{89}Y(p, p2n)^{87}Y$	100	-20.845	24.8-85	45	395	172 B0001	

$^{89m}Zr \rightarrow {}^{89g}Zr$

^{89m}Zr Half-life: 4.18 min.
Decay: IT (93.8 %), EC (4.7 %), β^+(1.5 %).
^{89g}Zr Half-life: 3.268 d.
Decay: EC (77 %), β^+(23 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{89}Y(p, n)^{89g}Zr$	100	-3.6166	6.38-19.9 3.55-6.73	14.4 >6.73	338 213	175 P0012 124 P0033	(22) 235 A0168
$^{89}Y(p, n)^{89m}Zr$	100	-4.2043	6.88-19.7 12	11.4	343 170	175 P0012 99 B0052	(8-12) 114 A0085
$^{89}Y(p, n)^{89}Zr$	100	-3.6166	12 7 , 8.1 3.66-5.84 3.9-44.2 5-85 400	 >5.84 12.8 12 	750 254,323 10.2 688 720 1.85	99 B0052 106 B0093 176 P0025 177 B0018 172 B0001 138 B0024	(22) 225 A0195
$^{90}Zr(p, X)^{89g}Zr$	51.54		1000		45.4	153 A0041	(22) 225 A0195
$^{91}Zr(p, X)^{89g}Zr$	11.32		1000		29.5	153 A0041	
$^{94}Zr(p, X)^{89g}Zr$	17.28		1000		89	153 A0041	
$^{90}Zr(p, pn)^{89}Zr$	51.54	-11.983	22.2		81	112 A0271	
$^{90}Zr(\alpha, \alpha n)^{89g}Zr$	51.54	-11.983	27.5-78.1	>78.1	423	178 P0126	

INDIUM-111

Half-life: 2.807 d.
Decay: EC (100 %). Principal γ-ray emissions: 171.28 keV (90.24 %), 245.248 keV (94 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{112}Cd(p, 2n)^{111}In$	24.13	-11.005	13.2-20.9 9.4-37.4 50-400	>20.9 22.8 <50	1070 1000 77.8	181 A0001 182 P0019 183	(22) 225 A0195
$^{109}Ag(\alpha, 2n)^{111}In$	48.161	-14.014	15-36 20.4-53.9 14.1-18.4	26 30.3 >18.4	1200 872 209	148 187 D0051 188 P0094	
$^{111}Cd(p, n)^{111}In$	12.80	-1.608	6.1-9.1 2.1-10.1 3.04-6.4 4.3-20.9 4.3-14.7 13.8-44.44 12 70-400	>9.1 >10.1 >6.4 11.8 13.1 <13.8 <70	450 540 200 696 530 560.7 810 6.55	180 A0135 102 B0065 137 B0048 181 A0001 185 P0019 186 A0335 99 B0052 183	(8-12) 250 A0212 (10.4) 238 A0287 (22) 225 A0195
$^{109}Ag(^{3}He, n)^{111}In$	48.161	6.564	10-39.6 12-45 14.55-42.06	20 19 19.89	2.2 4 4.56	184 A0319 185 186 A0335	

GENERATOR $^{113}Sn/^{113m}In$

^{113}Sn Half-life: 115.09 d.
Decay: EC (100 %).
^{113m}In Half-life: 1.658 h.
Decay: IT (100 %). Principal γ-ray emission: 391.690 keV (64.2 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{113}In(p , n)^{113}Sn$	4.3	-1.808					(22) 225 A0195
$^{115}In(p , 3n)^{113}Sn$	95.7	-18.15	22.2		11	112 A0271	(22) 225 A0195
$^{113}In(d , 2n)^{113}Sn$	4.3	-4.032					(8-12) 250 A0212 (22) 230 A0194
$^{112}Cd(^{3}He,2n)^{113}Sn$	24.13	-3.5				30	
$^{113}Cd(^{3}He,3n)^{113}Sn$	12.22	-10.0				30	
$^{111}Cd(\alpha , 2n)^{113}Sn$	12.80	-14.7				30	
$^{nat}Cd(^{3}He , xn)^{113}Sn$			5-120	38	400	189	
$^{nat}In(^{3}He, p xn)^{113}Sn$			20-115	55	850	189	
$^{nat}Cd(\alpha , xn)^{113}Sn$			10-140	55	270	189	
$^{nat}In(\alpha , p xn)^{113}Sn$			40-135	85	700	189	

GENERATOR $^{118}Te/^{118}Sb$

^{118}Te Half-life: 6.00 d.
Decay: EC (100 %).
^{118}Sb Half-life: 3.6 min.
Decay: β^+(74 %), EC (26 %). Maximum positron energy 2.7 MeV.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{121}Sb(p, 4n)^{118}Te$	57.3	-26.93	27-90	44	700	190	(35-58) 190
$^{117}Sn(^3He,2n)^{118}Te$	7.68	-4.1				30	
$^{118}Sn(^3He,3n)^{118}Te$	24.22	-13.4				30	
$^{116}Sn(\alpha, 2n)^{118}Te$	14.53	-17.59	19.7-29.7	>29.7	1500	191 A0217	
$^{123}Sb(p, 6n)^{118}Te$	42.7	-43.88				30	

GENERATOR $^{122}Xe/^{122}I$

^{122}Xe Half-life: 20.1 h.
Decay: EC (100 %).
^{122}I Half-life: 3.62 min.
Decay: β^+(77 %), EC (23 %). Maximum positron energy 3.1 MeV, range in water of about 15 mm. Principal γ-ray emission: 564.37 keV (18 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{127}I(p, 6n)^{122}Xe$	100	-45.06	55-85 50-67.5 660	70 >67.5	114 197 2.6	192 B0081 193, 194 195 R0005 A0026	
$^{127}I(d, 7n)^{122}Xe$	100	-47.28	62.5-89 62.32-77.11	85 >77.11	190 190	196 B0143 198 A0345	
$^{nat}Cs(p, spall)^{122}Xe$			350-590 660	<350	30 19.9	197 195	
$^{nat}Ba(p, spall)^{122}Xe$			365-590 660	<365	20 17.8	197 195	
$^{nat}La(p, spall)^{122}Xe$			310-590 660		≈21 25	197 195	

IODINE-123

Half-life: 13.2 h.
Decay: EC (100 %). Principal γ-ray emission: 158.989 keV (83.3 %)

Direct methods

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{124}Te(p, 2n)^{123}I$	4.816	-11.41	12.33-29.27 12.2-29.18 300 400	14.60 22.26	1298 1011.4 5.3 3.6	199 A0266 200 B0090 224 C0346 113 B0071	(10-23.5) 253 (12-25.8) 251 B0169 (22) 225 A0195
$^{123}Te(p, n)^{123}I$	0.908	-1.98	11.5		210	201	(10-20) 253
$^{122}Te(d, n)^{123}I$	2.6	2.71	7.46-33.95	11.5	351	202 A0234	(10.71-33.01) 202 A0234 (4) 252 A0128
$^{121,123}Sb(^{3}He,xn)^{123}I$			12.4-25.8	22.2	366	203 A0238	
$^{121}Sb(\alpha, 2n)^{123}I$	57.3	-15.35	9.7-28.2 14.6-26.5	27.6 ≥26.5	816 1110	203 A0238 204 R0004	

Indirect methods

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{124}Xe(p , 2n)^{123}Cs$ $[^{123}Cs \xrightarrow{\beta^+ 6\ min} {}^{123}Xe]$ + $^{124}Xe(p , p\ n)^{123}Xe$	0.10 0.10	-15.11					319 , 320
$^{127}I(p , 5n)^{123}Xe$	100	-36.76	45.4-62.4 46.4-75.6 38.1-159.1 45-85 660	53.5 57.5 57.2 55	484 372 292 269 3.8	205 A0265 206 A0161 207 R0007 192 B0081 195 A0062 R0005	
$^{127}I(d , 6n)^{123}Xe$	100	-38.99	45.6-86.7 62.31-77.14	70 <62.31	290 220	196 B0143 198 A0345	(62.31-77.14) 198 A0345
$^{123}Te(^3He,3n)^{123}Xe$	0.908	-13.16	20-38	26	178	208	(24.3-38.8) 208 A0326
$^{124}Te(^3He,4n)^{123}Xe$	4.816	-22.58	28-52	45	162	208	(31.5-52.2) 208 A0326
$^{122}Te(\alpha , 3n)^{123}Xe$	2.60	-26.81					(43.2) 208 A0326
Cs(p , *spall*)^{123}Xe			660 350-590	<350	29.3 40	195 197	
Ba(p , *spall*)^{123}Xe			660 365-590	<365	26 30	195 197	
La(p , *spall*)^{123}Xe			660 310-590 590	<310	31.9 30 35	195 197 96	

IODINE-124

Half-life: 4.18 d.
Decay: EC (77 %), β^+(23 %). Principal γ-ray emissions: 602.73 keV (61 %), 1325.51 keV (1.45 %), 1376.13 keV (1.66 %), 1509.48 keV (2.99 %) and 1690.98 keV (10.41 %).

Nuclear reactin	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{124}Te(p, n)^{124}I$	4.816	-3.942	9.6-29.3 9.95-29.2 400	12.41 14.54	521 456 1.3	199 A0266 200 B0090 113 B0071	(12-25.8) 251 B0169
$^{125}Te(p, 2n)^{124}I$	7.14	-10.527	400 300		3.12 4.41	138 B0024 224 C0346	(22) 225 A0195
$^{126}Te(p, 3n)^{124}I$	18.95	-19.637	400		3.52	138 B0024	
$^{127}I(p, p\,3n)^{124}I$	100	-25.842	30-85 250-6200	50 <250	201 50.4	192 B0081 209 C0347	
$^{nat}Te(p, xn)^{124}I$			11.75-33.97	29-32	186	199 A0266	(9.8-22.2) 254 A0078 (22) 235 A0168
$^{127}I(d, p\,4n)^{124}I$	100	-28.07	45.6-89.3 62.42-77.38	75.9 ≥77.38	150 163.7	196 B0143 198 A0345	
$^{nat}Te(d, xn)^{124}I$			6.86-13.43	11.27	8.3	202 A0234	(9.5-22.1) 254 A0078 (22) 230 A0194
$^{123}Sb(^3He, 2n)^{124}I$	42.7	-3.077	12.4-25.8	≤12.4	43.4	203 A0238	
$^{121}Sb(\alpha, n)^{124}I$	57.3	-7.883	11.5-26.5	18.28	557	204 R0004	
$^{nat}Sb(\alpha, xn)^{124}I$ =			9.7-28.2			203 A0238	(16.5-43.9) 254 A0078
$\frac{^{121}Sb(\alpha, n)^{124}I}{^{123}Sb(\alpha, 3n)^{124}I}$	57.3 42.7	-7.883 -23.665		12.2 >28.2	93 189		

XENON-127 m,g

^{127m}Xe: Half-life: 1.153 min.
Decay: IT(100 %). Principal γ-ray emissions: 124.74 keV (69 %), 172.5 keV (38 %).

^{127g}Xe: Half-life: 36.41 d.
Decay: EC (100 %). Principal γ-ray emissions: 145.25 keV (3.94 %), 171.13 keV (23.5 %), 202.85 keV (68 %), 374.9 keV (15.9 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{133}Cs(p , X)^{127g}Xe$	100		356-588	<356	88.2	197 B0180	
$^{nat}Ba(p , X)^{127g}Xe$			368-590 600	≤462	73.7 45.7	197 B0180 211 A0344	
$^{139}La(p , X)^{127g}Xe$	99.91		317-589	460	72.2	197 B0180	
$^{127}I(p , n)^{127}Xe$	100	-1.446	3-24.8 20-85	9.92 <20	471 68	166 B0056 192 B0081	(22) 225 A0195 (22) 235 A0168
$^{133}Cs(p , X)^{127}Xe$	100		351-588	<351	85.4	197 R0001 B0180	
$^{nat}Ba(p , X)^{127}Xe$			367-589	<367	72.5	197 R0001 B0180	
$^{139}La(p , X)^{127}Xe$	99.91		312-591	459	71.7	197 R0001 B0180	
$^{127}I(d , 2n)^{127}Xe$	100	-3.671	6.5-89.8 3.4-17.9 62.3 , 77.01	15.8 15	470 683 36.5;32.4	196 B0143 210 198 A0345	(22) 230 A0194

GENERATOR $^{128}Ba/^{128}Cs$

^{128}Ba: Half-life: 2.43 d.
Decay: EC (100 %).

^{128}Cs: Half-life: 3.62 min.
Decay: β^+(69 %), EC (31 %). Maximum positron energy 2.9 MeV. Principal γ-ray emission: 442.92 keV (26.8 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{133}Cs(p , 6n)^{128}Ba$	100	-43.98	48-68	65	290	212 A0320	
$^{128}Xe(^3He,3n)^{128}Ba$	1.91	-14.3				30	

YTTERBIUM-169 m,g

^{169m}Yb: Half-life: 46 s.
Decay: IT (100 %).

^{169g}Yb: Half-life: 32.022 d.
Decay: EC (100 %). Principal γ-ray emissions: 307.73 keV (10.80 %), 197.95 keV (34.9 %), 177.21 keV (21.5 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{169}Tm(p, n)^{169}Yb$	100	-1.689	3.3-43.9	10.5	163	177 B0018	

GENERATOR $^{178}W/^{178}Ta$

^{178}W: Half-life: 21.5 d.
Decay: EC (100 %).

^{178}Ta: Half-life: 9.31 m.
Decay: EC (98.9 %), β^+(1.1 %). Principal γ-ray emissions: 54.61 keV (24.3 %), 55.79 keV (45.2 %) and 63.16 keV (13.9 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{181}Ta(p, 4n)^{178}W$	99.998	-22.99	28-44.2	36.3	772	213 B0038	
$^{177}Hf(^3He,2n)^{178}W$	18.606	-3.7				30	
$^{178}Hf(^3He,3n)^{178}W$	27.297	-11.3				30	
$^{176}Hf(\alpha, 2n)^{178}W$	5.206	-17.9				30	

RHENIUM-186

Half-life: 3.777 d.
Decay: β^- (92.2 %), EC (7.8 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{186}W(p, n)^{186}Re$	28.6	-1.3763	130-396	<130	13.7	214	
$^{186}W(d, 2n)^{186}Re$	28.6	-3.6010	5.94-14 7-15.7 7-16.7	≥14 12.1 15.2	365 434 647	216 P0115 217 S0014 115 A0202	(8-12) 250 A0212
$^{187}Re(p, p n)^{186}Re$	62.60	-7.3714	250-440		≈67.4	215 C0299	

GENERATOR $^{195m,g}Hg/^{195m}Au$

^{195g}Hg: Half-life: 9.5 h
Decay: EC (100 %)

^{195m}Hg: Half-life: 1.73 d.
Decay: IT (54.2 %), EC (45.8 %).

^{195m}Au: Half-life: 30.5 s.
Decay: IT(100 %). Principal γ-ray emissions: 261.83 keV (67.9 %), 200.40 keV (1.70 %), 80.43 keV (1.06 %), 77.86 keV (4.01 %), 68.81 keV (11.4 %), 66.99 keV (6.72 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{197}Au(p, 3n)^{195m,g}Hg$	100	-17.9	20-42	27		27	27
$^{192}Pt(\alpha, n)^{195m,g}Hg$	0.79	-11.8				30	
$^{197}Au(d, 4n)^{195m,g}Hg$	100	-20.2	32.9-79.8	36.1	614	218	
$^{194}Pt(^3He,2n)^{195m,g}Hg$	32.9	-5.8				30	

THALLIUM-201

Half-life: 3.046 d.
Decay: EC (100 %). Principal γ-ray emission: 135.28 keV (2.67 %), 82.74 keV (4.4 %), 80.12 keV (16.1 %), 70.82 keV (46 %), 68.89 keV (26.9 %).

^{201}Tl can be produced either via direct reaction or as daughter of ^{201}Pb $\left[{}^{201}Pb \xrightarrow{EC\ 9.4\ h} {}^{201}Tl\right]$.

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{203}Tl(p, 3n)^{201}Pb$	29.524	-17.23	18.3-41.6	27.4	1250	219 B0168	(22) 225 A0195 (22) 235 A0168
$^{nat}Tl(p, xn)^{201}Pb$			17.2-44.1	27.1 >44.1	378 699	221 A0185	
$^{205}Tl(p, 5n)^{201}Pb$	70.476	-31.43	34.9-59 34-58.7	45.7 45.7	1020 880	219 B0168 220 A0180	
$^{nat}Pb(p, spall)^{201}Tl$			800		54.7	96	
$^{202}Hg(p, 2n)^{201}Tl$	29.80	-8.95	400		3.8	138 B0024	(22) 225 A0195
$^{nat}Hg(p, xn)^{201}Tl$							(14-50) 255
$^{209}Bi(p, spall)^{201}Tl$	100		590, 800		63, 58.9	96	

ASTATINE-211

Half-life: 7.214 h.
Decay: α (41.7 %), EC (58.3 %).

Nuclear reaction	%	Q [MeV]	Range [MeV]	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ EXFOR ref.	TTY EXFOR ref.
$^{209}Bi(\alpha, 2n)^{211}At$	100	-20.338	20.6-43.3 21.1-29.2	31 >29.2	980 906.5	222 A0246 223 A0249	

4. Summary tables

Tables 1-9 list the production routes better suited to the production of the radionuclides discussed in the previous section, for the energy range provided by different linacs. Table 1 lists the nuclear reactions for the 11 accelerator-produced radionuclides more commonly used in medicine. Tables 2-5 list the radionuclides which can be produced by a linac accelerating protons to 11 MeV, 30 MeV, 55 MeV and 70 MeV respectively, along with the reactions that can be exploited in the energy interval considered. Tables 3-5 give the radionuclides that can be produced in addition to those already listed in the previous table(s). Table 6 lists the radionuclides obtainable by 6 MeV deuterons, while table 7 gives the radionuclides that can additionally be produced by 15 MeV deuterons. Finally, tables 8 and 9 list the radionuclides which can be generated by 30 MeV and 55 MeV α-particles, respectively.

TAB. 1 **RADIONUCLIDES MORE COMMONLY USED IN MEDICINE**

NUCLIDE	T1/2	DECAY [%]	NUCLEAR REACTION	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ ref, EXFOR	TTY ref , EXFOR
^{11}C	20.38 min	β^+(100)	$^{14}N(p , \alpha)^{11}C$	7.49	176	41 R0024	(22) 225 A0195
				7.6	253	42 R0025	(4.49-22.36) 226 A0259
				7.4	243	43 R0010	(5.83-17.2) 44 A0286
				6.9	146	44 A0286	
			$^{10}B(d , n)^{11}C$	5.3	175	45	
				2.3	270	46 D0026	
				<2.93	139	47 A0166	
				9.2	101	37 A0330	
^{13}N	9.965 min	β^+(99.8) EC(0.2)	$^{16}O(p , \alpha)^{13}N$	8.5	40	40 P0051	(22) 225 A0195
				11.4	50		(6.18-22.66) 61 C0202
				14.6	40		(6.66-15.77) 61 C0202
				8	51.3	61 C0202	
				11.04	53.6		
				14.73	30.5		
				10.9	79	35 P0045	
				12.5	41		
				14.7	50		
			$^{12}C(d , n)^{13}N$	5	110	58	
				>3	260	62	
				2.30	200	63 P0130	
				3.98	153		
				>4.5	162		

NUCLIDE	T1/2	DECAY [%]	NUCLEAR REACTION	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ ref, EXFOR	TTY ref , EXFOR
^{15}O	2.037 min	β^+(99.9) EC(0.1)	$^{15}N(p , n)^{15}O$	6.6	230	60	
				6.5	190	64	
				6.45	182	65	
				6.41	142	66 A0313	(4-16) 66 A0313
				6.31	207	67 A0334	
			$^{14}N(d , n)^{15}O$	3.68	28	68	
				2.7	25	69	
				4.3	210	70 B0125	
				4.02	227	71 A0316	(1.08-12.28) 71 A0316
^{18}F	1.8295 h	β^+(96.9) EC(3.1)	$^{18}O(p , n)^{18}F$	7	40	74	(22) 225 A0195
				2.64	140	75	(3.76-22.37) 228 A0260
				3.02	220		
				3.37	190		
				3.86	280		
				5.2	630	76 A0235	
			$^{20}Ne(d, \alpha)^{18}F$	<24.7	11.6	79 A0175	(16.5) 231 B0176
			$^{16}O(^3He , p)^{18}F$	6.3	436	49	*Unavailable with a proton linac*
				>4.5	139	82	
				<13.9	135.9	83 B0151	
			$^{16}O(\alpha , p n)^{18}F$	≥40	250	84 P0121	(7.7-40.0) 83 B0151
							(55) 236 A0183
^{67}Ga	3.261 d	EC(100)	$^{68}Zn(p , 2n)^{67}Ga$	20	430	97 B0053	(22) 225 A0211

NUCLIDE	T1/2	DECAY [%]	NUCLEAR REACTION	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ ref, EXFOR	TTY ref , EXFOR
$^{68}Ge/^{68}Ga$	1.135 h	β^+(89) EC(11)	$^{69}Ga(p , 2n)^{68}Ge$	22	490	125 P0014	(22) 225 A0195
					360	111 B0050	(19.5) 240 R0034
			$^{71}Ga(p , 4n)^{68}Ge$	42.4	134	125 P0014	
$^{81}Rb/^{81m}Kr$	13 s	IT(100)	$Kr(p , xn)^{81}Rb$				(16-32) 248 A0185
							(10-43) 249
$^{82}Sr/^{82}Rb$	1.273 min	β^+(95) EC(5)	$^{85}Rb(p , 4n)^{82}Sr$	50	230	167 B0111	(37-70.8) 167 B0111
			$Rb,Mo(p , spall)^{82}Sr$		2.1	136	
					24.5	170	*These spallation reactions can be*
			$Rb(p , spall)^{82}Sr$		19.7	121	*produced only with energy above*
			$Y(p , spall)^{82}Sr$		2.59	121	*70 MeV .*
			$Mo(p , spall)^{82}Sr$		15,24.6	96	
^{111}In	2.807 h	EC(100)	$^{111}Cd(p , n)^{111}In$	>9.1	450	180 A0135	(8-12) 250 A0212
				>10.1	540	102 B0065	(10.4) 238 A0287
				>6.4	200	137 B0048	(22) 225 A0195
				11.8	696	181 A0001	
				13.1	530	182 P0019	
			$^{112}Cd(p , 2n)^{111}In$	>20.9	1070	181 A0001	(22) 225 A0195
				22.8	1000	182 P0019	
				<50	77.8	183	

NUCLIDE	T1/2	DECAY [%]	NUCLEAR REACTION	$E_{\sigma max}$ [MeV]	σ_{max} [mb]	σ ref, EXFOR	TTY ref, EXFOR
^{123}I	13.2 h	EC(100)	$^{124}Te(p , 2n)^{123}I$	14.60	1298	199 A0266	(10-23.5) 253
				22.26	1011.4	200 B0090	(12-25.8) 251 B0169
			$^{127}I(p , 5n)^{123}Xe\rightarrow$	53.5	448	205 A0265	
				57.5	372	206 A0161	
				57.2	292	207 R0007	
				55	269	192 B0081	
			$^{124}Xe(p , 2n)^{123}Cs\rightarrow$				
			$[^{123}Cs \xrightarrow{\beta^+ 6\ min} {}^{123}Xe]$ + $^{124}Xe(p , p\ n)^{123}Xe\rightarrow$			319 , 320	
^{201}Tl	3.046 h	EC(100)	$^{203}Tl(p , 3n)^{201}Pb\rightarrow$	27.4	1250	219 B0168	(22) 225 A0195
							(22) 235 A0168
			$^{205}Tl(p , 5n)^{201}Pb\rightarrow$	45.7	1020	219 B0168	
				45.7	880	220 A0180	

TAB. 2 **RADIONUCLIDES PRODUCED BY 11 MeV PROTONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{11}C	20.38 min	β^+(99.76) EC(0.24)	$^{14}N(p, \alpha)^{11}C$	3.81-13.96	7.49	176	41 R0026	(22) 225 A0195	*Diagnosis using PET*
				5-22	7.6	253	42 R0025	(4.49-22.36) 226 A0259	
				4.65-14.72	7.4	243	43 R0010	(5.83-17.2) 44	
				5.08	6.9	146	44 A0286	A0286	
^{13}N	9.965 min	β^+(99.8) EC(0.2)	$^{16}O(p, \alpha)^{13}N$	6.22-15.6	8.5	40	40 P0051	(22) 225 A0195	*Diagnosis using PET*
					11.4	50			
					14.6	40			
				6.66-15.77	8	51.3	61 C0202	(6.66-15.77) 61 C0202	
					11.04	53.6			
					14.73	30.5			
				9.7-15	10.9	79	35 P0045		
					12.5	41			
					14.7	50			
				6.7-9.27	7.99	139	56 B0175		
				6.51-7.71	>7.71	13.8	57		

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{15}O	2.037 min	β^+(99.9) EC(0.1)	$^{15}N(p,n)^{15}O$	5.5-13.5	6.6	230	60		*Diagnosis using PET*
				3.95-9	6.5	190	64		
				5.8-8.6	6.45	182	65		
				3.72	6.41	142	66 A0313	(4-16) 66 A0313	
^{18}F	1.8295 h	β^+(96.9) EC(3.1)	$^{18}O(p,n)^{18}F$	6-13	7	40	74	(22) 225 A0195	*Diagnosis using PET*
				2.5-3.9	2.64	140	75	(3.76-22.37) 228	
					3.02	220		A0260	
					3.37	190			
					3.86	280			
				2.3-14.7	5.2	630	76 A0235		
				7-13.5	<7	95	77		
^{51}Cr	27.04 d	EC(100)	$^{51}V(p,n)^{51}Cr$	6.7-13.3	10	540	101 B0045	(22) 225 A0195	*Diagnosis using SPECT. Non-absorbable markers and hematology tracers.*
				3.1-10.4	10.4	645	102 B0065		
				11.3-44.7	11.3	834	103 B0027		
				5-11	11	595	104 B0066		
				7-15	11	729	105 P0021		
^{89}Zr	3.268 d	EC(77) β^+(23)	$^{89}Y(p,n)^{89}Zr$	12		750	99 B0052	(22) 225 A0195	*Of potential application in therapy*
				7, 8.1		254,323	106 B0093		
				3.9-44.2	12.8	668	177 B0018		
				5-85	12	720	172 B0001		

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{111}In	2.807 d	EC(100)	$^{111}Cd(p, n)^{111}In$	6.1-9.1	>9.1	450	180 A0135	(8-12) 250 A0212	*Diagnosis using SPECT.*
				2.1-10.1	>10.1	540	102 B0065	(10.4) 238 A0287	*The optimum energy range*
				3.04-6.4	>6.4	200	137 B0048	(22) 225 A0195	*of this reaction is 15-4*
				4.3-20.9	11.8	696	181 A0001		*MeV. Lower yields are*
				4.3-14.7	13.1	530	185 P0019		*obtained with 11 MeV*
				13.8-44.44	<13.8	560.7	186 A0335		*protons.*

TAB. 3 **RADIONUCLIDES PRODUCED BY 30 MeV PROTONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{34m}Cl	32.23 min	IT(44.5) EC(1.5) β^+(54)	$^{35}Cl(p,pn)^{34m}Cl$	10-45 21.5-45		 120	90 86 B0049		*Of limited use.*
^{38}K	7.636 min	β^+(100)	$^{40}Ar(p\ ,\ 3n)^{38}K$					256	*Myocard. perf. using PET*
$^{62}Zn/^{62}Cu$	9.74 min	β^+(97) EC(3)	$^{63}Cu(p\ ,2n)^{62}Zn$	17-99.2 16-33 15.2-31.8 16.1-69.8 14-32.4	27 27 26.2 24 24	140 95 218 64 66	129 B0054 130 B0074 131 B0017 133 134 A0333	(22) 225 A0195	*Diagnosis using PET.*
^{67}Ga	3.261 d	EC(100)	$^{68}Zn(p\ ,2n)^{67}Ga$	15-85 21.5 400	20	430 780 2.34	97 B0053 111 B0050 138 B0024	(22) 225 A0195	*Diagnosis using SPECT.*
$^{68}Ge/^{68}Ga$	1.135 h	β^+(89) EC(11)	$^{69}Ga(p\ ,2n)^{68}Ge$	13-55 21.5	22	490 360	125 P0014 111 B0050	(22) 225 A0195 (19.5) 240 R0034	*Diagnosis using PET .*
^{75}Se	119.77 d	EC(100)	$^{75}As(p\ ,\ n)^{75}Se$	1.7-5.7 3.6-8.1 400 540,593	>5.7 7-8	251 477 1.40 1.88	107,109 B0068 106 B0093 138 B0024 121 D0029	(6.5-21.7) 241 A0022 (10.4) 238 A0287 (22) 225 A0195 (22) 235 A0168	*Diagnosis using SPECT.*

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{75}Br	1.62 h	β^+(71) EC(29)	$^{76}Se(p, 2n)^{75}Br$	16.5-34.5	21.4	520	155 A0253	(16-35) 245	*Diagnosis using PET.*
^{77}Br	2.37650 d	EC(99.3) β^+(0.3)	$^{78}Se(p, 2n)^{77}Br$	13.68-24.58	22	800	160 A0255		*Limited diagnostic use because of the high dose imparted. Potential applications in therapy.*
$^{81}Rb/^{81m}Kr$	13 s	IT(100)	$Kr(p, xn)^{81}Rb$	12-45	27			(16-32) 248 A0186 (10-43) 249	*Diagnosis using SPECT.*
$^{87}Y/^{87m}Sr$	2.795 h	IT(99.3) EC(0.3)	$^{88}Sr(p, 2n)^{87}Y$	15-33	25	1210	171 B0069	(22) 225 A0195	*Diagnosis using SPECT.*
^{111}In	2.807 d	EC(100)	$^{111}Cd(p, n)^{111}In$	6.1-9.1	>9.1	450	180 A0135	(8-12) 250 A0212	*Diagnosis using SPECT.*
				2.1-10.1	>10.1	540	102 B0065	(10.4) 238 A0287	
				3.04-6.4	>6.4	200	137 B0048	(22) 225 A0195	
				4.3-20.9	11.8	696	181 A0001		
				4.3-14.7	13.1	530	182 P0019		
				13.8-44.44	<13.8	560.7	186 A0335		
				12		810	99 B0052		
			$^{112}Cd(p, 2n)^{111}In$	13.2-20.9	>20.9	1070	181 A0001	(22) 225 A0195	
				9.4-37.4	22.8	1000	182 P0019		

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{123}I	13.2 h	EC(100)	$^{124}Te(p , 2n)^{123}I$ $^{124}Xe(p,2n)^{123}Cs \rightarrow ^{123}Xe$ + $^{124}Xe(p , p n)^{123}Xe$	12.33-29.27 12.2-29.18	14.60 22.26	1298 1011.4	199 A0266 200 B0090	(10.23.5) 253 (12-25.8) 251 B0169 (22) 225 A0195 319 , 320	*Diagnosis using SPECT.*
^{124}I	4.18 d	EC(77) β^+(23)	$^{124}Te(p , n)^{124}I$	9.6-29.3 9.95-29.2	12.41 14.54	521 456	199 A0266 200 B0090	(12-25.8) 251 B0169	*Potential applications in therapy.*
^{127}Xe	1.153 min	EC(100)	$^{127}I(p , n)^{127}Xe$	3-24.8 20-85	9.92 <20	471 68	166 B0056 192 B0081	(22) 225 A0195 (22) 235 A0168	*Lung ventilation using SPECT.*
$^{169m,g}Yb$	m:46 s g:32.022 d	IT(100) EC(100)	$^{169}Tm(p , n)^{169}Yb$	3.3-43.9	10.5	163	177 B0018		*Limited use in brain scintigraphy*
^{201}Tl	3.046 d	EC(100)	$^{203}Tl(p , 3n)^{201}Pb \rightarrow ^{201}Tl$	18.3-41.6	27.4	1250	219 B0168	(22) 225 A0195 (22) 235 A0168	*Diagnosis using SPECT.*

TAB. 4 **RADIONUCLIDES PRODUCED BY 55 MeV PROTONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
$^{44}Ti/^{44}Sc$	3.927 h	β^+(94) EC(6)	$^{45}Sc(p, 2n)^{44}Ti$	15-85	32	65	97 B0053	(14.5-22.3) 234 A0021 (22) 235 A0168 (22) 225 A0195	*Diagnosis using PET in bone diseases*
$^{68}Ge/^{68}Ga$	1.135 h	β^+(89) EC(11)	$^{71}Ga(p, 4n)^{68}Ge$	37-55	42.4	134	125 P0014		*Diagnosis using PET.*
^{73}Se	7.15 h	β^+(66) EC(34)	$^{75}As(p, 3n)^{73}Se$	25-50 25-45 400 540 ,593	35 33 , 35	350 300 4.32 2.8,2.67	148 150 , 151 138 B0024 121 D0029	(24.5-44.5) 150	*Diagnosis using PET.*
^{77}Kr	1.24 h	β^+(87) EC(13)	$^{79}Br(p, 3n)^{77}Kr$	24.6-64.7 23-51 25-85	35.7 36 35	178 150 260	163 A0185 159 164 B0171	(65) 247 R0030	*No more used in diagnostics; it is employed as generator of ^{77}Br.*
$^{82}Sr/^{82}Rb$	1.273 min	β^+(95) EC(5)	$^{85}Rb(p, 4n)^{82}Sr$	33.7-69.9	50	230	167 B0111	(37-70.8) 167 B0111	*Diagnosis using PET.*
$^{118}Te/^{118}Sb$	3.6 min	β^+(74) EC(26)	$^{121}Sb(p, 4n)^{118}Te$	27-90	44	700	190		*Limited use in PET applications.*

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
$^{178}W/^{178}Ta$	9.31 min	EC(99.8) β^+(1.1)	$^{181}Ta(p, 4n)^{178}W$	28-44.2	36.3	772	213 B0038		*Ventricular functionality by means of a proportional chamber*
$^{195m,g}Hg/^{195m}Au$	30.5 s	IT(100)	$^{197}Au(p, 3n)^{195m,g}Hg$	20-42	27		27	27	*SPECT angiography.*
^{201}Tl	3.046 d	EC(100)	$^{203}Tl(p, 3n)^{201}Pb \rightarrow ^{201}Tl$	18.3-41.6	27.4	1250	219 B0168	(22) 225 A0195 (22) 235 A0168	*Diagnosis using SPECT.*
			$^{205}Tl(p, 5n)^{201}Pb \rightarrow ^{201}Tl$	34.9-59	45.7	1020	219 B0168		
				34-58.7	45.7	880	220 A0180		

TAB. 5 **RADIONUCLIDES PRODUCED BY 70 MeV PROTONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
$^{52}Fe/^{52m}Mn$	21.1 min	β^+(97) EC(1.25) IT(1.75)	$^{55}Mn(p, 4n)^{52}Fe$	40-73	54	1.4			*Heart diagnosis using PET.*
$^{122}Xe/^{122}I$	3.62 min	β^+(77) EC(23)	$^{127}I(p, 6n)^{122}Xe$	55-85 50-67.5	70 >67.5	114 197	192 B0081 193 , 194		*Of potential use in PET diagnostics.*
^{123}I	13.2 h	EC(100)	$^{127}I(p,5n)^{123}Xe \rightarrow ^{123}I$	45.4-62.4 46.4-75.6 38.1-159.1 45-85	53.5 57.5 57.2 55	484 372 292 269	205 A0265 206 A0161 207 R0007 192 B0081		*Diagnosis using SPECT.*
$^{128}Ba/^{128}Cs$	3.62 min	β^+(69) EC(31)	$^{133}Cs(p, 6n)^{128}Ba$	48-68	65	290	212 A0320		*Ventricular perfusion using PET.*

TAB. 6 **RADIONUCLIDES PRODUCED BY 6 MeV DEUTERONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{11}C	20.38 min	β^+(99.76) EC(0.24)	$^{10}B(d,n)^{11}C$	1.5-12	5.3	175	45		*Diagnosis using PET.*
				0.5-3.2	2.3	270	46 D0026		
				2.93-11	<2.93	139	47 A0166		
				7-16.01	9.2	101	37 A0330		
^{13}N	9.995 min	β^+(99.8) EC(0.2)	$^{12}C(d,n)^{13}N$	2-20	5	110	58		*Diagnosis using PET.*
				0.4-3	>3	260	62		
				1.95-4.5	2.30	200	63 P0130		
					3.98	153			
					>4.5	162			
^{15}O	2.037 min	β^+(99.9) EC(0.1)	$^{14}N(d,n)^{15}O$	2-5	3.68	28	68		*Diagnosis using PET.*
				0.9-5.3	2.7	25	27		
				0.6-14.35	4.3	210	70 B0125		
				1.08-12.28	4.02	227	71 A0316	(1.08-12.28) 71 A0316	
				0.5-3.2	>3.2	300	46 D0026		

TAB. 7 **RADIONUCLIDES PRODUCED BY 15 MeV DEUTERONS**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{18}F	1.8295 h	β^+(96.9) EC(3.1)	$^{20}Ne(d, \alpha)^{18}F$	24.7-76	<24.7	11.6	79 A0175	(16.5) 231 B0176	*Diagnosis using PET.*
^{38}K	7.636 min	β^+(100)	$^{40}Ca(d, \alpha)^{38}K$	1.9-5.5	>5.5	4.77	93		*Myocardial perfusion using PET.*
^{186}Re	3.777 d	β^-(92.2) EC(7.8)	$^{186}W(d, 2n)^{186}Re$	5.94-14 7-15.7 7-16.7	≥14 12.1 15.2	365 434 647	216 P0115 217 S0014 115 A0202	(8-12) 250 A0212	*Therapy of brain cysts, as colloid.*

TAB.8 **RADIONUCLIDES PRODUCED BY 30 MeV α-PARTICLES**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{30}P	2.498 min	β^+(99.9) EC(0.1)	$^{27}Al(\alpha, n)^{30}P$	4.86-13.05	10.1	41	87 A0181		*PET.*
^{34m}Cl	32.23 min	IT(44.5) β^+(54) EC(1.5)	$^{31}P(\alpha, n)^{34m}Cl$	6.5	7	28	92		*Limited used*
^{43}K	22.3 h	β^-(100)	$^{40}Ar(\alpha, p)^{43}K$	11.6-36.7	18	68	95 P0125		*Replaced by ^{201}Tl.*
$^{68}Ge/^{68}Ga$	1.135 h	β^+(89) EC(11)	$^{nat}Zn(\alpha, xn)^{68}Ge$	20-38	31	150	144		*Diagnosis using PET.*
^{77}Br	2.3765 d	EC(99.26)	$^{75}As(\alpha, 2n)^{77}Br$	15-27.5	21.76	850	162 A0346	(15-29) 162 A0346	*Of potential use in therapy*
				13.8-28.1	26.3	803	161 A0243	(28) 243 R0032	
				20-40	25	950	159 A0184	(20-40) 159 A0184	
^{111}In	2.807 d	EC(100)	$^{109}Ag(\alpha, 2n)^{111}In$	15-36	26	1200	148		*Diagnosis using SPECT.*
				20.4-53.9	30.3	872	187 D0051		
				14.1-18.4	>18.4	209	188 P0094		
^{211}At	7.214 h	α(41.7) EC(58.3)	$^{209}Bi(\alpha, 2n)^{211}At$	30.6-43.3	31	980	222 A0246		*Therapy by monoclonal antibodies.*
				21.1-29.2	>29.2	906.5	223 A0249		

TAB. 9 **RADIONUCLIDES PRODUCED BY 55 MeV α-PARTICLES**

NUCL.	T1/2	DECAY [%]	NUCLEAR REACTION	RANGE [MeV]	$E_{\sigma M}$ [MeV]	σ_M [mb]	σ ref, EXFOR	TTY ref, EXFOR	APPLICATIONS
^{18}F	1.8295 h	β^+(96.9) EC(3.1)	$^{16}O(\alpha, p\,n)^{18}F$	21-40	≥40	250	84 P0121	(55) 236 A0183	*Diagnosis using PET.*
^{75}Br	1.62 h	β^+(75.5) EC(24.5)	$^{75}As(\alpha, 4n)^{75}Br$	40.3-71.7 42.6-106	55 53.8	186 268	155 A0253 157 A0232		*Of limited use in PET diagnostics*

5. Conclusions

Proton and deuteron energies below about 10 MeV and 5 MeV respectively do not allow efficient production of radionuclides of medical interest, although limited amounts of the positron emitters (^{11}C, ^{13}N, ^{15}O and ^{18}F) can probably be obtained also at these lower energies. A Belgian company, Ion Beam Applications, is marketing a small 3 MeV deuteron cyclotron, to be used as "generator" of the ultra-short lived ^{15}O nuclide. A linac accelerating protons to 11 MeV can efficiently produce the four positron emitters plus ^{51}Cr, ^{89}Zr and the clinically important ^{111}In, although with a yield not optimized.

In addition to the above radionuclides, 30 MeV protons allow the production of a number of radionuclides relevant to SPECT diagnostics: ^{67}Ga, the generator $^{81}Rb/^{81m}Kr$, ^{111}In, ^{201}Tl and ^{123}I by the reactions $^{124}Te(p,2n)$ and $^{124}Xe(p,2n)^{123}Cs \rightarrow ^{123}Xe \rightarrow ^{123}I$, plus the β^+ generator $^{68}Ge/^{68}Ga$. Of the two production routes leading to ^{123}I, the former yields a product with a significantly high level of the contaminant ^{124}I. The latter gives ^{123}I of higher purity but on the other hand the target material is much more expensive and the irradiation system and radiochemical processing are much more complex. Other less common radioisotopes such as ^{38}K, $^{62}Zn/^{62}Cu$, ^{75}Se, ^{75}Br, $^{87}Y/^{87m}Sr$, ^{127}Xe and $^{169m,g}Yb$ can also be produced, along with ^{77}Br and ^{124}I which have a potential use for future applications in therapy.

55 MeV protons can be employed to produce the generator $^{82}Sr/^{82}Rb$ and ^{201}Tl by employing the reaction $^{205}Tl(p,5n)^{201}Pb \rightarrow ^{201}Tl$. In addition, a number of radionuclides of limited use can be produced, such as ^{73}Se and ^{77}Kr as well as generators, both β^+ emitters - $^{44}Ti/^{44}Sc$, $^{68}Ge/^{68}Ga$ via $^{71}Ga(p,4n)$ and $^{118}Te/^{118}Sb$ - and single photon emitters - $^{178}W/^{178}Ta$ and $^{195m,g}Hg/^{195m}Au$.

70 MeV protons allow the production of the generators $^{52}Fe/^{52m}Mn$ and high purity ^{123}I via the reaction $^{127}I(p,5n)^{123}Xe \rightarrow ^{123}I$, besides radionuclides of more limited use such as $^{122}Xe/^{122}I$ and $^{128}Ba/^{128}Cs$.

The availability of a deuteron beam in addition to protons does not add any significant production capability, except the possibility of producing ^{18}F via the reaction $^{20}Ne(d,\alpha)$ at energies of about 15-20 MeV. On the other hand, if a proton beam is not available, a number of medically useful radionuclides can be made available via deuteron induced reactions, "in primis" the physiological positron emitters.

The only interesting possibility offered by α-particles with energies up to 30 MeV is the production of ^{211}At via the reaction $^{209}Bi(\alpha,2n)$. This radionuclide has a potential application in labelling monoclonal antibodies for metabolic therapy. Other radioisotopes can be produced by proton induced reactions at energies below 30 MeV. Similarly, there are no production routes where α-particles with energy greater than 30 MeV offer some advantages over protons.

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Appendix. Basic formulae for radionuclide production

The "thin-target-yield" (tty) is a fundamental quantity for the computation of both yield and radionuclidic purity of accelerator produced radioisotopes (see ref. [7], page 99). A common definition of "thin-target" is a target in which the energy loss is negligible with respect to the beam energy:

$$\frac{\Delta E}{E} \cong 0.01 - 0.05$$

In the "thin-target" calculations, the particle energy E is assumed to be the mean value of the energy in the target itself. In case of either monoisotopic or highly enriched targets the tty is:

$$tty = \frac{\lambda \cdot (S \cdot \rho) \cdot \left(\frac{N_{av}}{M}\right) \cdot \sigma(E)}{Q \cdot \left[\left(\frac{dE}{dX}\right)_E \cdot \Delta X\right]} = y(E) \qquad \left[Bq \cdot C^{-1} \cdot MeV^{-1}\right]$$

In which:

λ = decay constant		$[s^{-1}]$
$S\rho = \Delta x$ =mass target thickness		$[g\ cm^{-2}]$
S = geometrical target thickness		[cm]
ρ = target density		$[g\ cm^{-3}]$
N_{av}= Avogadro number		$[at\ mol^{-1}]$
M = target atomic mass		$[g\ mol^{-1}]$
$(S\rho)(N_{av}/M) = N$		$[at\ cm^{-2}]$
$\sigma(E)$ = reaction cross-section at energy E		$[cm^2]$
Q = total integrated charge		[C]
$(dE/dx)_E = S(E)$ = target stopping power at energy		$[MeV\ g^{-1}\ cm^2]$

$E=(E^{in}+E^{out})/2$ where:

E^{in}= mean energy of the particles incident on the target

E^{out}= mean energy of the particles emerging from the target

$(dE/dx)_E \Delta x = \Delta E$ = "thin-target" energy loss [MeV] at energy E [MeV]

In case of non-pure target elements (alloys, stoichiometric or non-stoichiometric compounds, mixtures of known composition, etc), the total stopping power is:

$$S_T(E) = \sum_1^k w_i \cdot S_i(E)$$

where:

$S_i(E)$ is the stopping power of i-th target element at energy E

w_i is the weight fraction of i-th target element

The range for an energy loss $\Delta E=E_0-E$, where E_0 is the incident energy is:

$$R_T = \int_{E_0}^{E} \frac{dE}{S_T(E)} \qquad \left[g\ cm^{-2}\right]$$

In case of a multiisotopic target:

$$tty = \frac{\lambda N}{Q \cdot \Delta E} \sum_i^n f_i \cdot \sigma_i(E) = y(E)$$

In which:

f_i = isotopic fraction ($\Sigma_i f_i=1$)	
$\sigma_i(E)$ = cross section of reaction induced on i-th target isotope at energy E	[cm^2]
$M = \Sigma_i f_i M_i$ = target atomic mass	[g mol^{-1}]
M_i = atomic mass of i-th target isotope	[g mol^{-1}]

The tty is computed at the "End Of an Instantaneous Bombardament" (EOIB) and has the analytical meaning of the slope (at the beginning of irradiation) of the growing curve of a radionuclide vs. irradiation time τ, per unit particle energy loss:

$$y^{EOIB}(E) = \left[\frac{d}{d\tau}\left(\frac{d(a/I)}{dE}\right)\right]_{\tau=0} \qquad \left[Bq\ C^{-1}\ MeV^{-1}\right]$$

In which:

a = activity of the product	[Bq]
I = beam intensity	[A]
τ = irradiation time	[s]
dE = differential thin-target energy loss	[MeV]
a/I = h = activity produced per beam intensity unit	[Bq A^{-1}]

In the simple case of first order decay, the tty is calculated from the experimental data by the conventional equation:

$$y^{EOIB}(E) = \frac{c_\gamma}{(\alpha_\gamma \varepsilon_\gamma \Delta) Q \cdot \Delta E}\left(\frac{\lambda\Delta}{1-e^{-\lambda\Delta}}\right)\left(\frac{\lambda\tau}{1-e^{-\lambda\tau}}\right)\cdot e^{\lambda t} = \frac{c_\gamma}{(\alpha_\gamma \varepsilon_\gamma \Delta)\cdot Q \cdot \Delta E} D(\Delta)\cdot G(\tau) e^{\lambda t}$$

In which:

c_γ = net counts of γ-emission of energy E_γ at time t	[counts]
t = waiting time from EOB to the beginning of the measurement	[s]
α_γ = abundance of γ-emission of energy E_γ	[γ emitted· dis^{-1}]
Δ = counting time	[s]
τ = irradiation time	[s]
ε_γ = total efficiency at energy E_γ	[γ detected · γ $emitted^{-1}$]
$D(\Delta)$ = correction for decay during measurement	
$G(\tau)$ = correction for decay during irradiation	
$e^{\lambda t}$ = correction for decay from EOB to the beginning of measurement	

In the case of a radionuclide emitting more than one γ line, the mean value of the tty is calculated as a weighted average. More complex equations must be used in cases when either metastable levels or radioactive chains are induced in the target.

It is possible to calculate the activity h (per intensity unit) produced at the end of a bombardment (EOB) of generic duration τ, by integration of the following differential equation:

$$\dot{h}(E,\tau) = y^{EOIB}(E) - \lambda \cdot h(E,\tau)$$

which leads to:

$$h^{EOB}(E,\tau) = \frac{y^{EOIB}(E)}{\lambda}\left(1-e^{-\lambda\tau}\right) = h^{EOSB}(E)\cdot F(\tau) \qquad \left[Bq\ A^{-1}\ MeV^{-1}\right]$$

where:

h^{EOSB} = saturation activity per intensity unit at energy E, at EOSB	[activity/current]
$F(\tau)$ = growing factor	[no-dimensions]

It is relevant to remember that in the case of short-lived radioisotopes, from a practical point of view the saturation activity per intensity unit, h^{EOSB}, is generally considered a more relevant parameter than y^{EOIB}.

The Thick-Target Yield (TTY) is, by definition:

$$TTY^{EOIB} = Y^{EOIB}(E,\Delta E) = \int_{E^{out}}^{E^{in}} y^{EOIB}(E)dE = \frac{\lambda\left(\frac{N_{av}}{M}\right)}{Q}\int_{E-\Delta E}^{E}\frac{\sigma(E)}{S(E)}\,dE \qquad \left[Bq\ C^{-1}\right]$$

in which: ΔE = thick-target energy loss [MeV]
$E^{out} = E^{in} - \Delta E$ [MeV]

This definition holds at both EOIB and EOB, the integration of both $y^{EOIB}(E)$ and $h^{EOB}(E,\tau)$ vs. energy being possible:

$$H^{EOB} \equiv H^{EOB}(E,\Delta E,\tau) = \int_{E^{out}}^{E^{in}} h^{EOB}(E,\tau)\,dE \qquad \left[Bq\ A^{-1}\right]$$

The TTY of a nuclear reaction can be calculated by numerical and sometimes analytical integration of the tty, as a function of both incident particle energy E^{in} in a thick-target and particle energy loss ΔE in the target itself.

Finally, the activity which is theoretically produced at an incident energy E, with a beam intensity I, after an irradiation of duration τ on a thick-target inducing an energy loss ΔE, is given by:

$$\text{activity} = H^{EOB}(E,\ \Delta E,\ \tau)\cdot I \qquad [Bq]$$

The Thick Target Yield can therefore be calculated from a tty function determined experimentally or calculated theoretically. The data of experimental yield are often lower than the theoretical value, in particular if obtained with high beam currents. The difference between experimental and theoretical yields becomes larger with increasing beam current and target thickness. This phenomenon is due to the evaporation of the produced radionuclide, to the radiation damage of the target and to beam inhomogeneity, i.e. to phenomena related to the high power density deposited in the target [21, 22].

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