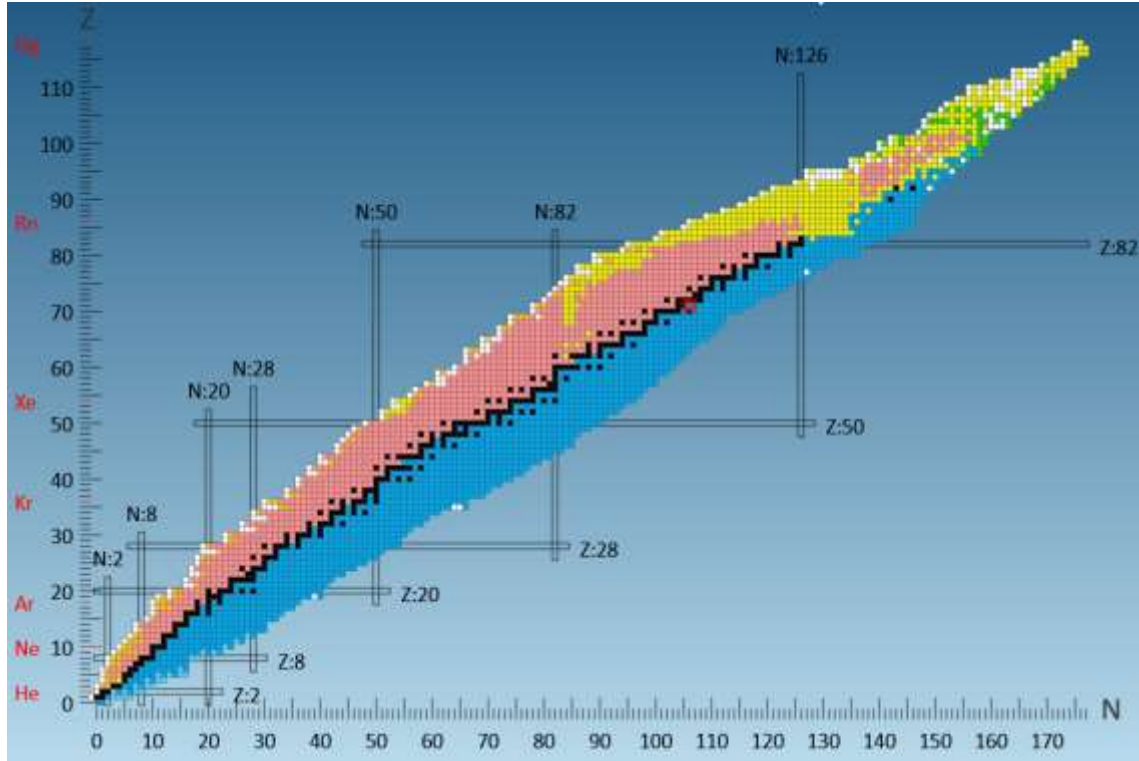


(Cyclotron-produced)

Radionuclides for medicine

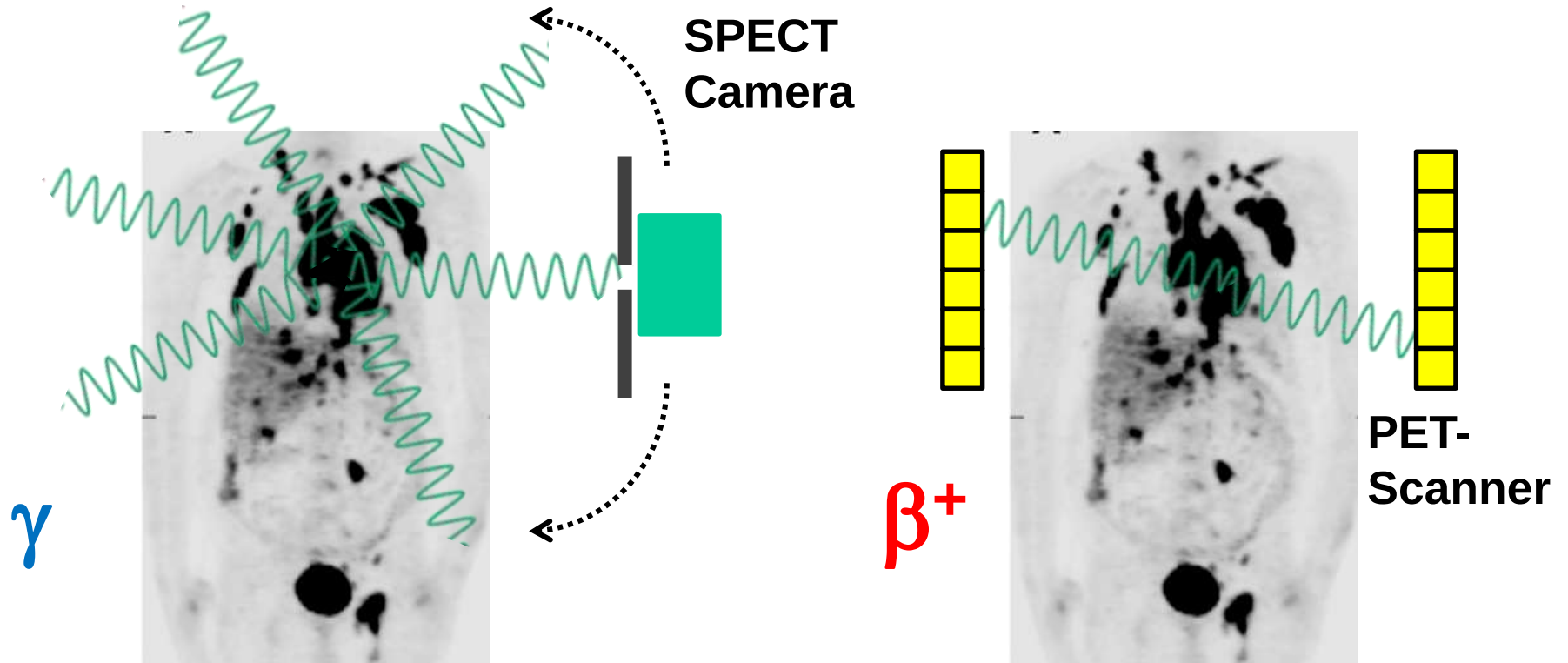


Ulli Köster

ILL Grenoble, France



The alphabet of nuclear medicine



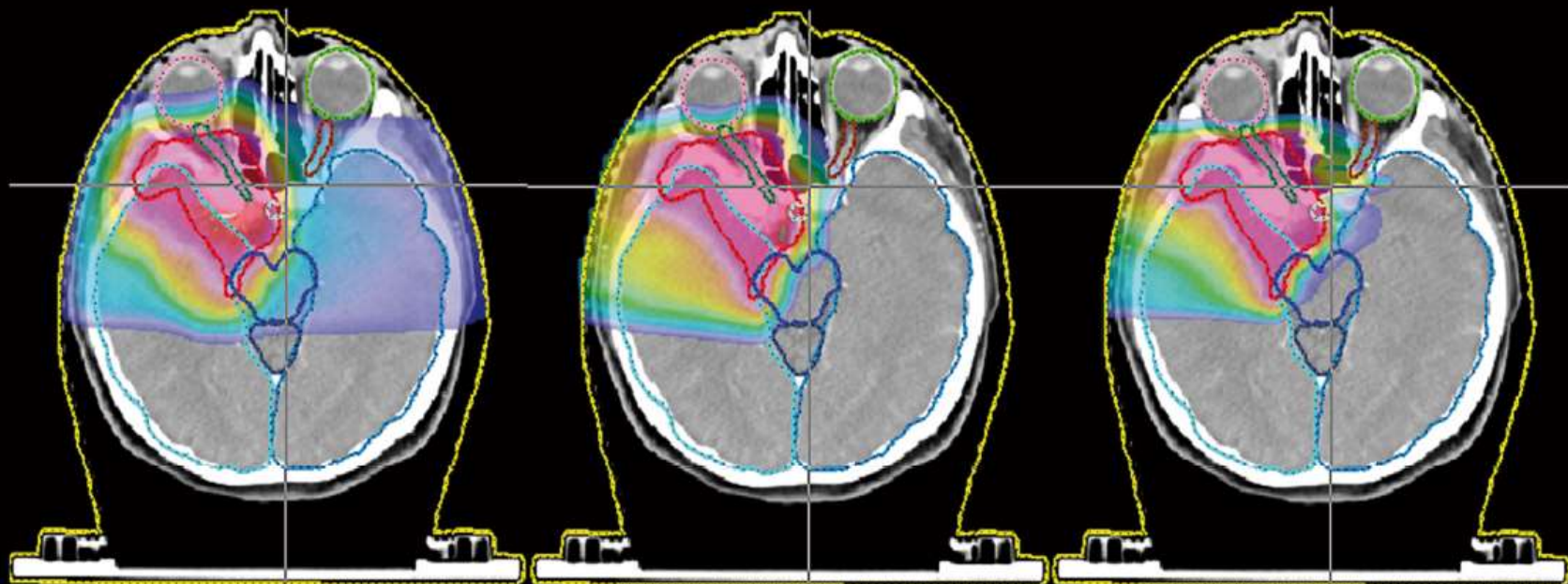
Progress in cancer treatment



IMXT

protons

carbon ions



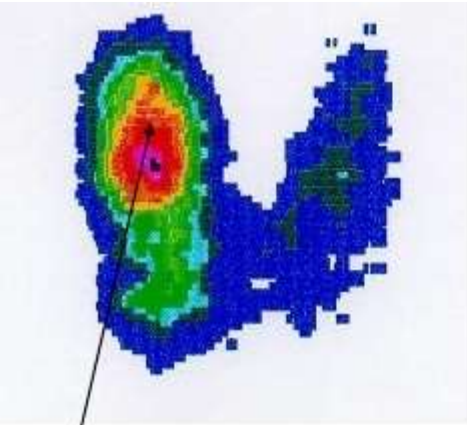
52.5
GyE

5.0
GyE

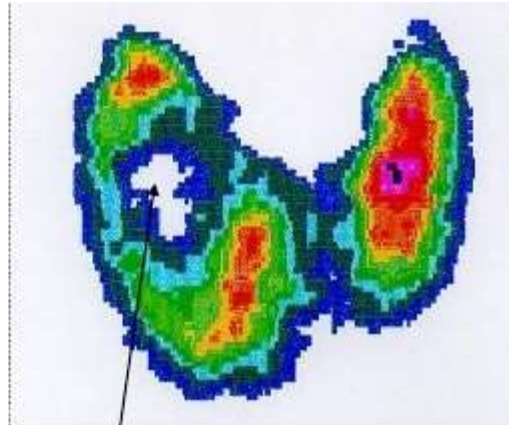
How can one treat such patients?



Thyroid scintigraphy and therapy



Hot nodule – Rt. lobe



Cold nodule – Rt. lobe

I^{123}

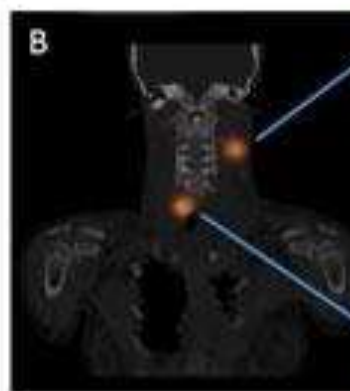
13.2 h

ϵ
no β^+
 γ 159



I^{123} -I Diagnostic
Whole Body
Scan

I^{123} -I DxWBS with
SPECT-CT



I^{131}

8.0 d

β^- 1.0, 1.8,...
 γ 364, 637...

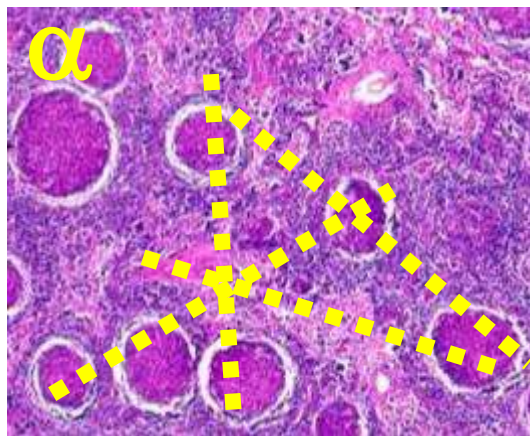
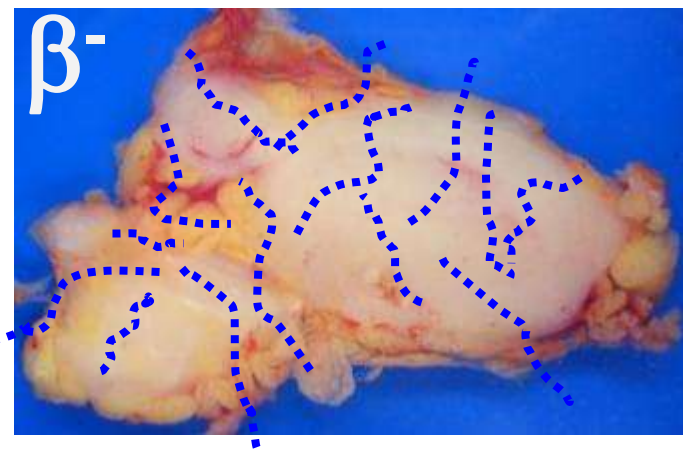
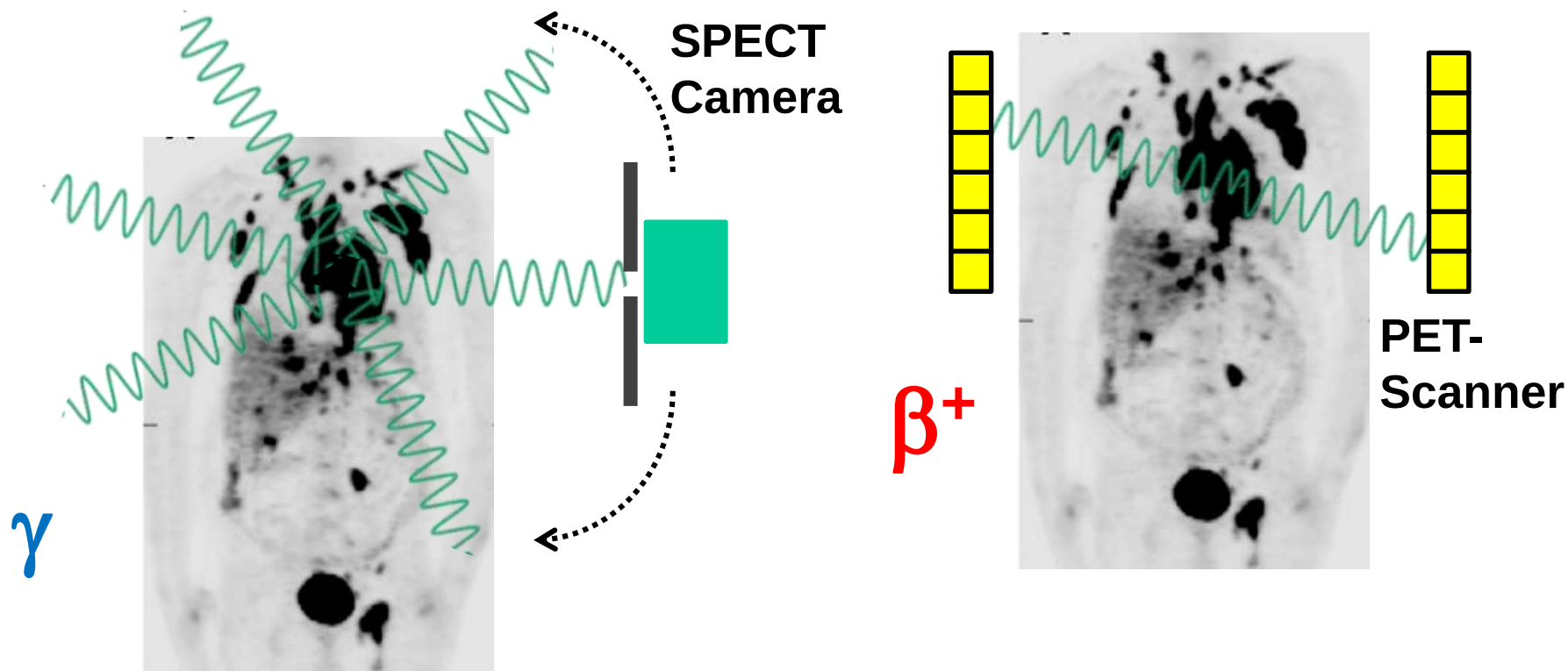
I^{123} -, I^{131} - or $^{99m}TcO_4^-$ for scintigraphy

I^{131} - for therapy

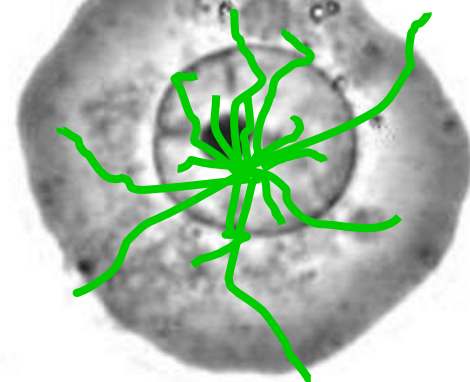


(Papillary) thyroid cancer has the **highest survival** of all malignant cancers!

The Nuclear Medicine Alphabet



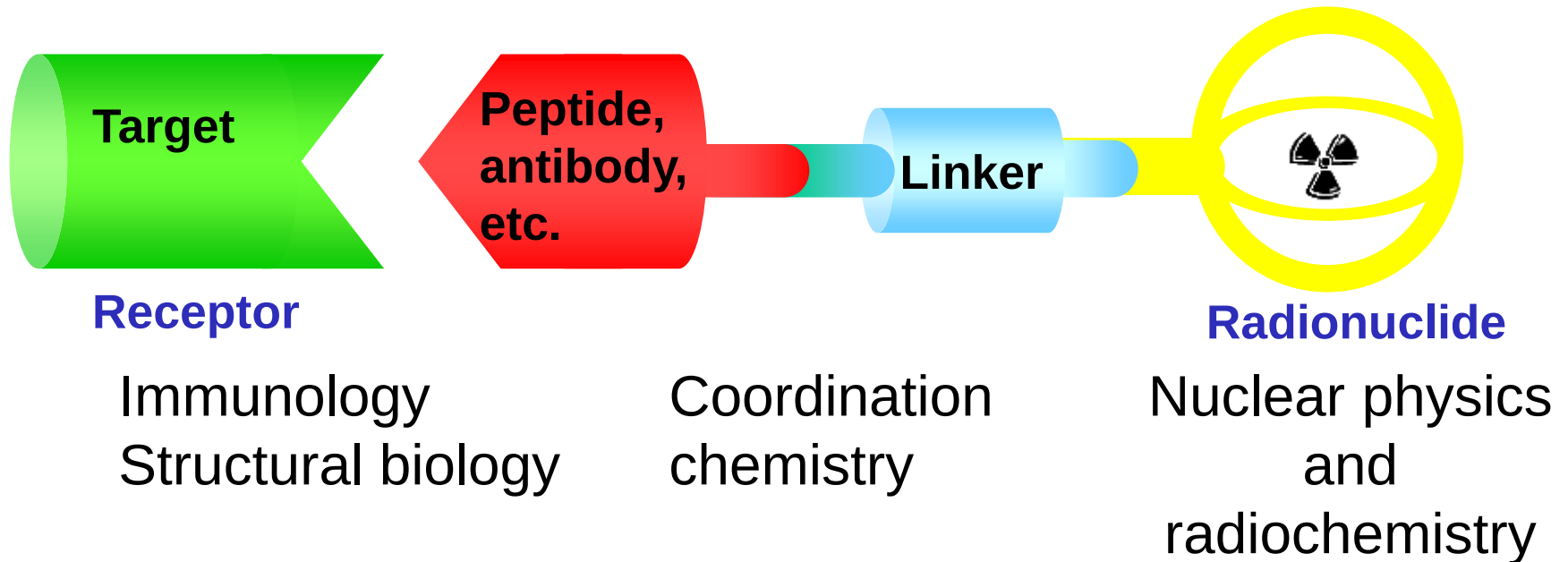
Auger- e^-



Multidisciplinary collaboration to fight cancer

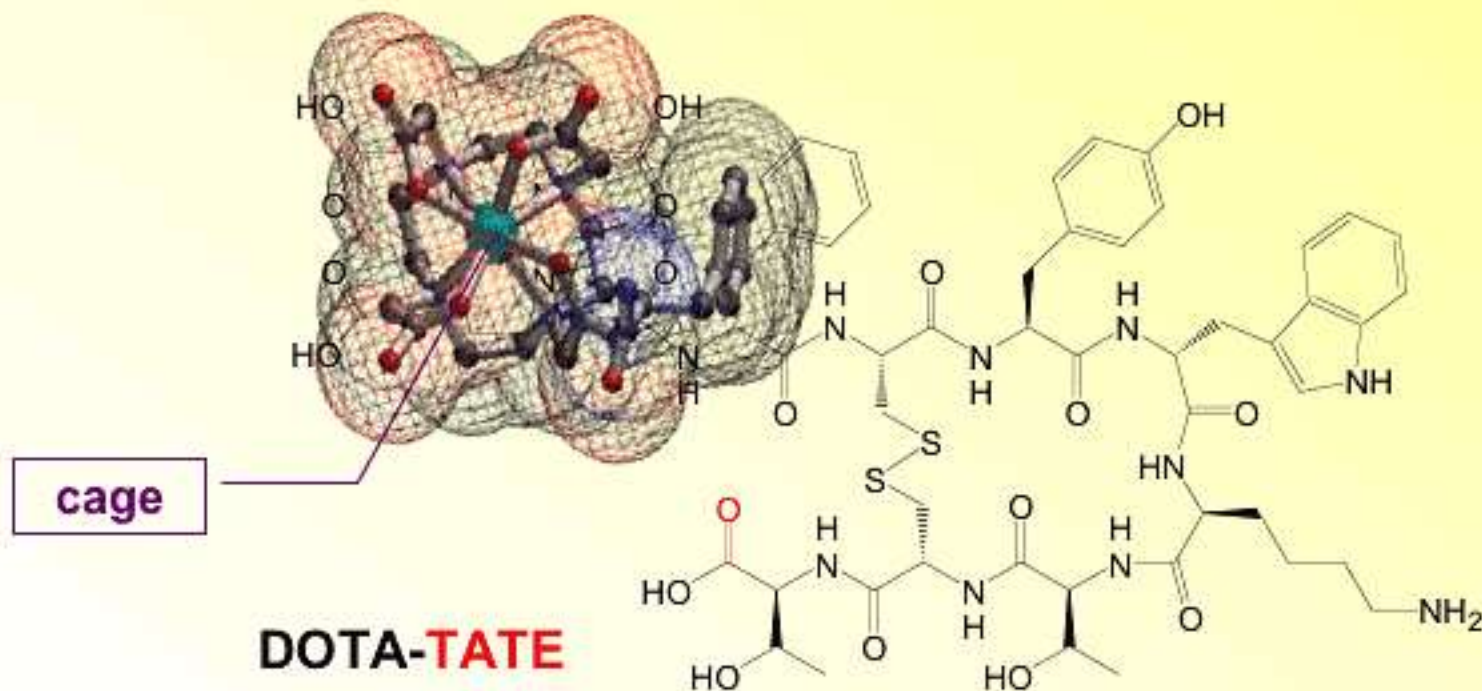
Targeted Radionuclide Therapy (TRT)

Radioligand Therapy (RLT)



Nuclear medicine and medical physics

Structural Formula of DOTA-TOC/TATE



1,4,7,10-tetraazacyclododecantetraacetate

^{111}In

^{90}Y

^{67}Ga

^{177}Lu

^{68}Ga

^{213}Bi

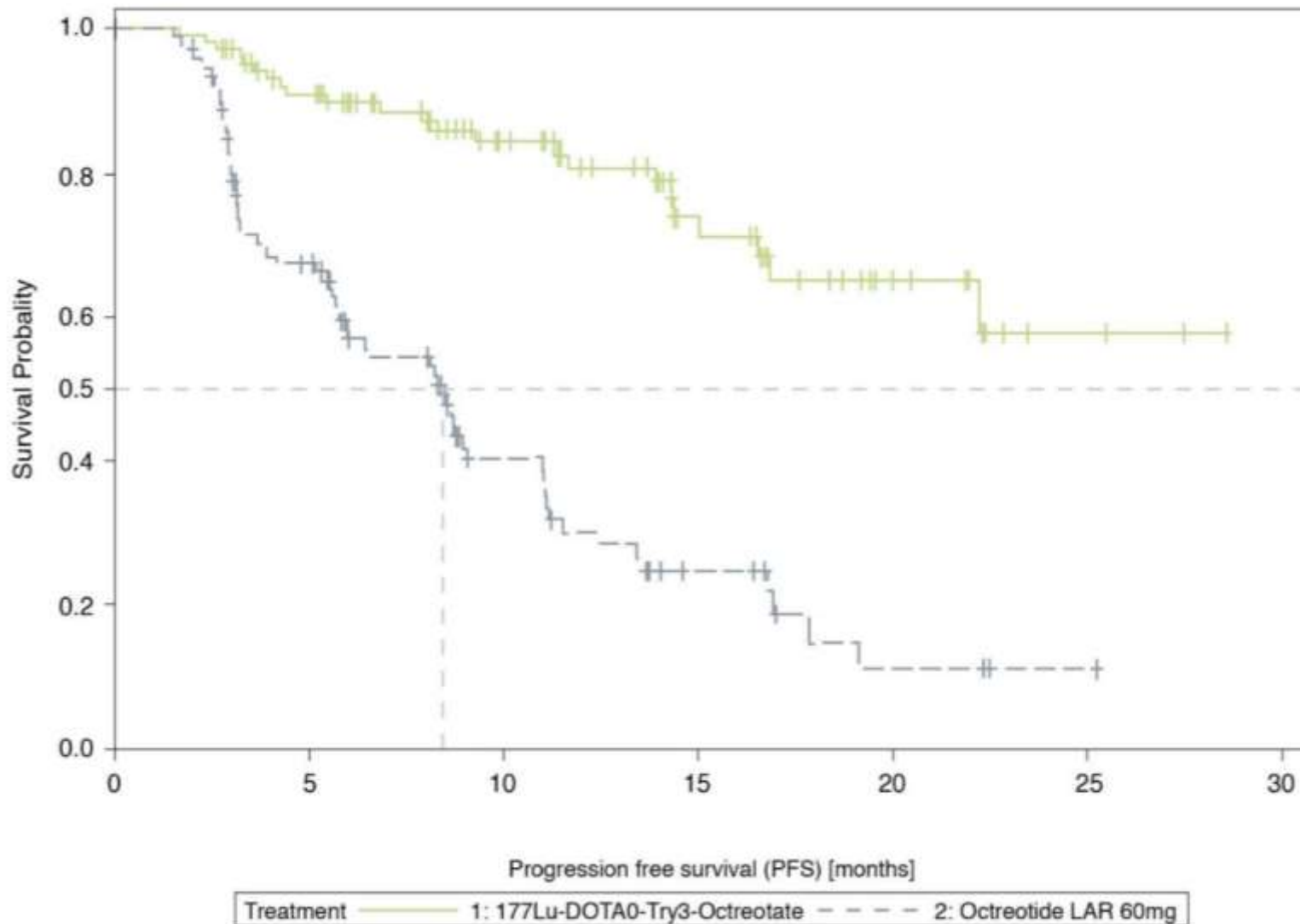
$$\text{IC}_{50} (\text{Y}^{\text{III}}) = 1.6 \pm 0.4 \text{ nM}$$

Helmut Maecke, EANM-2007.

^{177}Lu -Peptide Receptor Radionuclide Therapy of midgut neuroendocrine tumors



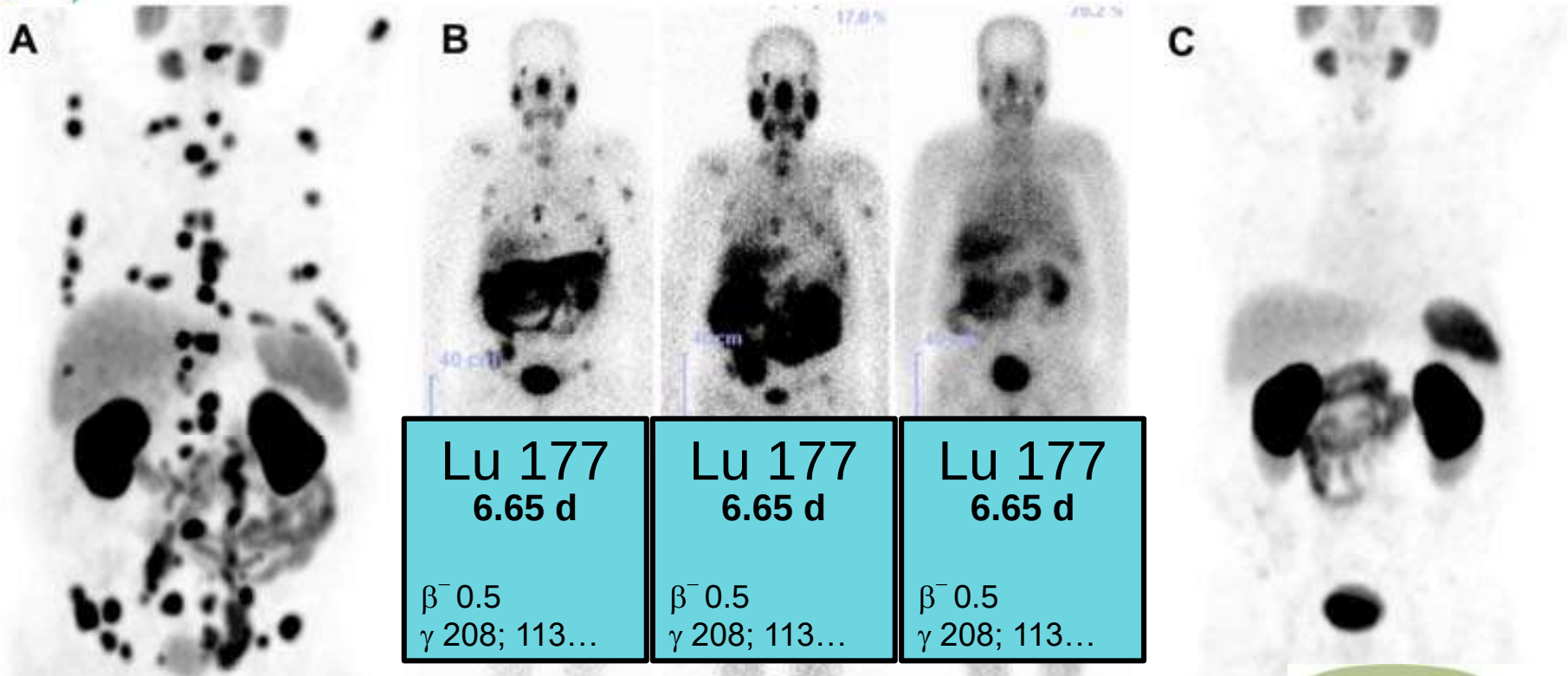
29.1.2018
FDA Approval
of Lutathera



J. Strosberg et al., N Engl J Med 2017;376:125.



^{177}Lu -radioligand therapy of advanced prostate cancer



C. Kratochwil et al., *Eur J Nucl Med Mol Imaging* 2015;42:987.

M. Weineisen et al., *J Nucl Med* 2015;56:1169.

R.P. Baum et al., *J Nucl Med* 2016;57:1006.

C. Kratochwil et al., *J Nucl Med* 2016;57:1170.

K. Rahbar et al., *J Nucl Med* 2017;58:85.

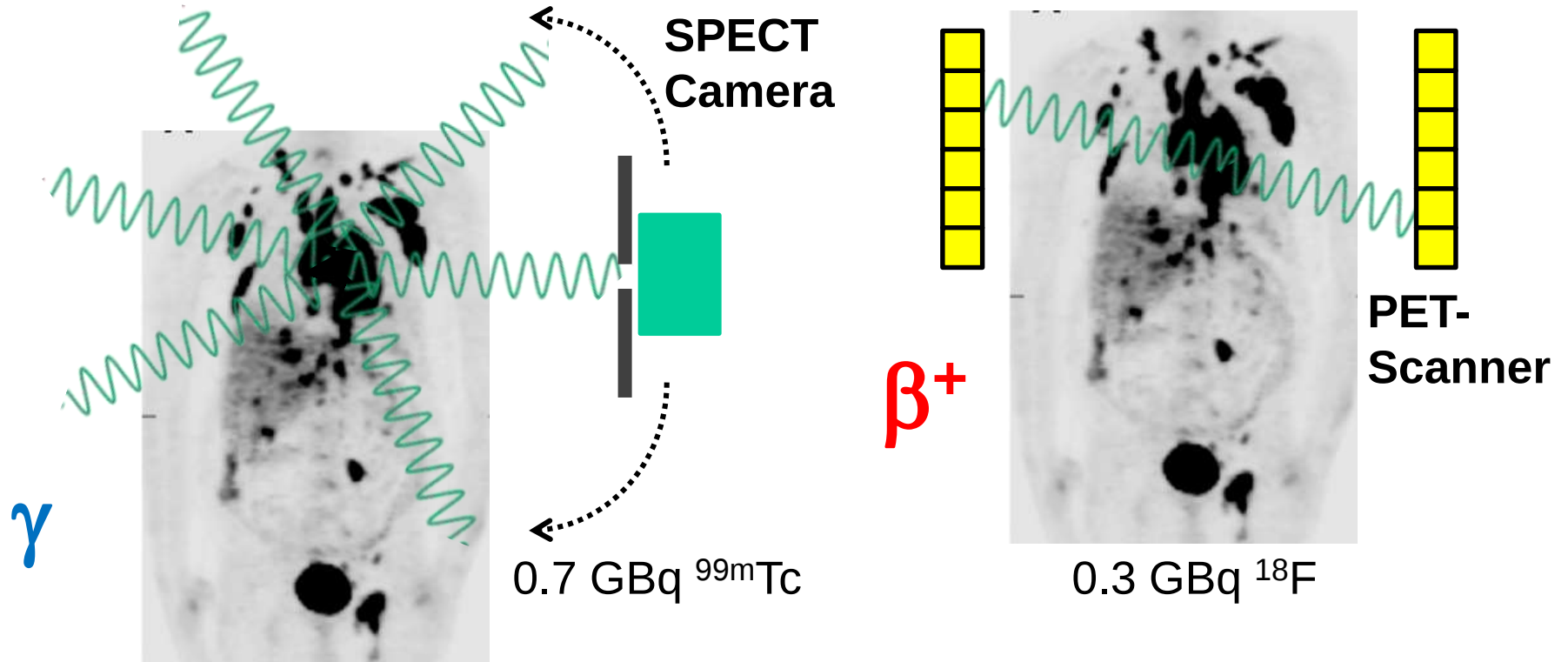
M.S. Hofman et al., *Lancet Oncol* 2018;19:825.

O. Sartor et al., *N Engl J Med* 2021;385:1091.

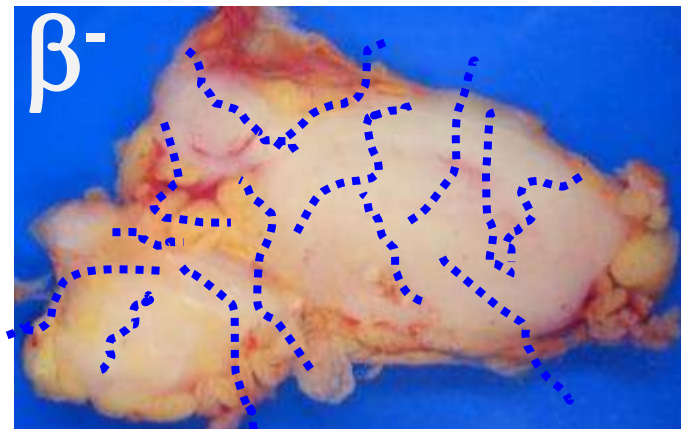
Approval
23.3.2022 FDA
11.8.2022 MHRA
9.12.2022 EMA



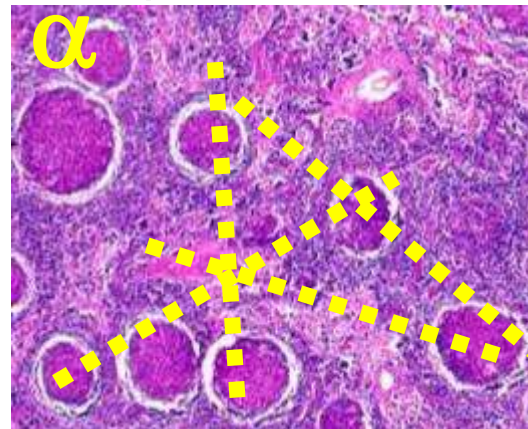
The Nuclear Medicine Alphabet



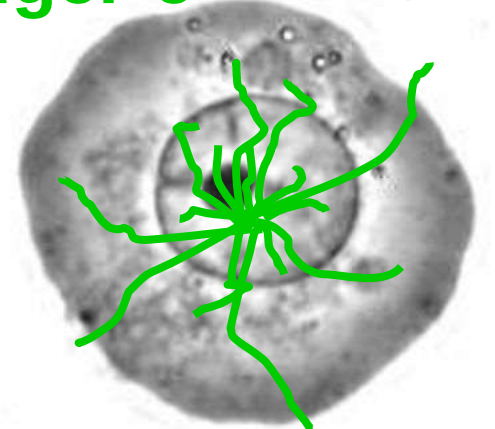
7 GBq ^{177}Lu



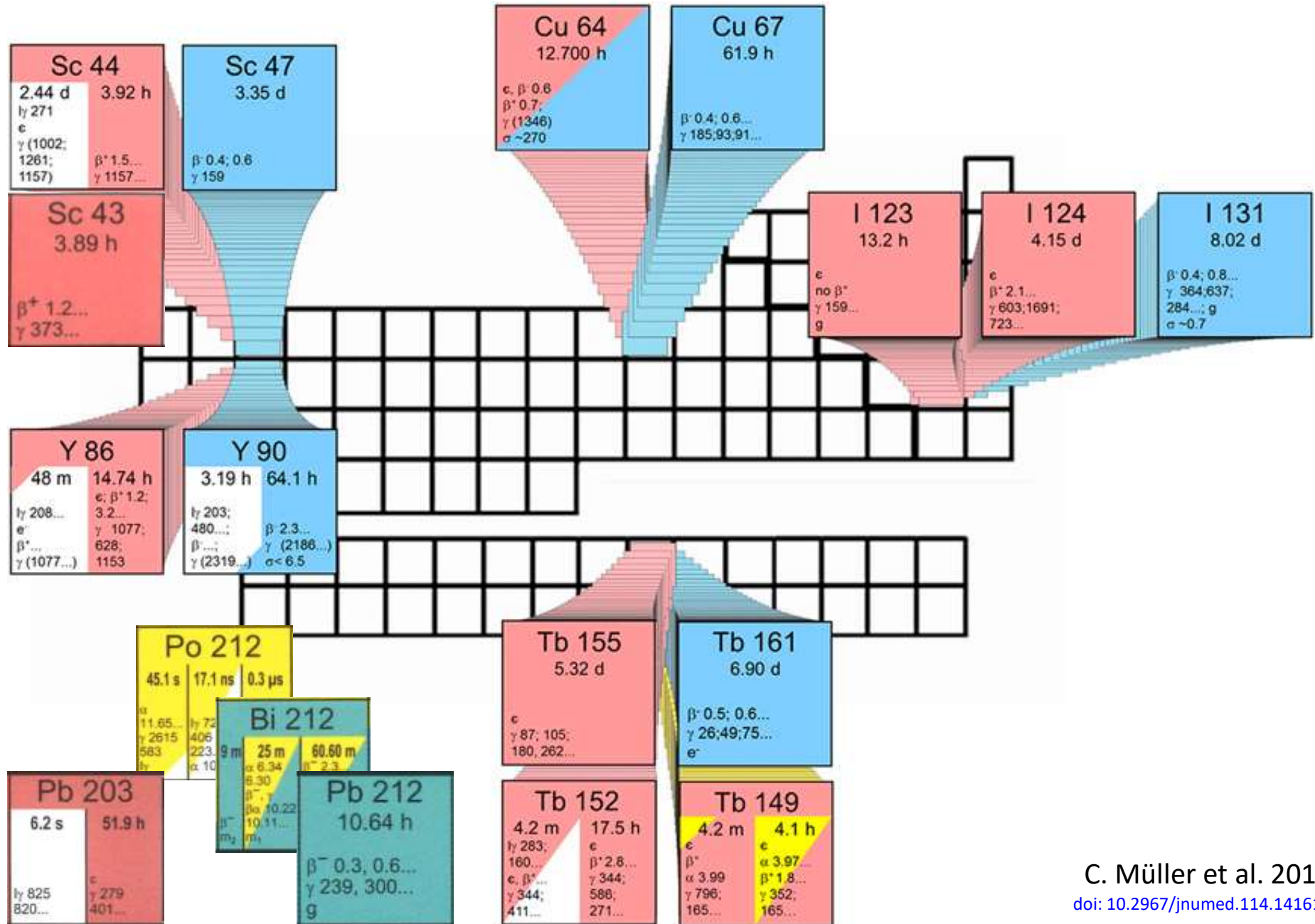
8 MBq ^{225}Ac



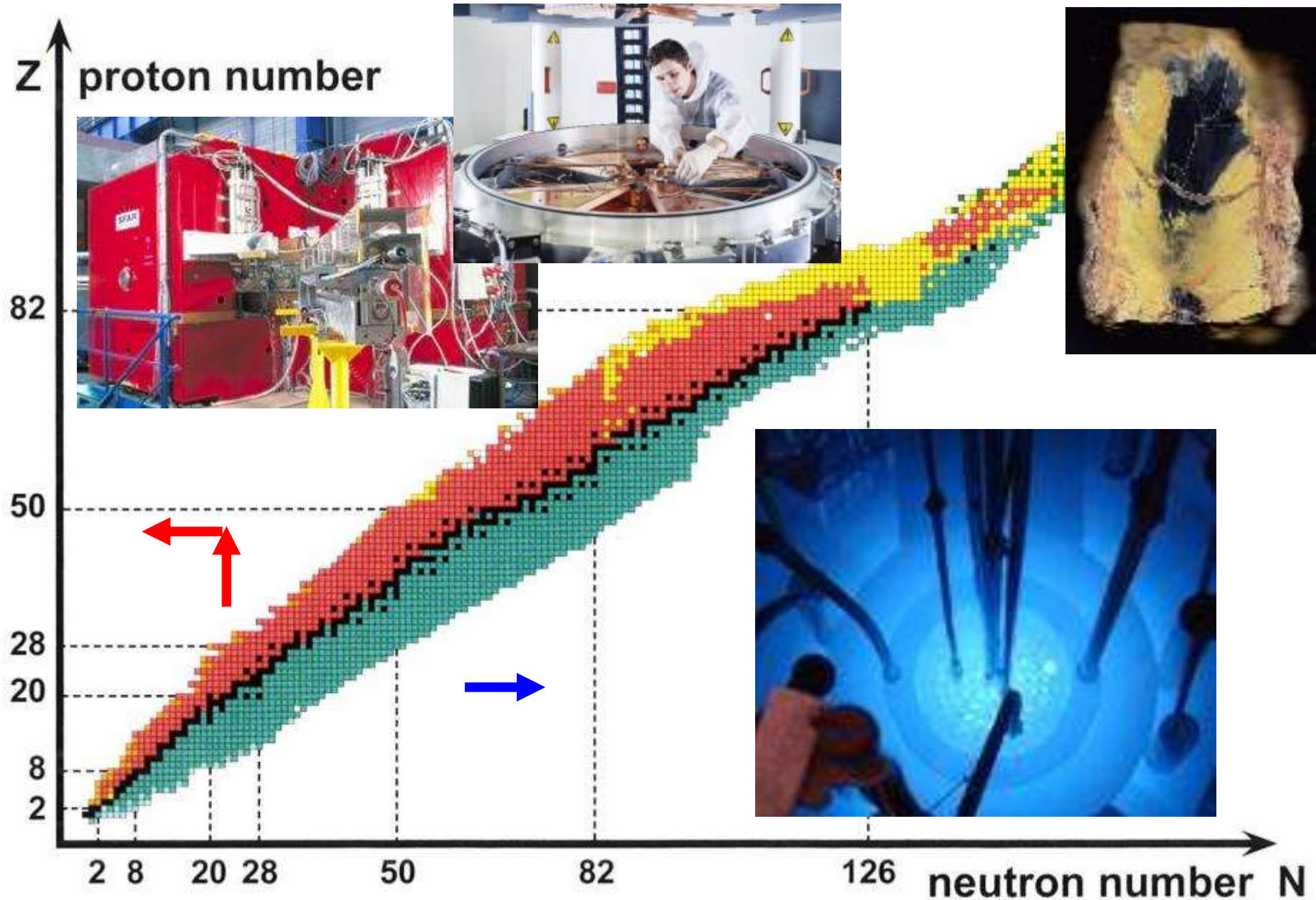
Auger- e^- ? MBq



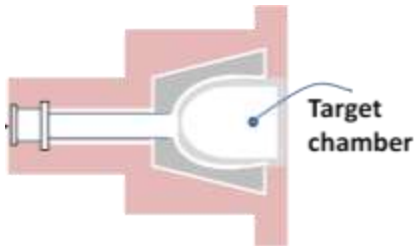
Matched pairs for theranostics



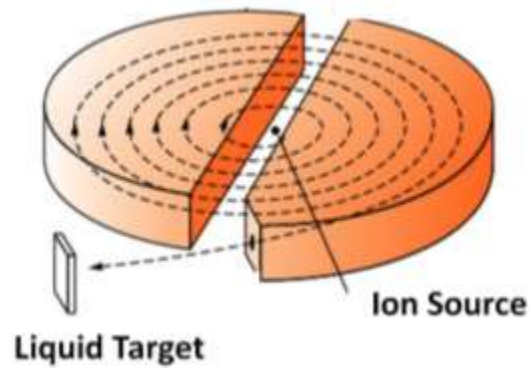
The “Alpine divide” of radionuclide production



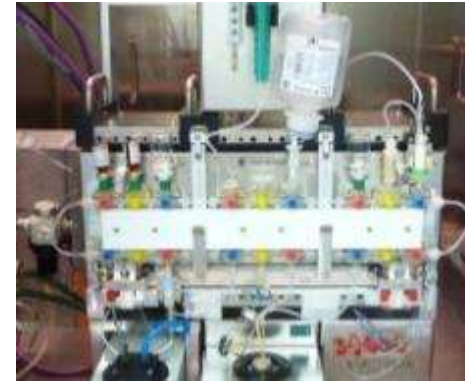
^{18}F production via $^{18}\text{O}(p,n)$



H_2^{18}O (water)

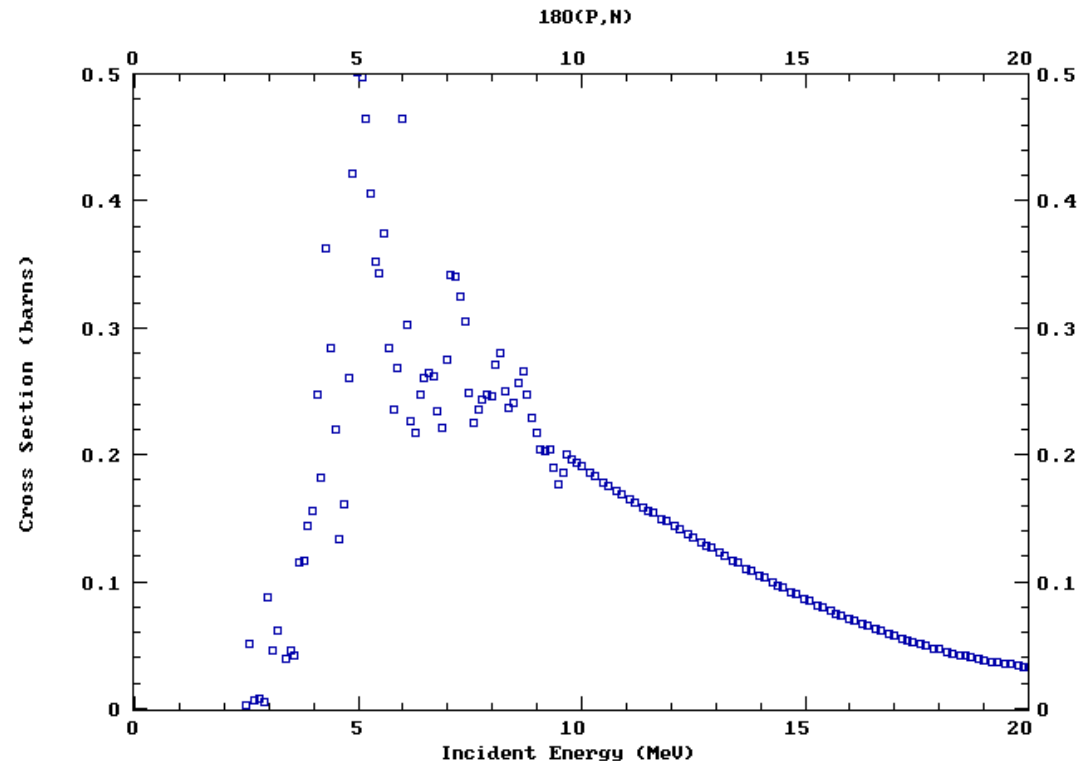


Cyclotron irradiation



Transformation into FDG

F 17 64.49 s	F 18 109.728 m	F 19 100
β^+ 1.7... $\gamma?$	β^+ 0.634 no γ	σ 0.00951
O 16 99.757	O 17 0.038	O 18 0.205
σ 0.000173	σ 0.000540 $\sigma_{n,\alpha}$ 0.235	σ 0.000150

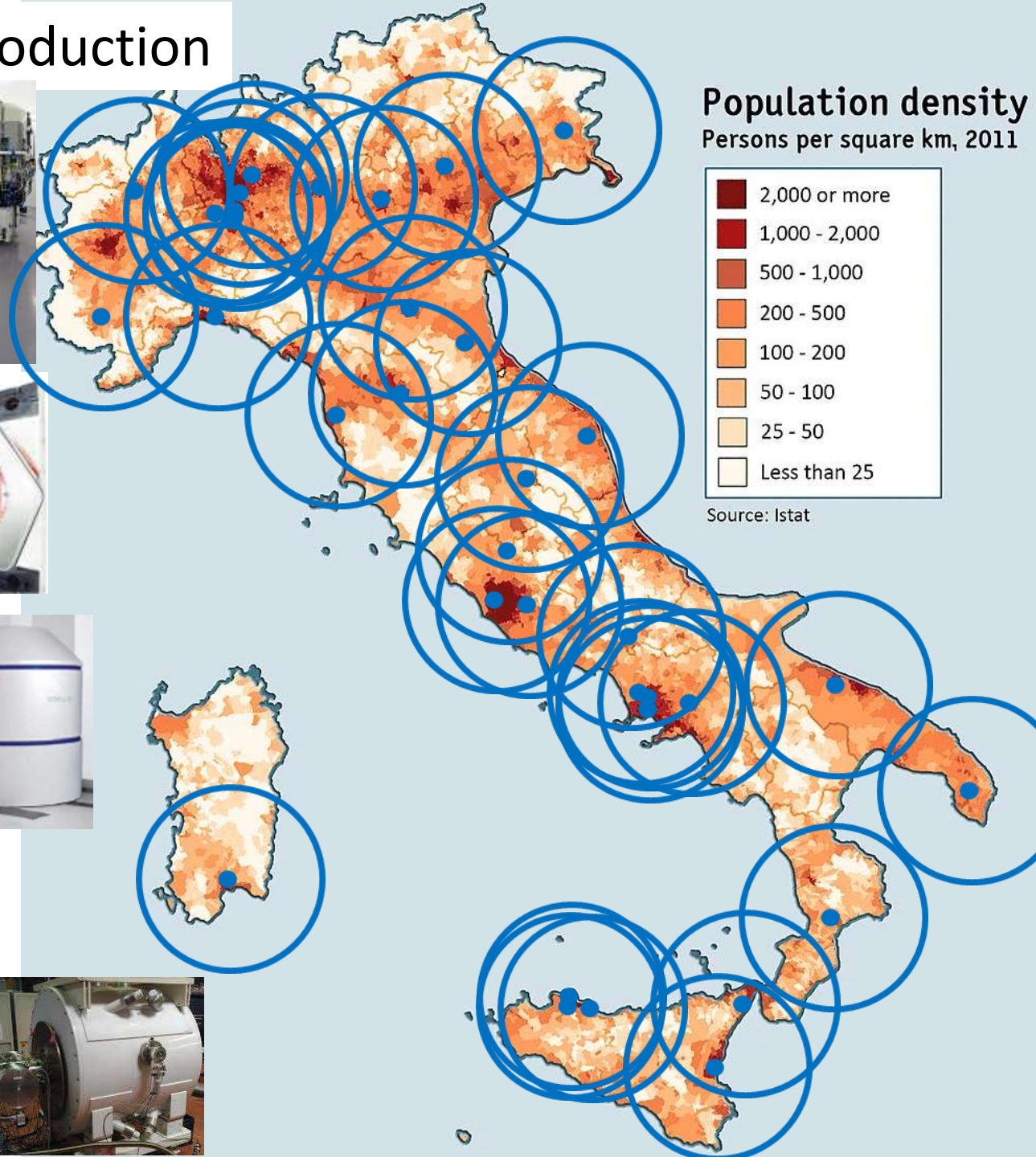


Cyclotrons for ^{18}F production

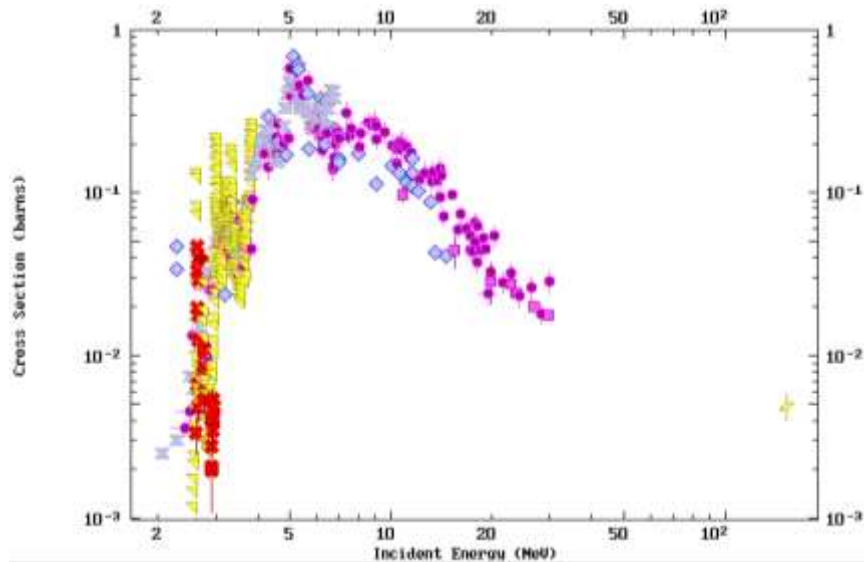
F 18
110 m
 $\beta^+ 0.633$
no γ



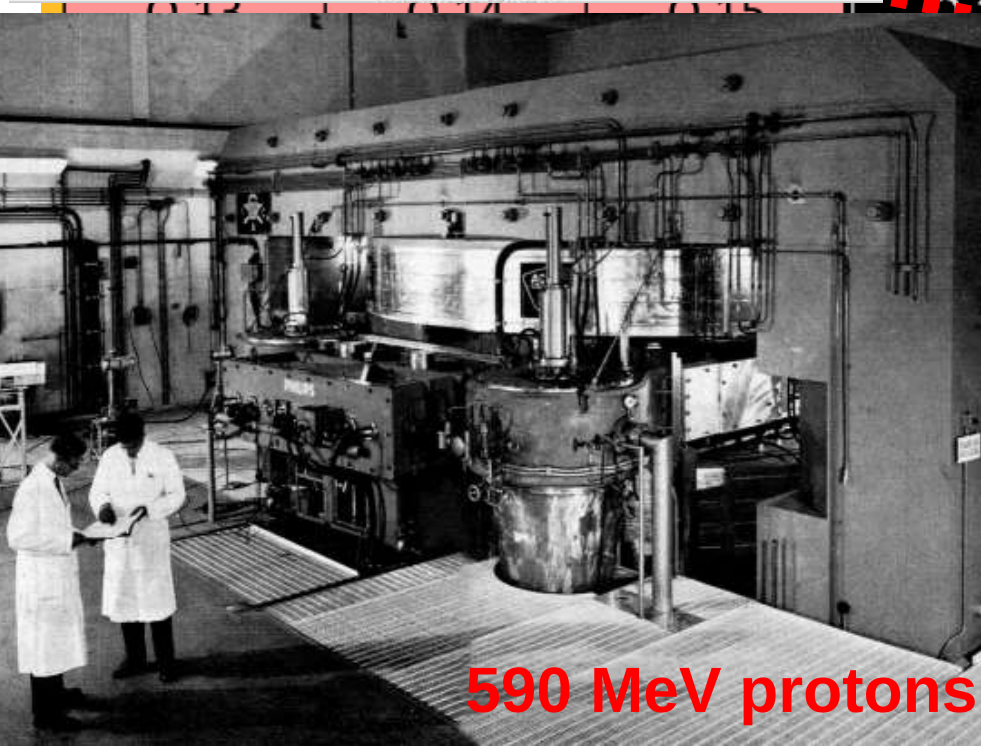
13x IBA cyclone 18
11x GE PETtrace 16.5
9x GE Minitrace 9.6
4x Siemens Eclipse 11
2x ACSI TR19
1x PMB Isotrace 12



^{18}F production via $^{18}\text{O}(\text{p},\text{n})$



Ne 18 1.6654 s 3.4... 1042...	Ne 19 17.254 s β^+ 2.2... γ (110, 197 1357...)
F 17 64.49 s 1.7...	F 18 109.728 m β^+ 0.634 no γ



590 MeV protons

O 16 57 σ 0.00510 σ_n 0.235	O 17 0.038 σ 0.000150	O 18 0.205 β^- 3.3, 4.8... γ 197, 1357...
N 16 5.25 μs β^- 3.3 β^- 3.4... γ 6129 7115... IT 120 β^- ...	N 17 7.13 s β^- 3.2, 8... β_n 1.16, 0.39... γ 871, 2184 $\beta\alpha$ 1.25, 1.41	N 18 0.619 ms β^- 9.4, 11.9... γ 1982, 822 1652, 2473... $\beta\alpha$ 1.08, 2.28... β_n 0.58, 2.44...

Tochon-Danguy, Townsend et al.,
J Fluorine Chem 1988;44:33.

(p,n) reactions

Sc 44 58.61 h IT 271 ϵ γ 1002 1126 1157 β^+ 1.5 γ 1157... σ 9.8 + 17.4	Sc 45 100
Ca 43 0.135 σ 6.2	Ca 44 2.086 σ 0.88

Mn 52 21.1 m β^+ 2.6... γ 1434... IT 378 ϵ γ 320 σ < 10	Mn 53 5.591 d 3.7 · 10 ⁶ a β^+ 0.6... γ 4 936 744... σ 70
Cr 51 27.704 d ϵ γ 320 σ < 10	Cr 52 33.789 σ 0.86

Cu 64 12.7004 h ϵ γ (1346) β^- 0.6, β^+ 0.7 σ ~270	Cu 65 30.85 σ 2.17
Ni 63 100 a β^- 0.07 no γ σ 24.4	Ni 64 0.9256 σ 1.63

Ga 68 67.71 m β^+ 1.9... γ 1077, (1883...) σ 1.92	Ga 69 60.108 σ 1.92
Zn 67 4.04 σ 7.5 $\sigma_{n,p}$ 0.000159	Zn 68 18.45 σ 0.072 + 1.0 $\sigma_{n,p}$ < 2E-5

Y 86 47.4 m IT (10), e^- γ 208 β^+ ... γ (1077) 1153... ϵ , β^+ 1.2 3 γ 485 628 1153... β^+ ... m	Y 87 14.74 h 13.37 h 79.8 h IT 381 ϵ β^+ ... γ 485 389 m
Sr 85 67.63 m IT (7...) e^- γ 232 no β^+ γ 151...	Sr 86 64.849 d 9.86 no β^+ γ 514... σ 0.791 + 0.24

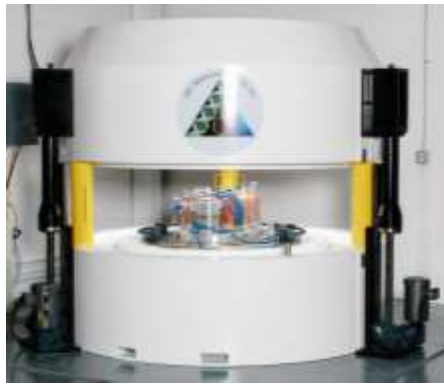
Zr 89 4.161 m IT 588 ϵ β^+ 0.9, 2.4 γ 1507 m ϵ	Zr 90 78.41 h 809.2 ms 51.45 IT 2319 133 γ 2186... σ 0.014
Y 88 106.626 d ϵ β^+ ... γ 1836, 898...	Y 89 15.66 s 100 IT 909 σ 0.001 + 1.279

I 124 4.15 d ϵ β^+ 2.1... γ 603, 1691 723...	I 125 59.407 d ϵ γ 35, e^- g σ 894
Te 123 0.89 119.2 d IT (88 247), e^- γ 159 $\sigma_{n,p}$ 5E-5	Te 124 4.74 ϵ no γ σ 430 σ 0.85 + 5.45

Pb 203 6.21 s IT 825 γ 820, (5) e^- ϵ	Pb 204 51.92 h 66.93 m 1.4 IT 912... γ 899 375... σ 0.703
Tl 202 12.23 d ϵ γ 440, (520...)	Tl 203 29.52 σ 11.4 $\sigma_{n,p}$ < 0.0003

odd-odd or even-odd product nuclides

Cyclotrons for (p,n) reactions: <12 MeV



ABT BG-75
7.5 MeV, 1-5 μ A



GE Minitrace
9.6 MeV, 50 μ A



IBA Cyclone Key
9.2 MeV, 100 μ A
*also Cyclone 10/5
and Cyclone 11*



Siemens Eclipse
11 MeV, 80-120 μ A



PMB-ALCEN Isotrace
12 MeV, 100 μ A

(p,2n) reactions

Cu 60 23.7 m β^+ 2.9, 3.8... γ 1332, 1792 826...	Cu 61 3.339 h β^+ 1.2... γ 283, 656, 67 1185...	Cu 62 9.67 m β^+ 2.9... γ (1332...) σ 4.50	Cu 63 69.15
Ni 59 7.6·10 ⁴ a ϵ , β^+ ... no γ σ 73, $\sigma_{n,\alpha}$ 12.3 $\sigma_{n,p}$ 2.0, σ_{abs} 88	Ni 60 26.2231 σ 2.45	Ni 61 1.1399 σ 2.1 $\sigma_{n,\alpha} < 0.000030$	Ni 62 3.6345 σ 14.9

In 109 1.34 m ϵ β^+ 0.8... γ 204 624... IT 650	In 110 69.1 m 4.92 h ϵ β^+ ... β^+ 2.3... γ 658, 885 937...	In 111 7.7 m 2.8047 d ϵ γ 204 171... IT 537	In 112 20.67 m 14.88 m β^+ 1.6... γ 64... β^+ 0.7... IT 151, e^-	In 113 99.476 m 4.281 σ 8.1 + 3.9
Cd 108 0.888 σ 0.72	Cd 109 461.9 d ϵ , no γ m σ 700, $\sigma_{n,\alpha}$ 0.05	Cd 110 12.470 σ 0.035 + 11	Cd 111 48.50 m 12.795 IT 151, e^- γ 245 σ 6.9	Cd 112 24.109 σ 0.028 + 2.2

Tc 98 4.2·10 ⁶ a β^- 0.4 γ 745, 652 σ 0.93 + 7	Tc 99 6.0072 h 2.111·10 ⁵ a IT (143, 2) e^- γ 141 β^- ... γ (90...) γ (90...) σ 22.8	Tc 100 15.65 s β^- 3.2... γ 540, 59... σ 2.2, $\sigma_{n,\alpha}$ 4E-7	Tc 101 14.2 m β^- 1.3... γ 307, 545...
Mo 97 9.582 σ 2.2, $\sigma_{n,\alpha}$ 4E-7	Mo 98 24.292 σ 0.130	Mo 99 65.924 h β^- 1.2... γ 740, 181 778... m, g	Mo 100 9.744 1·10 ¹⁸ a $2\beta^-$... γ 540, 591... σ 0.199

Ac 224 2.78 h ϵ γ 216, 132... α 6.142, 6.060 6.214... C14	Ac 225 9.920 d α 5.830, 5.793 5.732... γ 100, (150, 18 63...), e^- C14	Ac 226 29.37 h β^- 0.9, 1.1 ϵ , α 5.40 230, 158, 230 180...	Ac 227 21.772 a β^- 0.04... γ (38...), e^- α 4.953, 4.941... γ (100, 160...), e^- σ 880, $\sigma_i < 2.9E-4$
Ra 223 11.4366 d α 5.7162, 5.6067... γ 269, 154, 324... e^- C14 σ 130, $\sigma_i < 0.7$	Ra 224 3.6319 d α 5.6854, 5.4486... γ 241... C14 σ 12.0	Ra 225 14.9 d β^- 0.3, 0.4 γ 40, e^-	Ra 226 1600 a α 4.78... γ 186... C14 σ 13.7, $\sigma_i < 5E-5$

odd-even product nuclides
(p,n) product much shorter-lived

Cyclotrons for (p,2n) reactions: 16-20 MeV



IBA Cyclone 18
18 MeV, 150 μ A



GE PetTrace
16.5 MeV, 100 μ A



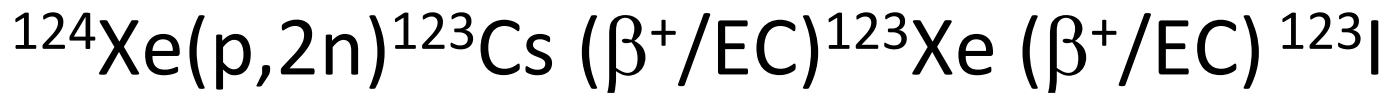
ASCI TR19
12-19 MeV, -400 μ A



IBA Cyclone Kiube
13/14/15/18 MeV, -300 μ A



ASCI TR24
12-25 MeV, 300/500/800 μ A



Cs 122 4.2 m 21.0 s β^+ γ 331 497, 638 560... β^+ 5.8... γ 331...		Cs 123 1.7 s 5.86 m IT (62) e^- γ 95... 64..., e^- 997...		Cs 124 6.3 s 30.9 s IT 65 e^- ... γ 212, 90 97, 65... β^+ 4.9... γ 354 915 493...		Cs 125 46.7 m ϵ, β^+ 2.1... γ 526, 112 412... 6...		Cs 126 1.6 m β^+ 3.8... γ 389, 491 925...		Cs 127 6.25 h ϵ, β^+ 0.7, 1.1... γ 411, 125 462... g	
Xe 121 38.8 m		Xe 122 20.1 h		Xe 123 2.050 h		Xe 124 0.095 $1.8 \cdot 10^{22}$ a		Xe 125 56.9 s 16.9 h ϵ β^+ ... γ 188, 243 55... IT 141, e^- γ 111 $\sigma_{n,\alpha} \sim 0.03$		Xe 126 0.089 σ 0.25 + 2.47	
		I 122 3.6 m β^+ 1.5... γ 149, 178 30...		I 123 13.2230 h ϵ no β^+ γ 159... g		I 124 4.15 d ϵ β^+ 2.1... γ 603, 1691 723...		I 125 59.407 d ϵ γ 35, e^- g σ 894			
		Te 121 164.2 d 19.17 d (82), e^- 212... ϵ γ 573 508... 1102...		Te 122 2.55 σ 0.42 + 3.48		Te 123 0.89 119.2 d IT (88 247), e^- γ 159		Te 124 4.74 > $9.2 \cdot 10^{16}$ a ϵ no γ σ 430 $\sigma_{n,\alpha} 5E-5$		σ 0.85 + 5.45	

$^{69}\text{Ga}(p,2n)^{68}\text{Ge} \Rightarrow ^{68}\text{Ge}/^{68}\text{Ge}$ generator

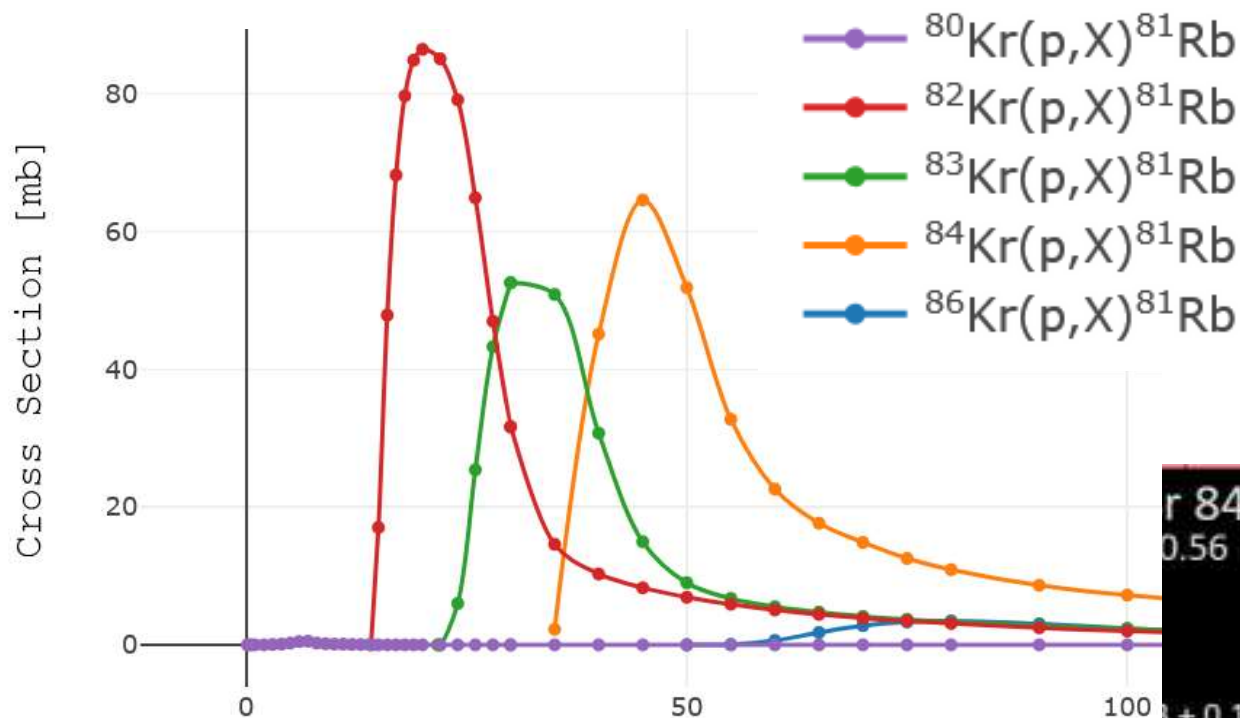
Ge 67 18.7 m β^+ 3.0, 3.2... γ 167, 1473...	Ge 68 270.93 d ϵ no β^+ no γ σ 1.0	Ge 69 39.05 h ϵ β^+ 1.2... γ 1107, 574 872, 1336...	Ge 70 20.52 σ 3.05	Ge 71 11.43 d ϵ no γ	Ge 72 27.45 σ 0.89
Ga 66 9.304 h β^+ 4.2... γ 1039, 2752 834, 2190 4296...	Ga 67 78.278 h ϵ no β^+ γ 93, 185, 300...	Ga 68 67.71 m β^+ 1.9... γ 1077, (1883...)	Ga 69 60.108 σ 1.92	Ga 70 21.14 m β^- 1.7... γ (1040, 176...) ϵ	Ga 71 39.892 σ 4.62
Zn 65 243.93 d ϵ , β^+ 0.3 γ 1115... σ 66, $\sigma_{n,\alpha}$ 2.0	Zn 66 27.73 σ 0.62, $\sigma_{n,\alpha} < 2\text{E-}5$	Zn 67 4.04 σ 7.5 $\sigma_{n,\alpha}$ 0.000159	Zn 68 18.45 σ 0.072 + 1.0 $\sigma_{n,\alpha} < 2\text{E-}5$	Zn 69 13.756 h 56.4 m IT 439 β^- ... γ (574)	Zn 70 0.61 $\geq 3.8 \cdot 10^{18}$ a $2\beta?$ σ 0.0087 + 0.083

$^{203}\text{Tl}(p,3n)^{201}\text{Pb} \Rightarrow \text{chem.sep. (EC)}^{201}\text{Tl} \Rightarrow \text{chem.sep.}$

Pb 201 60.8 s 9.33 h ε β ⁺ IT 629	Pb 202 3.54 h 5.25·10 ⁴ a IT 787... γ 422 961... ε γ 490 460, 5... ε no γ α?	Pb 203 6.21 s 51.92 h IT 825 γ 820, (5) e γ 279 401...	Pb 204 66.93 m 1.4 IT 912... γ 899 375... σ 0.703	Pb 205 1.70·10 ⁷ a ε no γ σ ~5	Pb 206 24.1 σ 0.027
Tl 200 26.1 h ε β ⁺ ... γ 368, 1206, 579 828...	Tl 201 3.0422 d ε γ 167, 135...	Tl 202 12.23 d ε γ 440, (520...)	Tl 203 29.52 σ 11.4 σ _{n,α} < 0.0003	Tl 204 3.78 a β ⁻ 0.8 ε no γ, g σ 21.6	Tl 205 70.48 σ 0.104
Hg 199 42.67 m 16.94 IT 374... e ⁻ γ 158... σ 2150	Hg 200 23.14 σ 15.0	Hg 201 13.17 σ 4.9	Hg 202 29.74 σ 4.91	Hg 203 46.59 d β ⁻ 0.2 γ 279	Hg 204 6.82 σ 0.43

The diagram illustrates decay paths between isotopes. A solid green arrow points from the Pb 201 cell to the Tl 200 cell. A dashed red arrow points from the Pb 203 cell to the Tl 202 cell. Another dashed red arrow points from the Pb 203 cell to the Tl 201 cell.

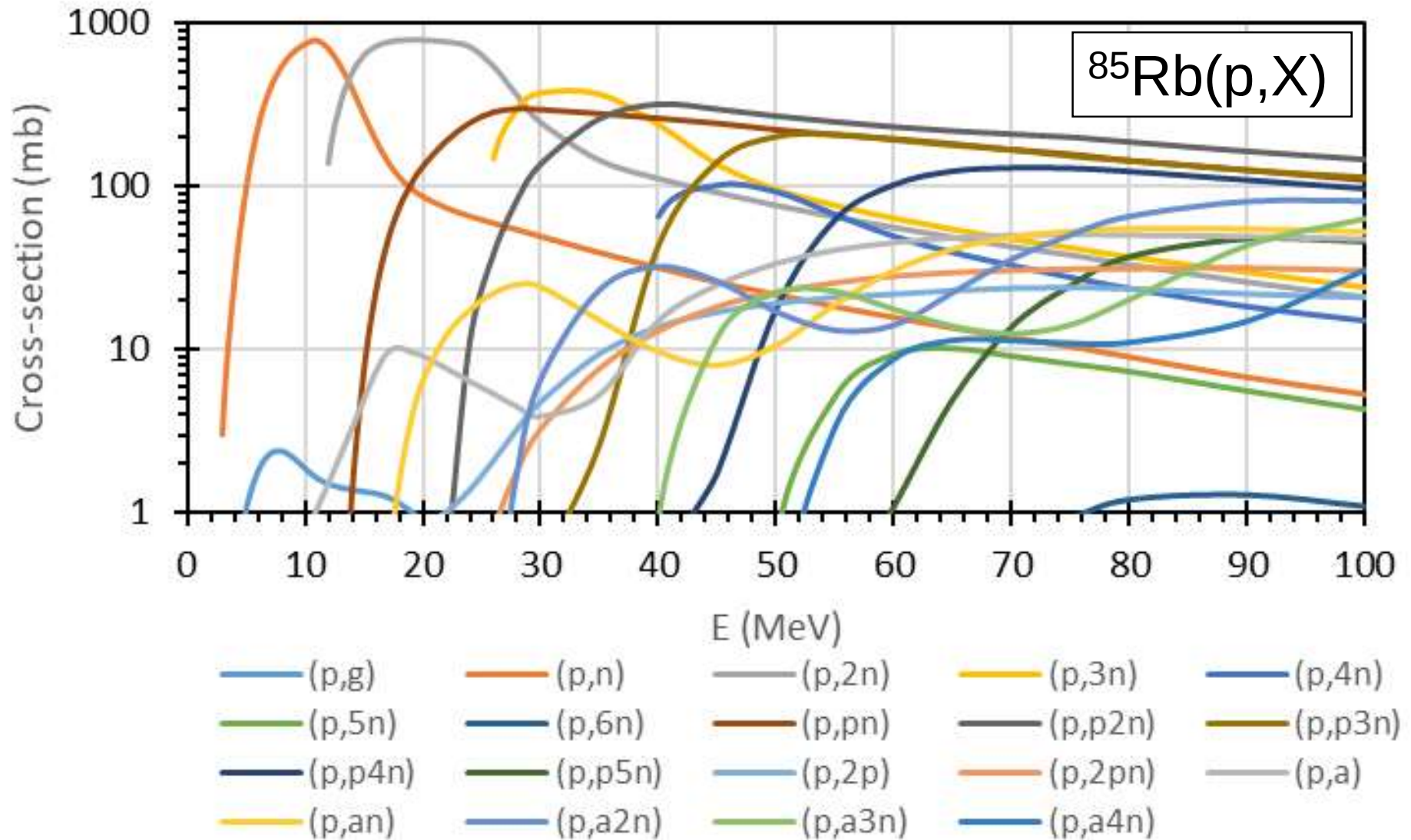
$^{\text{nat}}\text{Kr}(p,X)^{81}\text{Rb} \Rightarrow ^{81}\text{Rb}/^{81\text{m}}\text{Kr}$ generator



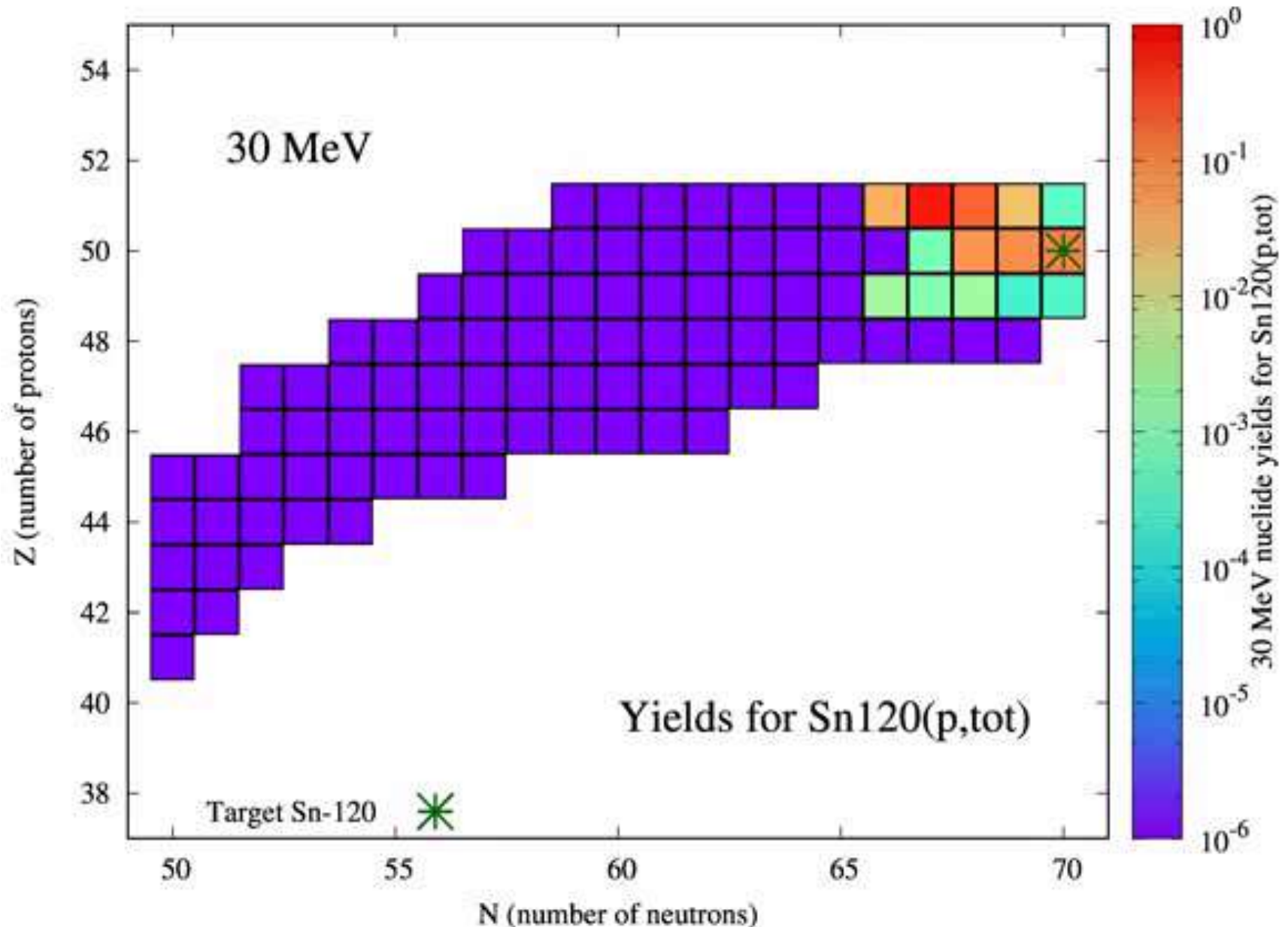
Kr 84		Sr 85		Sr 86
0.56		67.63 m	64.849 d	9.86
IT (7...)				
e ⁻				
γ 232				
ε, no β ⁺				
γ 151...				
σ 0.199				

Rb 79		Rb 80		Rb 81		Rb 82		Rb 83		Rb 84		Rb 85
22.9 m		30 s		30.5 m	4.572 h	6.472 h	1.2575 m	86.2 d		20.26 m	32.82 d	72.17
β ⁺ 1.8, 2.5...				IT 86, e ⁻		ε β ⁺ 0.8		ε, no β ⁺				
γ 688, 183, 143		β ⁺ 4.7...		ε, β ⁺ ...		γ 1.1...		γ 520, 53		IT 464		
130, 505..., e ⁻		γ 616...		γ (50...)		γ 4.6...		553...		216, e ⁻		
g, m				e ⁻ , g		m		σ		σ _{n,p} 12		σ 0.056 + 0.438
Kr 78		Kr 79		Kr 80		Kr 81		Kr 82		Kr 83		Kr 84
0.355		50 s	35.04 h	2.286		13.10 s	2.29·10 ⁵ a	11.593		1.83 h		56.987
1.4·10 ²² a												
2ε		ε				ε		ε		IT (32)		
σ 0.18 + 4.53		IT 130		σ 4.53 + 6.97		IT 190		σ 15.1 + 3.9		e ⁻		σ 0.086 + 0.042
		e ⁻				ε		γ (276)		γ 9, e ⁻		
		398								σ 197		
		606..., g										

Energy dependence of cross-sections



Energy dependence of cross-sections



$^{85/87}\text{Rb}(p,4n/6n)^{82}\text{Sr} \Rightarrow ^{82}\text{Rb}/^{82}\text{Rb}$ generator

Sr 80 1.8 h ϵ γ 589, 175 553...	Sr 81 22.2 m β^+ 2.7, 3.0 γ 154, 148, 443 188... g	Sr 82 25.35 d ϵ no β^+ no γ g	Sr 83 4.95 s 32.41 h ϵ β^+ 1.3 763 IT 259 418	Sr 84 0.56 ϵ β^+ 0.655 189	Sr 85 67.63 m 64.849 d IT (7...) e^- γ 232 no β^+ γ 131... γ 514...	Sr 86 9.86 σ 0.791 + 0.24
Rb 79 22.9 m β^+ 1.8, 2.5... γ 688, 183, 143 130, 505..., e^- g, m	Rb 80 30 s β^+ 4.7... γ 616...	Rb 81 30.5 m 4.572 h IT 86, e^- ϵ , β^+ ... γ (50...) e^- , g	Rb 82 6.472 h 1.2575 m ϵ β^+ 0.8 1.6... γ 777, 554 619... IT?	Rb 83 86.2 d ϵ , no β^+ γ 520, 530 553... m, g	Rb 84 20.2 m 2.62 d IT 464 216, e^- γ 248	Rb 85 72.17 σ 0.056 + 0.438
Kr 78 0.355 $1.4 \cdot 10^{22}$ a 2 ϵ σ 0.18 + 4.53	Kr 79 50 s 35.04 h ϵ β^+ 0.6... γ 261 398 606..., g	Kr 80 2.286 σ 4.53 + 6.97	Kr 81 13.10 s $2.29 \cdot 10^5$ a IT 190 ϵ γ (276)	Kr 82 11.593 σ 15.1 + 3.9	Kr 83 1.83 h 11.500 IT (32) e^- γ 9, e^- σ 197	Kr 84 56.987 σ 0.086 + 0.042

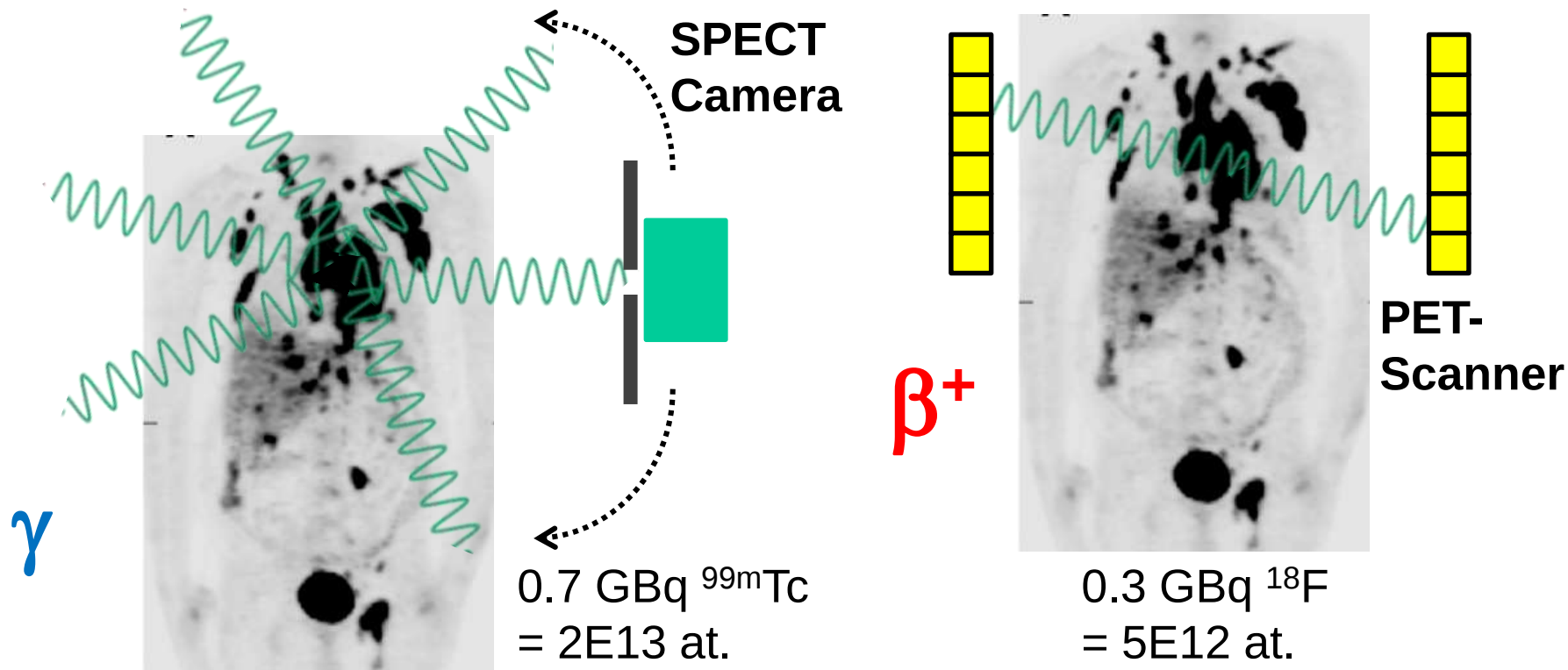
$^{159}\text{Tb}(p,5n)^{155}\text{Dy} \Rightarrow \text{chem.sep. (EC)}^{155}\text{Tb} \Rightarrow \text{chem.sep.}$

Dy 154 $3.0 \cdot 10^6 \text{ a}$ α 2.87	Dy 155 9.9 h ϵ β^+ 0.9, 1.1... γ 227...	Dy 156 0.056 σ 32 $\sigma_{n,\alpha} < 0.009$	Dy 157 8.14 h ϵ β^+ ... γ 326...	Dy 158 0.095 σ 43 $\sigma_{n,\alpha} < 0.006$	Dy 159 144.4 d ϵ γ 58, e^-	Dy 160 2.329 σ 55
Tb 153 2.34 d ϵ , β^+ ... γ 212, 110, 102 170, 83...	Tb 154 22.7 h 9.994 h 21.5 h ϵ γ 248 347 1420 123... IT ϵ γ 123 248 540... IT ϵ β^+ ... γ 123 1274...	Tb 155 5.32 d ϵ γ 87, 105, 180 262...	Tb 156 5.3 h 24.4 h 5.35 d IT 88 e^- , g ϵ β^+ ... β^- ? IT γ 50	Tb 157 71 a ϵ γ 534 199 1222... γ (54), e^-	Tb 158 10.75 s 130 a ϵ γ 944 962 80..., e^- β^- 0.9... IT (110) e^-	Tb 159 100 σ 23.8
Gd 152 0.20 $1.08 \cdot 10^{14} \text{ a}$ α 2.147 σ 755, $\sigma_{n,\alpha}$ 0.007	Gd 153 240.4 d ϵ γ 97, 103, 70... σ 22460 $\sigma_{n,\alpha}$ 0.033	Gd 154 2.18 σ 85	Gd 155 14.80 σ 60330 $\sigma_{n,\alpha}$ 8E-5	Gd 156 20.47 σ 1.8	Gd 157 15.65 σ 254000 $\sigma_{n,\alpha}$ 0.00055	Gd 158 24.84 σ 2.22

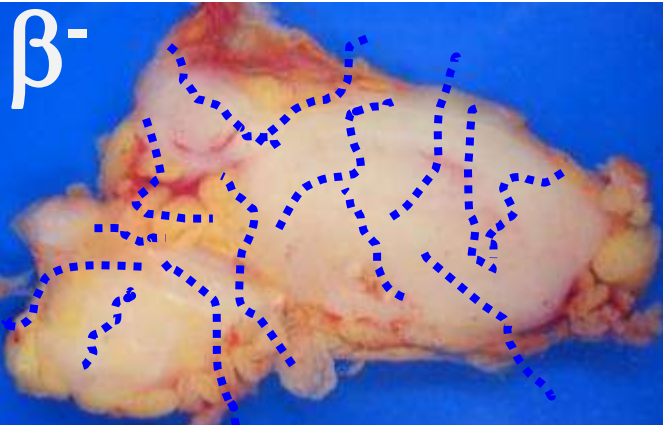
Diagnostic radionuclides

- Most short-lived: hours
⇒ decentralized production network
or generators with centralized production
- Few longer-lived: days
⇒ centralized production

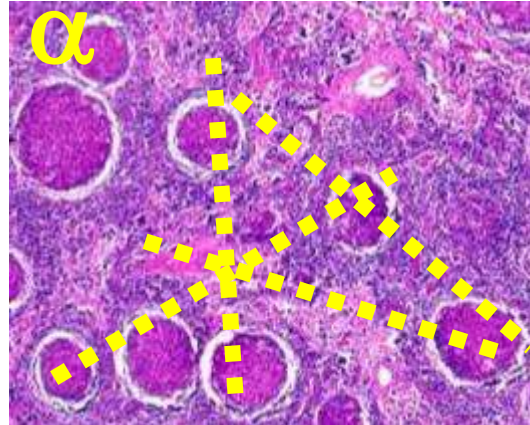
The Nuclear Medicine Alphabet



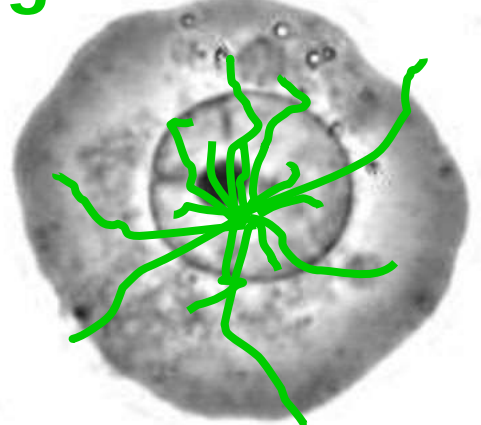
7 GBq $^{177}\text{Lu} = 6\text{E}15 \text{ at.}$



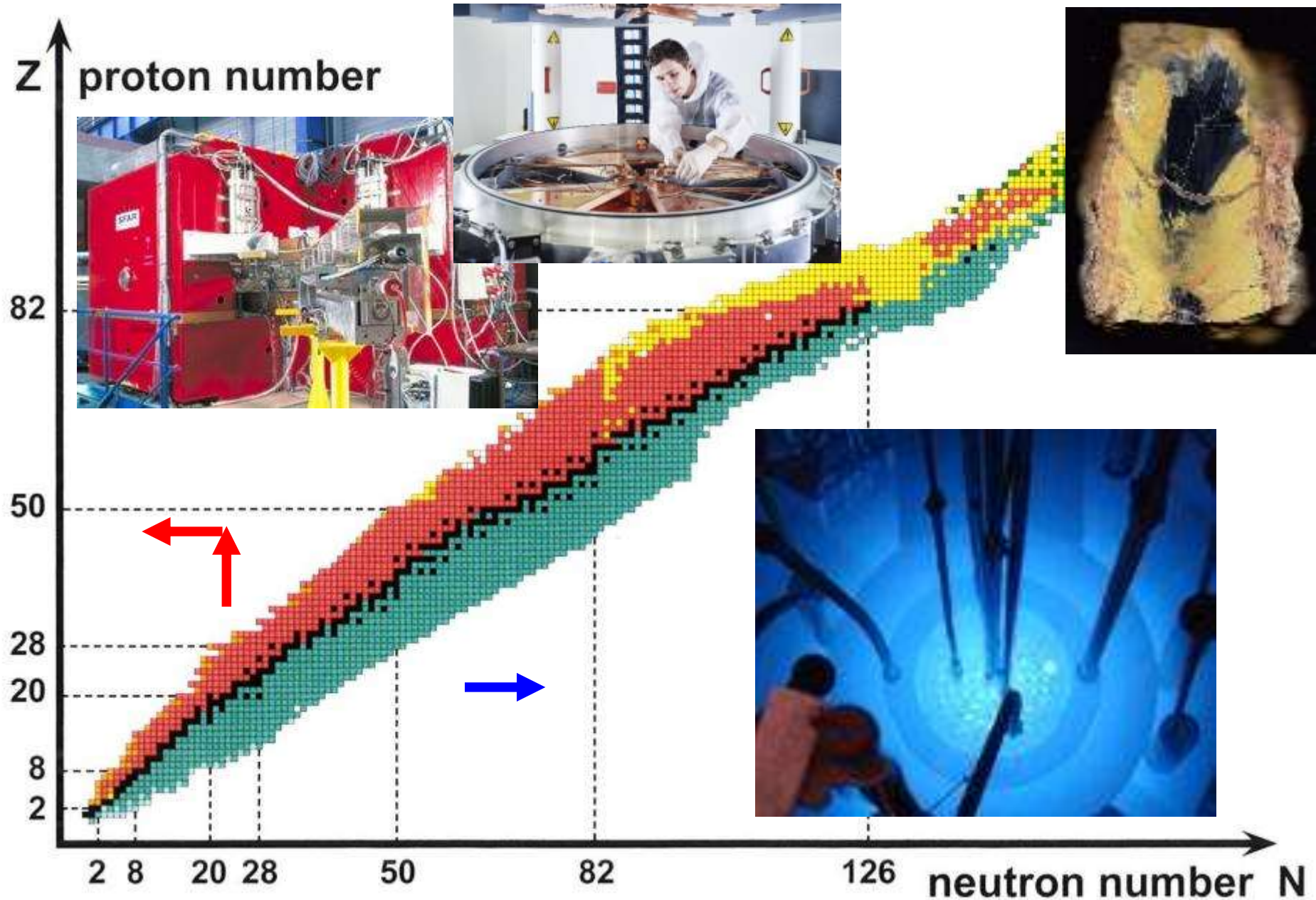
8 MBq $^{225}\text{Ac} = 1\text{E}13 \text{ at.}$



Auger-e⁻ ? MBq

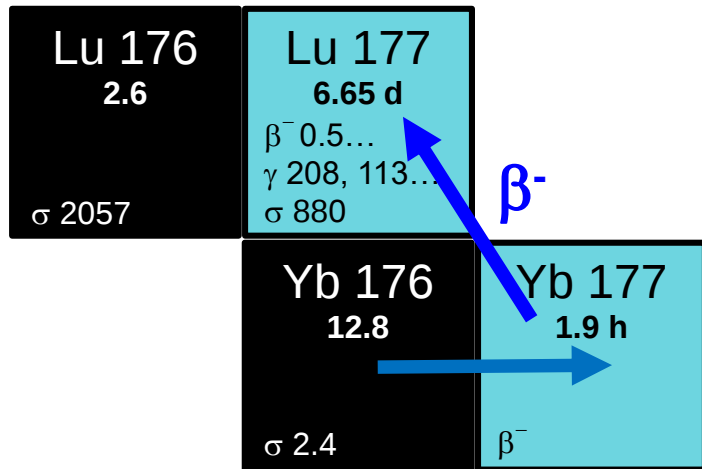


The “Alpine divide” of radionuclide production

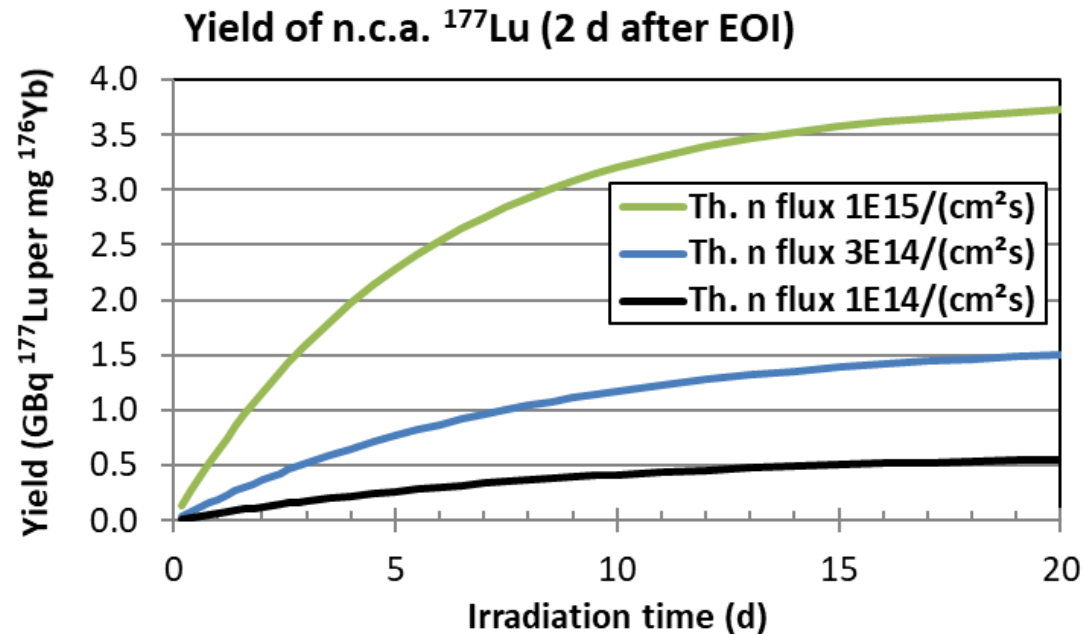


Production of no-carrier-added ^{177}Lu

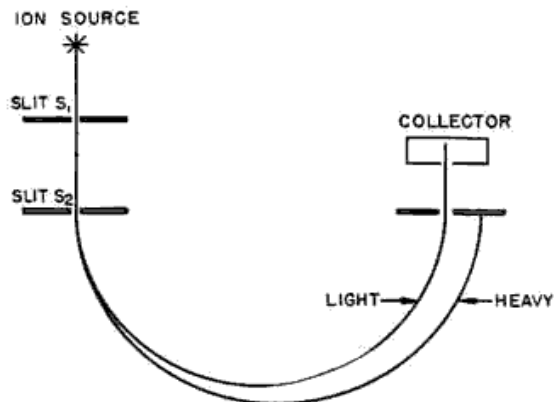
Indirect production



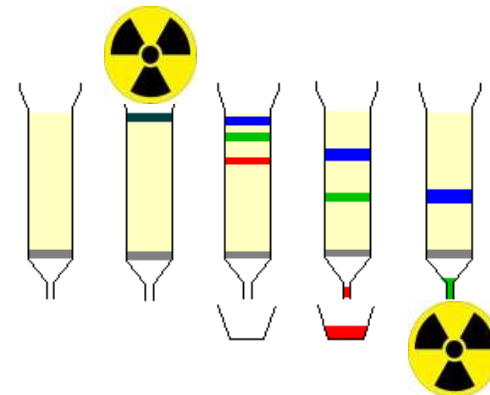
Specific activity $\approx$ theoretical
Yield depends on σ and Φ



*Estimate for 100% enriched ^{176}Yb ;
depends in reality also on neutron spectrum, self shielding, etc.*



Calutron enrichment of ^{176}Yb



Radiochemical $^{177}\text{Lu}/^{176}\text{Yb}$ separation

Competitive advantage of higher neutron flux



Enriched
 ^{176}Yb



Reactor
irradiation



Radio-
chemical
separation



ILL: The highest neutron flux in Western Europe

$1.5 \cdot 10^{15} \text{ n.cm}^{-2}\text{s}^{-1}$



Yb 176

Lu 177
94.4%
T_{1/2} 6.7 d
β⁻ 100%



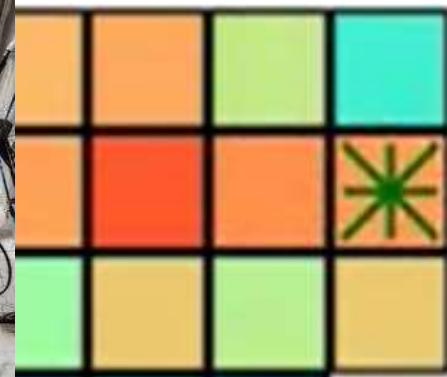
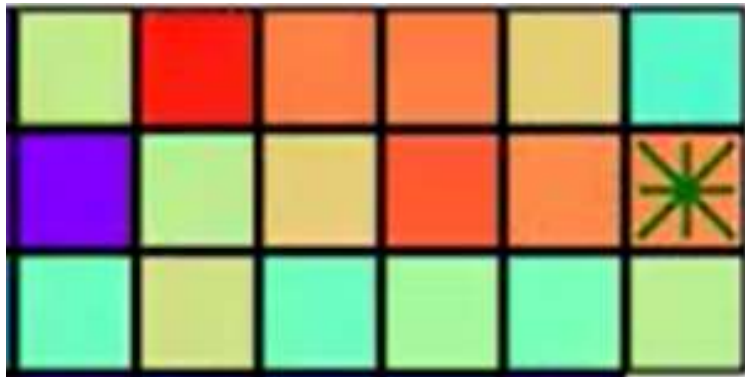
Therapeutic radionuclides

- Longer-lived: days – weeks
⇒ centralized production
- Higher activity and number of atoms per patient
⇒ high productivity production is essential
- High-flux reactors can provide huge activities of most β^- emitters (^{177}Lu , ^{161}Tb , ^{90}Y ...)
- Accelerator-production may only be competitive for few β^- emitters not well accessible by (n,γ)

$^{68}\text{Zn}(p,2p)$ or $^{70}\text{Zn}(p,\alpha)$: $^{67}\text{Cu}/^{64}\text{Cu}$ tradeoff !

Ga 65 15 m β^+ 2.1, 2.2... γ 115, 61, 153 752...	Ga 66 9.304 h β^+ 4.2... γ 1039, 2752 834, 2190 4296...	Ga 67 78.278 h ϵ no β^+ γ 93, 185, 300...	Ga 68 67.71 m β^+ 1.9... γ 1077, (1883...)	Ga 69 60.108 σ 1.92	Ga 70 21.14 m β^- 1.7... γ (1040, 176...) ϵ	Ga 71 39.892 σ 4.62
Zn 64 49.17 σ 0.731 $\sigma_{n,\alpha}$ 1.1E-5 $\sigma_{n,p} < 1.2E-5$	Zn 65 243.93 d ϵ, β^+ 0.3 γ 1115... σ 66, $\sigma_{n,\alpha}$ 2.0	Zn 66 27.73 σ 0.62, $\sigma_{n,\alpha} < 2E-5$	Zn 67 4.04 σ 7.5 $\sigma_{n,\alpha}$ 0.000159	Zn 68 18.45 σ 0.072 - 1.0 $\sigma_{n,\alpha} < 2E-5$	Zn 69 13.756 h 56.4 m IT 439 β^- ... γ (574) β^- 0.9... γ (310...) σ 0.0087 + 0.083	Zn 70 0.61 $\geq 3.8 \cdot 10^{18}$ a
Cu 63 69.15 σ 4.50	Cu 64 12.7004 h ϵ γ (1346) β^- 0.6, β^+ 0.7 $\sigma \sim 270$	Cu 65 30.85 σ 2.17	Cu 66 5.1 m β^- 2.6... γ 1039, (834...) σ 135	Cu 67 61.9 h β^- 0.4, 0.6... γ 185, 93, 91...	Cu 68 3.75 m 30.9 s IT 111, 637 e^- γ 84, 526... β^- 1.6, 2.7... γ 1078 1341... β^- 3.4 4.4... γ 1078 1262...	Cu 69 2.85 m β^- 2.7... γ 1007, 834 531... g

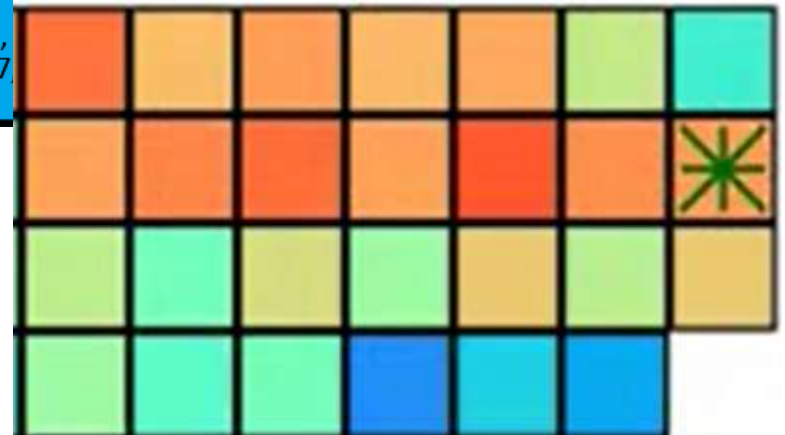
40 MeV



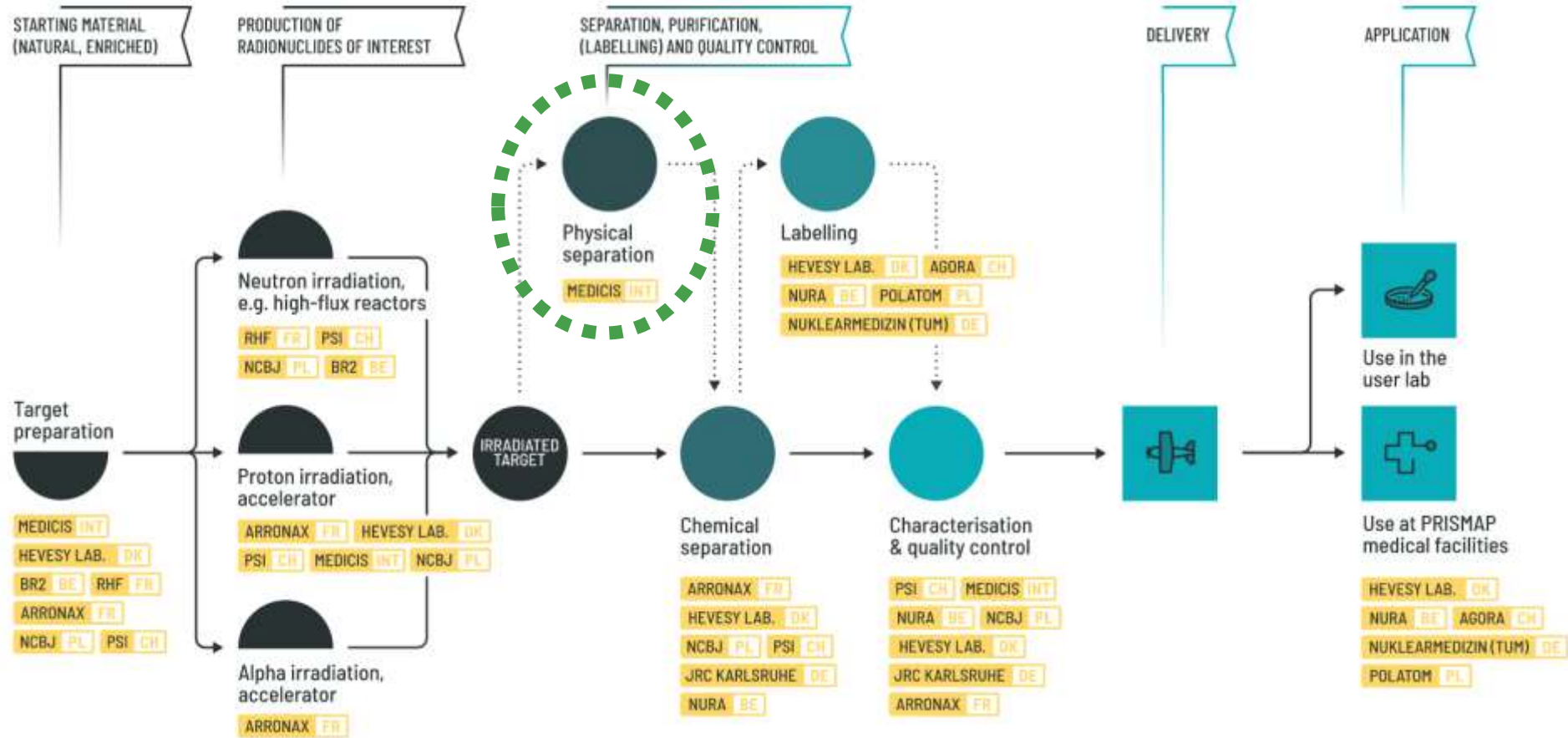
$^{48}\text{Ti}(p,2p)$ or $^{50}\text{Ti}(p,\alpha)$ or $^{51}\text{V}(p,p\alpha)$: $^{46}\text{Sc}/^{47}\text{Sc}$ ratio !

V 46 442.62 ms β^+ 6.0... γ (4317...)	V 47 32.6 m β^+ 1.9... γ (1794...)	V 48 15.9735 d ϵ β^+ 0.7... γ 984, 1312 944...	V 49 330 d ϵ no γ	V 50 0.250 $2.65 \cdot 10^{17}$ a ϵ β^- γ 1554, (783) σ 40.8, $\sigma_{n,p}$ 0.0007	V 51 99.750 σ 4.94
Ti 45 3.08 h β^+ 1.0... γ (720...)	Ti 46 8.25 σ 0.59	Ti 47 7.44 σ 1.63	Ti 48 73.72 σ 8.32	Ti 49 5.41 σ 1.87	Ti 50 5.18 σ 0.179
Sc 44 58.61 h IT 271 ϵ γ 1002 1126 1157 β^+ 1.5... γ 1157...	Sc 45 100 σ 9.8 + 17.4	Sc 46 18.75 s IT 143 β^- 0.4 γ 1126 889... σ 8.0	Sc 47 83.79 d 3.3492 d β^- 0.4, 0.6 γ 159	Sc 48 43.67 h β^- 0.7... γ 984, 1312 1038...	Sc 49 57.18 m β^- 2.0... γ (1762, 1623)
Ca 43 0.135 σ 6.2	Ca 44 2.086 σ 0.88	Ca 45 162.61 d β^- 0.258... γ (12), e^- $\sigma \sim 15$	Ca 46 0.004 σ 0.74	Ca 47 4.536 d β^- 0.7, γ 1297 489...	Ca 48 0.187 $1.9 \cdot 10^{19}$ a

70 MeV



PRISMAP: the European medical radionuclides programme



<http://prismap.eu>



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Cyclotrons ≥ 30 MeV



IBA Cyclone 30
30 MeV, 800/1500 μA



IBA Cyclone IKON
13-30 MeV, 500..1500 μA



ASCI TR30
15-30 MeV, -1500 μA



IBA Cyclone 70
30-70 MeV, 750 μA



BSC 70p
35-70 MeV, 750 μA

What to do with a 70 MeV cyclotron ?

- Commercial production: ^{82}Sr , ^{68}Ge
- Potential commercial production: ^{81}Rb , ^{123}I
- “R&D towards production” and
“production for (pre-)clinical R&D”:
 ^{67}Cu , ^{47}Sc , ^{155}Tb , ^{152}Tb , Auger e^- emitters, etc.
radiotracers of noble metals/Pt group metals