Preclinical studies with non-standard and carrier-free radioisotopes from ISOLDE-CERN

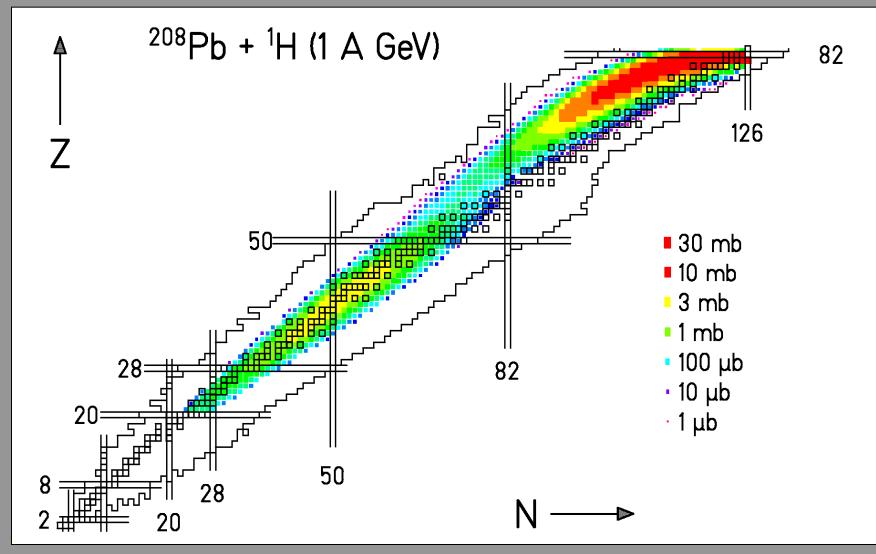
Gerd-J. BEYER Isotope Technologies Dresden (ITD), Germany formerly CERN and Hôpital Universitaire de Genève, Switzerland

> **Ulli Köster** Institut Laue Langevin, Grenoble, France

> > Helge Ravn formerly CERN

PHYSICS FOR HEALTH IN EUROPE WORKSHOP 2-4 February 2010

High-energy proton induced reactions



High-energy proton induced reactions can produce most of the isotopes of the chart of nuclides.

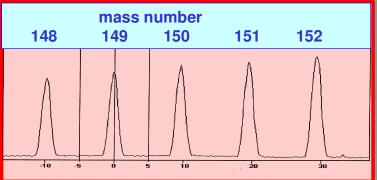
Isotope Separation On-Line

target - ion source

proton beam (1.4 GeV)

analysing magnet

radioactive ion beams



Radioisotopes available at ISOLDE-CERN

1 H			Isoto	Isotopes on-line separated at ISOLDE												2 He	
з Li	3 4 Be		Long	Long-lived isotopes available at ISOLDE 5 6 7 8 B C N O F										9 F	10 Ne		
11 Na	l 12 Mg		Deca	Decay daughters of ISOLDE beams 13 14 15 16 Al <mark>Si P</mark> S Cl									17 Cl	18 Ar			
19 K	Ca	Sc	22 Ti	23 V	Cr	Mn	Fe	Co	28 Ni	Cu	30 Zn	31 Ga	Ge	As	Se	35 Br	36 Kr
37 Rb	7 38 Sr	39 Y	40 Zr	41 Nb	42 Mo					47 Ag	48 Cd	49 In		51 Sb	52 Te	: 53 	54 Xe
55 Cs	Ba	La	Hf	Ta	W	<mark>Re</mark>	<mark>Os</mark>	lr 🛛	Pt 🛛	Au	Hg	П	Pb	Bi	Po	At	Rn
87 Fr	7 88 Ra	89 <mark>Ac</mark>	104 Rf	105 Db	106 Sg	107 Bh	108 Hs			111 Rg	112	113	114	115	116		118

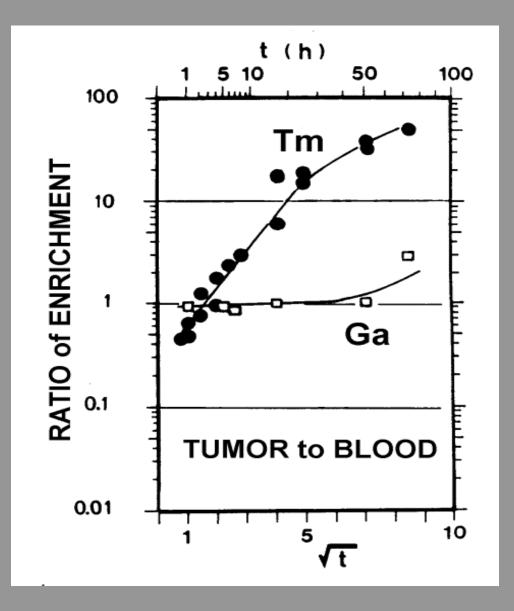
	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	•	Pr	Nd	Pm 👘	Sm	63 Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th		Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	103 Lr

Currently available: more than 1000 different radioisotopes Saturation activities of longer-lived radioisotopes: GBq and more

Content:

- Bio-Medical research performed at ISOLDE illustrating potential and possibilities
- Identify questions that require access to non-standard research isotopes
- Future possibilities at CERN

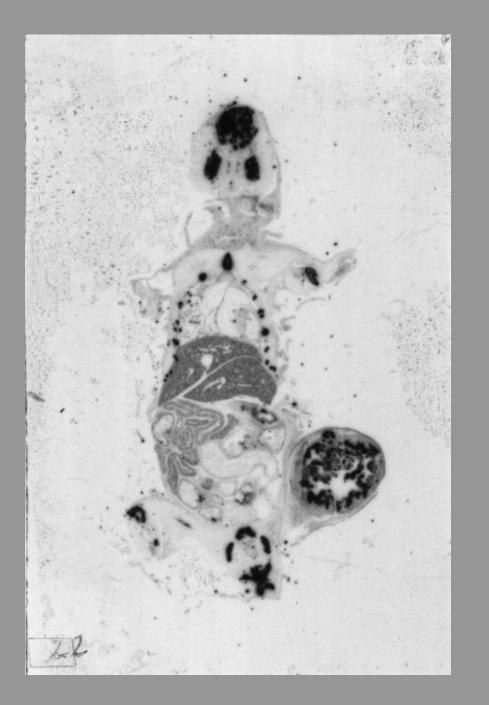
Main Focus: Endoradionuclide Therapy



Direct comparison ⁶⁷Ga-Citrate and 167**Tm-Citrate** in tumor bearing mice

Lanthanides show much faster blood clearance compared to Ga

G.J.Beyer, W.G.Franke, K.Hennig et al. Intern.J.Appl.Rad.Isot. 29, 673 (1978)

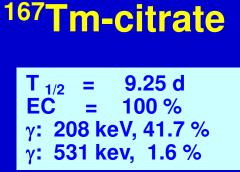


Autoradiogram of a whole body sagittal slice of a tumor bearing mouse 24 hours after injection of 0.4 MBq of ¹⁶⁷Tm-Citrate

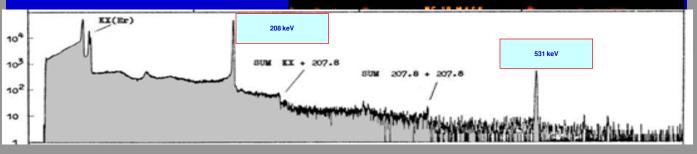
Lanthanides are unspecific tumor seeking tracers

G.J.Beyer, R.Münze et al., in: "Medical Radionuclide Imaging 1980" IAEA Vienna, (1981)Vol.1 p.587

1980



Production route: Ta (p,spallation) CERN – ISOLDE on-line mass separation cation exchange



Planar scintigraphy of the

head of a lymphoma

patient 5 h p.i.

2 mCi

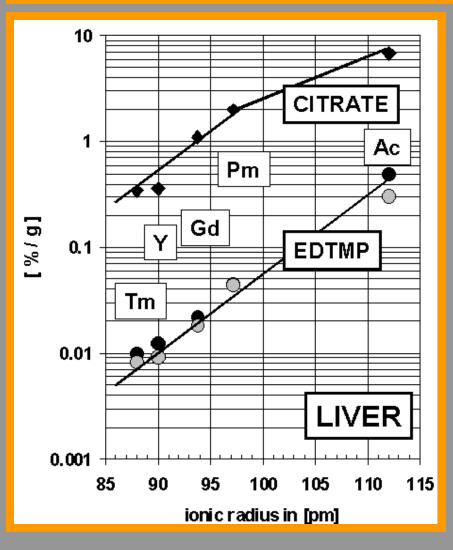
¹⁶⁷**Tm**-

citrate

First scintigraphic examination in humans using mass-separated lanthanides produced at CERN ISOLDE

G.J.Beyer et al., Medical Radionuclide Imaging 1980, IAEA Vienna (1981) 587

Simultanous injection of an isotope cocktail of rare earth isotopes

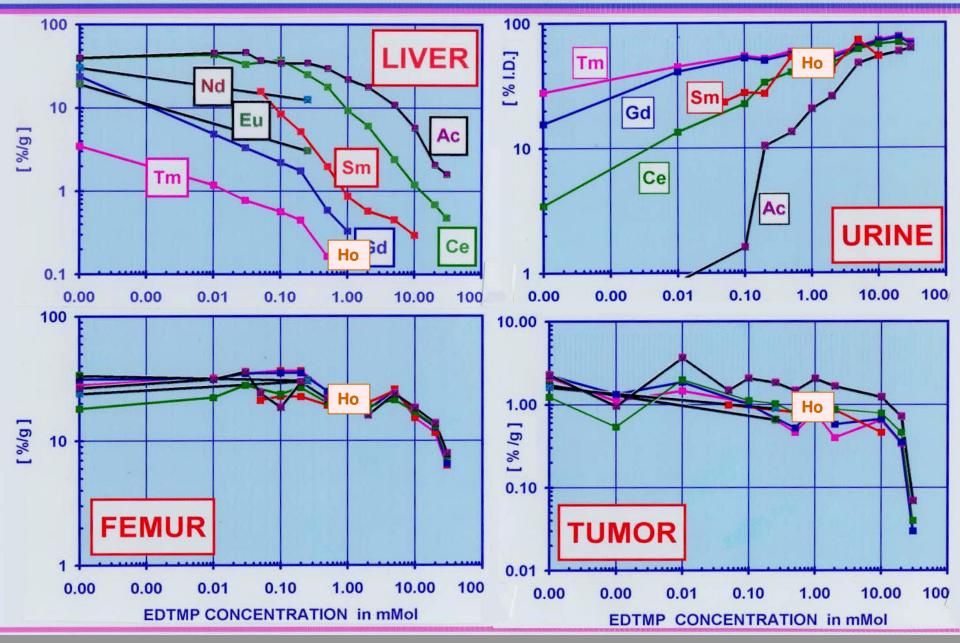


Liver uptake of ²²⁵Ac and a mixture of carrier-free radioyttrium and radio-lanthanides (¹⁶⁷Tm, ⁸⁸Y, ¹⁵³Gd, ¹⁴³Pm and ²²⁵Ac, injected in citrate and EDTMP containing solution) in tumor bearing rats (mamma carcinoma) 5 hours after injection. The injected volume was 0.5 ml, the ligand concentration was 20 mMol at pH=7

G.J.Beyer, R.Bergmann et al., Isotopenpraxis 26,111 (1990)

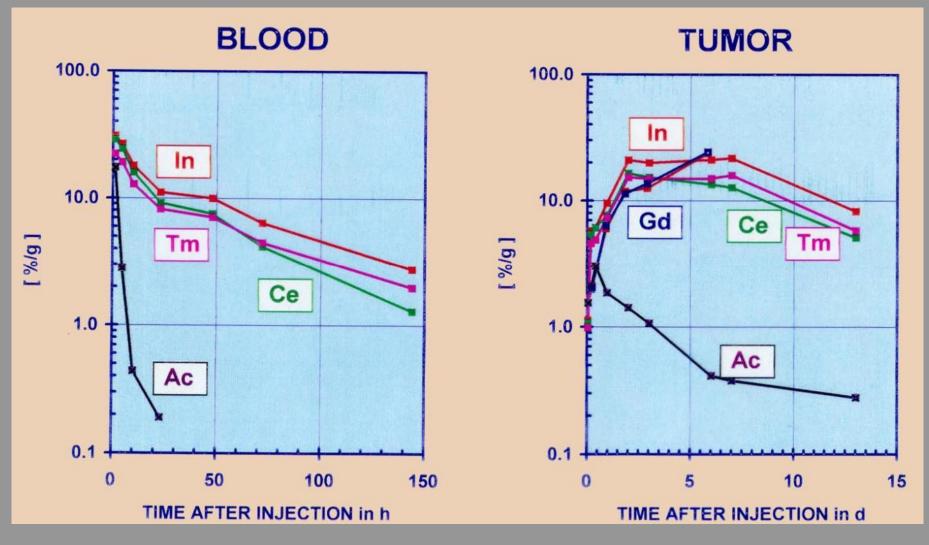
LOW MOLECULAR WEIGHT CHELATORS: EDTMP

BIODISTRIBUTION

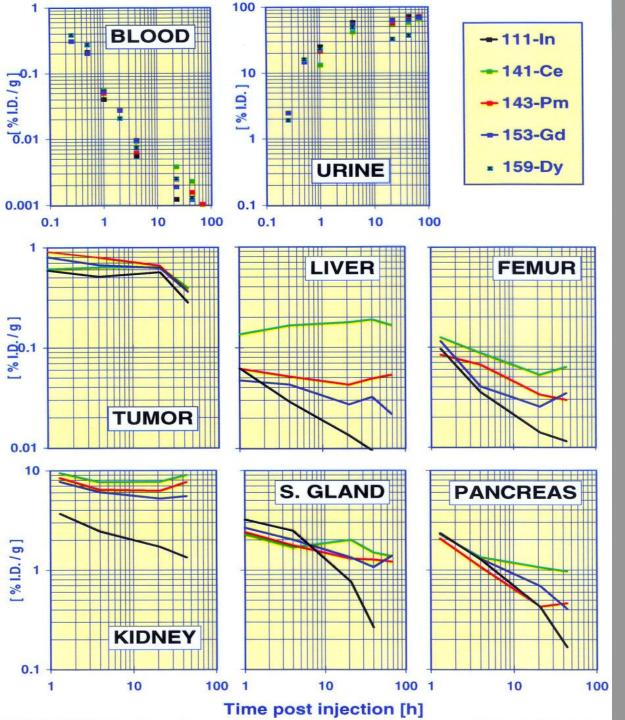


G.J.Beyer, R.Offord, G.Künzi et al. Nuclear Medicine and Biology 24 : 367-372, (1997)

Aminobencyl-DTPA-anti CEA-mab: Comparison of ¹¹¹In with radiolanthanides

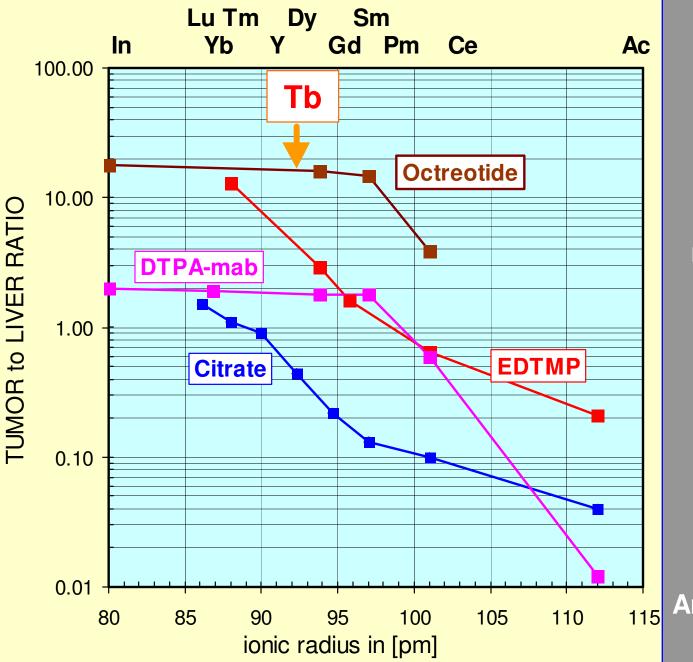


G.J.Beyer, R.E.Offord, G.Künzi et al. Journal of Labelled Compounds and Radiopharmaceuticals, XXXVII, 292, (1995)



Octreotideaminobencyl-DTPA: Comparison ¹¹¹In with Ianthanides

G.J.Beyer, R.E.Offord, R.Werlen et al. Europ.J.Nuclear Medicine **23**, 1132, (1996)



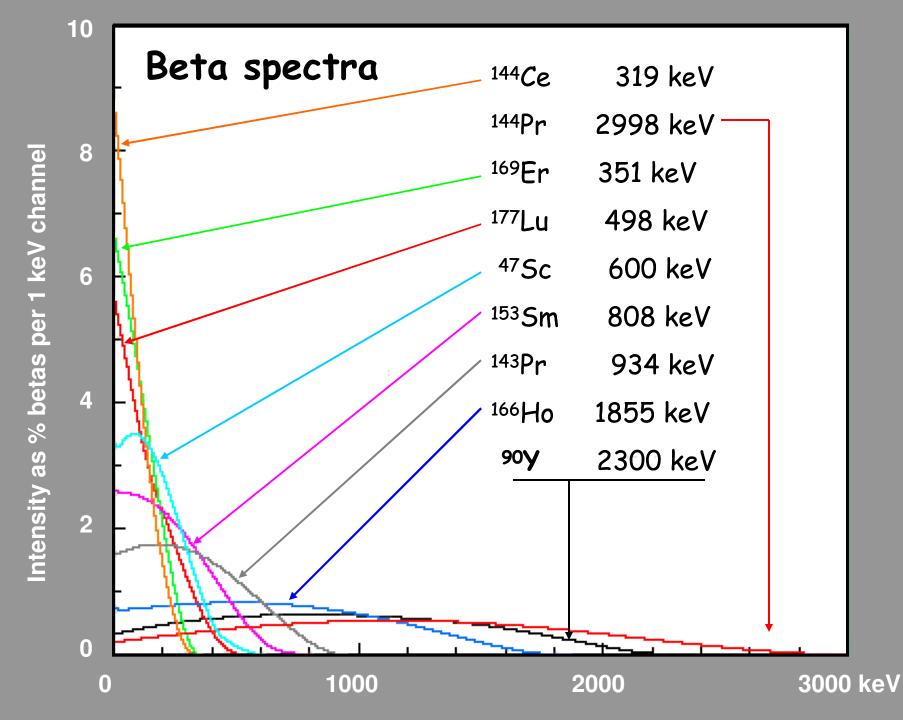
Comparison of the bio-distribution of different tumor seeking tracers labeled with radio-lanthanides, ²²⁵Ac and ¹¹¹In

free chelates: Citrate EDTMP specific tracers: Octreotide and Mab Linker: Aminobenzyl-DTPA

Questions to be answered:

 Relationship between particle-energy and therapeutic response, depending on tumor size Variation of radionuclides with different particle-energy:
→ need for metallic B⁻-emitters with very different energy
→ need for alpha emitting nuclides

2. Relationship between radiation dose delivered
to a lesion and the therapeutic response
Individual in-vivo dosimetry by quantitative PET imaging:
→ need for B+-emitting metallic radionuclides



Selected radionuclides of the Rare Earth Elements with therapeutic potential

NUCLIDE	T1/2	Radiation	Emax	E(mean)	range	volume	Εγ	Ι γ(*)	production
			[MeV]	[MeV]	[µm]	factor	[keV]	[%]	route
149-Tb	4.1 h	α	3967.0	3.97	28	1	s.Tab.1		see Tab.1
47-Sc	3.3 d	β,γ	0.6	0.161	300	1 200	159	70	47-Caß> 47-Sc generator
90-Y	64.1 h	β	2.3	0.934	4 200	3 400 000	no		90-Sr ß> 90-Y generator
137m-Ce	34.4 h	е	0.2	0.203	500	5 700	254	11	136-Ce (n,γ) 137m-Ce reactor
141-Ce	32.5 d	β,γ	0.6	0.171	400	2 900	145	48.4	235-U (n,f) fis.prod. reactor
									141-Pr (p,n) 141-Ce cyclotron
142-Pr	19.1 h	β,γ	2.2	0.809	3 500	2 000 000	1576	3.7	142-Pr(n,γ)143-Ceβ> 143-Pr reactor
143-Pr	13.6 d	β	0.9	0.315	900	33 000	no		142-Ce(n,γ)143-Ceβ>143-Pr reactor
147-Nd	11 d	β,γ	0.9	0.27	700	16 000	91	28	235-U (n,f) fis.prod. reactor
							531	13	146-Nd (n,γ) 147-Nd reactor
149-Pm	53.1 h	β	1.1	0.366	1 100	61 000	weak		148-Nd(n,γ)149-Ndβ>149-Pm reactor
153-Sm	46.7 h	β,γ	0.8	0.269	1 000	57 000	103	28.3	152-Sm (n,γ) 153-Sm reactor
159-Gd	18.6 h	β,γ	1.0	0.312	800	23 000	364	10.8	158-Gd (n,γ) 159-Gd reactor
161-Tb	6.9 d	β,γ	0.6	0.195	800	26 000	75	9.8	160-Gd(n,γ)161-Gdβ>161-Tb reactor
166-Ho	26.8 h	β,γ	1.9	0.694	3 400	2 200 000	80.6	6.2	164-Dy(2n,γ)166-Dyβ>166-Ho reactor
169-Er	9.4 d	β	0.3	0.103	200	360	no		168-Er (n,γ) 169-Er reactor
175-Yb	4.2 d	β,γ	0.5	0.13	250	700	396	6.5	174-Yb (n,γ) 175-Yb reactor
177-Lu	6.7 d	β,γ	0.5	0.147	300	1 200	208	11	176-Yb(n,γ)177-Ybβ>177-Lu reactor

See presentation by M. Miederer for alpha-emitting ¹⁴⁹Tb.

ß* emitters for in vivo dosimetry

Scintigraphic abdominal images 5 & 24 h p.i. affected by carcinoid with extensive hepatic and paraaortal metastases.

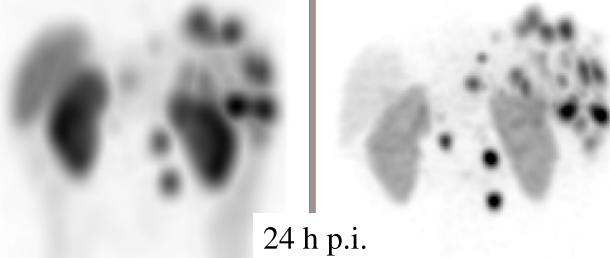
Patients:

- 3 patients with metastases of carcinoid tumor
 - (histologically confirmed)
 - No the rapy with unlabeled somatostatin > 4 weeks
- Age: 46 67 years, male
- All were candidates for a possible ⁹⁰Y-DOTATOC therapy

unider

[⁸⁶Y]DOTA-DPhe¹-Tyr³octreotide PET





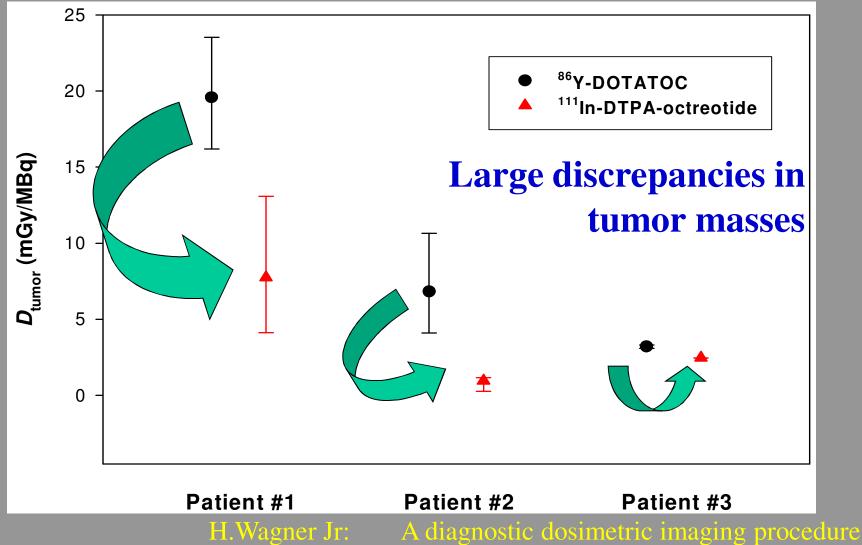


[¹¹¹In]DTPA-

SPECT



Radiation doses for [⁹⁰Y]DOTATOC therapy (based on [⁸⁶Y]DOTATOC-PET)



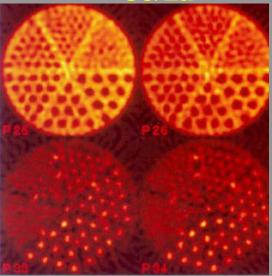
F.Rösch et.al.

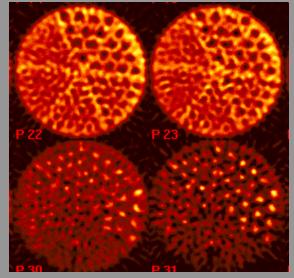
will be unavoidably a part of the protocol for the radioimmuno therapy (individual in vivo dosimetry).

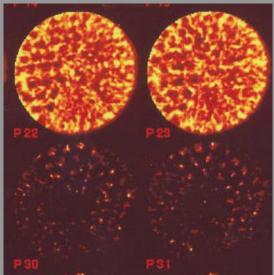
Rar	e Eart	h Ele	men	Positron Emitters				
Nuclide	T 1/2	% B +	MeV	MeV γ / %	Production Route			
⁴³ Sc	3.9 h	88	1.2		⁴³ Ca (p,n) ⁴³ Sc, ⁴⁴ Ca (p,2n) ⁴³ Sc			
⁴⁴ Sc	3.9 h	94	1.5		⁴⁴ Ti decay (generator), ⁴⁵ Sc (p,2n) ⁴⁴ Ti V, Ti (p,spall)			
85m Y	4.9 h	67	2.3	238 34	⁸⁶ Sr (p,2n) ^{85m} Y, ISOLDE			
86 Y	14.7 h	32	1.2	637 33 1077 83	⁸⁶ Sr (p,n) ⁸⁶ Y ISOLDE			
¹³⁴ Ce ¹³⁴ Pr	75.9 h 6.7 m	EC 64	2.7	No 605	Ta, Er, Gd (p,spall) ¹³² Ba (α,2n) ¹³⁴ Ce			
¹³⁸ Nd ¹³⁸ Pr	5.2 h 1.5 m	EC 76	3.4	No 789 4	Ta, Er, Gd (p,spall) ¹³⁶ Ce (α,2n) ¹³⁸ Nd, ISOLDE			
¹⁴⁰ Nd ¹⁴⁰ Pr	3.4 d 3.4 m	EC 50	2.4	No No	Ta, Er, Gd (p,spall), ISOLDE ¹⁴¹ Pr (p,2n) ¹⁴⁰ Nd,			
¹⁴² Sm ¹⁴² Pm	72.4 m 40.5 s	6 78	1.5 3.9	No No	Ta, Er, Gd (p,spall), ISOLDE ¹⁴² Nd (α,4n) ¹⁴² Sm			
¹⁵² Tb	17.5 h	20	2.8	Div	Ta (p,spall) ISOLDE ¹⁵² Gd (p,4n) ¹⁴⁹ Tb, ¹⁴² Nd(¹² C,5n) ¹⁴⁹ Dy			

¹³⁴Ce/La

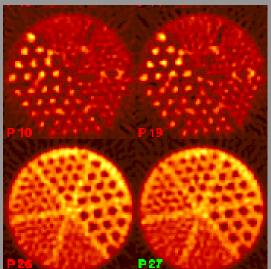






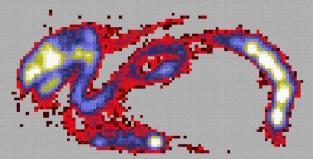


Positron emitting radiolanthanides

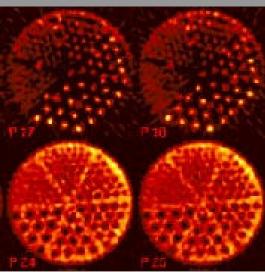


PET phantom studies

¹⁴²SmEDTMP in vivo study



CERN Grey Book 1997 Cover page









a-emitters for therapy

Summary

- High-energy proton induced reactions can produce essentially all isotopes of medical interest
- High energy protons in combination with mass separation (on-line or off-line) provide a universal production method for R&D isotopes.
- These radioisotopes are practically carrier-free and of high purity.
- The universality of ISOLDE enables systematic biokinetic studies, simultaneously with different isotopes and different tracers.
- Already today ISOLDE can supply quantities of metallic PET-isotopes and α-emitters for preclinical and clinical "phase 0" studies in RIT.



Applied Radiation and Isotopes 63 (2005) 157-178

www.elsevier.com/locate/apradiso

The US national isotope program: Current status and strategy for future success

Mark J. Rivard^{a,*}, Leo M. Bobek^b, Ralph A. Butler^c, Marc A. Garland^d, David J. Hill^{e,1}, Jeanne K. Krieger^f, James B. Muckerheide^g, Brad D. Patton^e, Edward B. Silberstein^h

The most demanding isotope supply challenge concerns the isotopes used in R&D, an area in which quantities are small, production techniques are not well established, and costs are high. Isotopes for R&D use without proven markets and profitability are not being adequately supplied.

Future of ISOLDE Isotopes for Nuclear Medicine

What should be done at CERN:

- Launch a new European collaboration for bio-medical and nuclear medicine studies with carrier-free radioisotopes from ISOLDE and other sources.
- Rebuild a radiochemical laboratory at ISOLDE for on-site chemical purification of radioisotopes.
- Prepare technological solutions for larger-scale isotope production with coming accelerator upgrades (LINAC4, SPL).

Possible longterm future: MW protons on Hg target

Radio- isotope	Half-life T _{1/2}	X-section (mb)	Production rate (per s)	Alterr production	native processes	Applications
192-lr	74 d	2.58E+00	1.0E+14	(n,γ)	reactor	Sealed sources for industry and cancer therapy
188-W/Re	69 d	6.90E-02	2.7E+12	(2n,y)	HFR	Radio-immuno-therapy with 188-Re
178-W/Ta	22 d	8.08E+00	3.1E+14	(p,4n)	accelerator	Generator with potential in PET
177-Lu	6.7 d	6.31E-02	2.4E+12	(n,y)	reactor	Therapy with labelled antibodies and peptides
166-Ho	25.8 h	5.30E-03	2.0E+11	(Π ,γ)	reactor	Therapy with labelled antibodies and peptides
149-Tb	4.12 h	9.21E-01	3.5E+13	1		Targeted Alpha Therapy, single cancer cell targeting
148-Gd	74.6a	5.31E-01	2.1E+13	spallation	accelerator	Low-energy alpha sources
153-Sm	46.75 h	1.41E-03	0.6E+11	(n,y)	reactor	Therapy of bone metastases
127-Xe	76.4 d	9.22E-02	3.5E+12	(p,x)	accelerator	SPECT, lung ventilation and brain perfusion
117m-Sn	13.6 d	1.78E-01	0.7E+13	(Π ,γ)	HFR	Systemic radionuclide therapy
99-Mo/99m-Tc	66 h	2.78E-01	0.6E+13	(n, f)	reactor	Most important radionuclide for nuclear medical imaging
89-Sr	50.5 d	5.39E-01	2.1E+13	(n,γ), (n,p)	reactor	Palliative therapy of bone metastases
82-Sr/Rb	25.5 d	1.36E-01	0.5E+13	(p,4n)	accelerator	Generator, PET, myocardial perfusion
68-Ge/Ga	288 d	9.38E-02	3.6E+12	(p,2n), spall.	accelerator	Different PET imaging procedures, calibration of PET
67-Cu	61.9 h	3.83E-01	1.5E+13	(p,γ)	accelerator	Therapy with labelled antibodies and peptides
44-Ti/Sc	47.3 y	1.77E-03	0.7E+11	spallation	accelerator	Generator, great potential for PET
32-Si	101 y	3.03E-02	1.2E+12			Important isotope for R&D and technical application
26-AI	7.16e5 y	6.05E-03	2.3E+11	(p,n)	cyclotron	Important isotope for R&D and technical application
28-Mg	20.9 h	1.45E-02	0.6E+12			Important isotope for R&D
				See po	oster I	D120

Thank you

for your kind attention

Gerd Beyer

Production Routes

			9s	215	24 \$ 88 \$	42 \$ 35,6 \$		213 18 9.3 18	2.2.00 21.0	48 m	5,8m 56m -2m
				B*	245 005	. / . /	8 82 15 1				
			γ 1688; 662; 504	γ 1091; 1073; 1584	653, 394, 7 803, 551	α 4.61 0 4.52 <u>γ</u> 776 <u>γ</u> 527 α→m	- 18 358	2 2 99 L 200 B 2 2 99 L 200 B 2 2 5 2 98 L 200 B 2 2 5 2 98 L 200 B 2 2 98 L 200 B 2 2 99 L 200 B 2 2 90	812 112 877 171	β* 1.8 γ 240; 136	v 1572. v 138 v 138. 446. 267
			Dy 147	Dy 148 3.1 m	Dy 149 4.1 m	Dy 150 7.2 m	Dy 151	Dy 152 2,4 h	Dy 153 6,29 h	Dy 154 ~ 10 ⁷ a	Dy 155 10,0 h
i	ndir	ect			β* 2 101: 1777;	β ⁺ α 4,23 γ 397	4 07 7 386 19-1148	ting and	ε;β* α 3,46		е В ⁺ 0.9; 1,1
					789; 1806 g: m	0	176. g:m	1 K 21	y 81; 214; 100; 254	α 2.87	y 227
	Tb 144	Tb 145	Tb 146	b 147	Tb 148	Tb 149 4,2m 4,1h	Tb 150	Tb 15 25 s 17,6 b	Tb 152 4,2 m 17,5 h	Tb 153 2,34 d	Tb 154 23h 9,0h 21h
	irec	t ro	utes	7.1124	+ 4.0	β+ 0.3.99 9 β+ 1.8 9 296 165 165	20 x 2,53		1/283 1 10 6+2.8 -344	β*	1420, 748, 774 1420, 748, 7274
0.1.1.10	4743	1	1417	198. 894. 1795. 140.	632 489 882 632		22	2080. BB	411	102.83	123 540
Gd 142 1,5 m	Gd 143	Gd 144 4,5 m	Gd 145 85 s 23,9 m	Gd 146 48,3 d	Gd 147 38,11	~ 90 a	Gd 14 9,5 d	Gd 150 1,8 · 10 ⁶ a	120	3 1 152 20 1,+- 10 ¹⁴ a	Gd 153 241,6 d
β ⁺ γ 179	β ⁺ γ 272, β ⁺ 588, γ 259, 799, 205, 668, 464_	β* 3.3 y 333; 347;	hy 721 β ⁺ 2.3 β ⁺ y 387; 1881;	A.	ε. β* γ 229: 396		ε; α 3,01 γ 150; 299;		ε: α 2,60 γ 154; 243;	a 2.14	
9	and a second second second	630 Eu 143	Eu 144	Eu 145	929 Eu 146	3,183 E8,147	347 Eu 148	α 2,72 Eu 149	175 Eu 150	e 1100 Eu 151	γ97; 103 Eu 152
Eu 141 3,3 s 40,0 s	Eu 142 1,22 m 2,4 s	2,6 m	10,2 s	5,93 d	4,51 d	24.0d	55,6 d	93,1 d	12,6 h 35,8 a	47,8	96m 9,3h 13,33a
v (394; v 394; 893) 385; iv (96) 383; e^; m 593p	β ⁺ 4.8 γ 768, 1023, β ⁺ 7.0 557	β ⁺ 4,1 γ 1107; 1537; 1913; 108;	β* 5.2	8 1.7. 7 894; 1659;	ε. β* 1,5, 2,1 γ 747; 633;	ε; β ² ; φ 2,91 γ 197; 12	ε; β*; α 2,63 γ 550; 630; 611	r y 328: 277	8+ + + + 334 7,834 + 439	a 4,0+3300+ 5900	17 90 141 15 122
Sm 140	557 y 768 Sm 141	1805; g Sm 142	Y 1660; 878	Sm 144	Sm 145	678. Sm 46	Sm 147	Sm 148	Sm 149	Sm 150	Sm 151
14,8 m	22,6 m 10,2 m	72,4 m	65 s 8,83 m	3,1	340 d	1,03-10 ⁸ a	15.0 1.06 · 10 ¹¹ a	11.3 7 · 10 ¹⁵ a	13,8	7,4	93 a
β ⁺ 1,9 γ 226; 140	5 ⁺ 2.9	ε β ⁺ 1,0 γ (679)	h 754 β*	a~07	ε;γ61;(492) e ⁻ α ~ 110	02.5	α 2,234 α 64	α 1.96 σ 2.7	o 41000	o 102	β ⁻ 0,1 γ (22); e ⁻ σ 15000
Pm 139	Pm 140	Pm 141	Pn 142	Pm 143	Pm 144	P n 145	Pm 146	Pm 147	Pm 148	Pm 149	Pm 150
4,15 m β ⁺ 3,0	5,95 m 9,2 s β* 3.2. β* 5.1. γ 1028. γ774;	20,9 m β ⁺ 2,7 γ 1223: 886:	40,5 s	265 d	1,0 a	7,7 a	5,53 a ε: β ⁻ 0.8 y 454 747 736	2,62 a	41.3 d 5.37 d p*0.4 p*2.5 1.0 + 550	53,1 h β ⁻ 1.1.	2,7 h B-2.3; 3.4
y 403; 463; 368 9	β [*] 3.2. β [*] 5.1. ¹ / ₇ 1028. ¹ / ₇ 774; 774: 717, 420. 1499.	9 1223, 660, 194; 1346 9	13,8	no β* γ 742	47	72; (67)	736.0 8400	γ(121) α85+96	* 500. 5465. Fy(761)* 915. o 22000 or 2000	γ 286. α 1400	y 334; 1325; 1166
Nd 138	Nd 139	Nd 140 3.37 d	Nd 141	Nd 142 27,13	Nd 143	Nd 144 23,80	Nd 145 8,30	Nd 146 17,19	Nd 147 10.98 d	Nd 148 5.76	Nd 149 1,73 h
	5,5 h 29,7 m ⁶ ⁶ ⁷ ¹⁴ ,73k ⁶ ⁸ ⁸ ¹ ¹ ¹	3,37 0	62 s 2,5 h s 3 0,8 by 757 y 11127.	27,15		2,1·10 ¹⁵ a	0,00	11.10	(IT 0.8: 0.9	0,10	6-1.4:1.6.
γ 326; (200) g	982,708 7405. 7/(231): e ⁻ 1074	ε πο γ	р+ т (971) 1147)	σ 18,7	o 325 o _{n.o} 0,0174	α 1,83 σ 3,6	0.42	o 1,3	791:531 e	a 2,48	y 211; 114; 270
Pr 137 76.6 m	Pr 138	Pr 139 4.5 h	Pr 140 3,4 m	Pr 141 100	Pr 142	Pr 143 13,57 d	Pr 144 7,2 m 17.3 m	Pr 145 5,98 h	Pr 146 24,0 m	Pr 147 13,6 m	Pr 148
ε; β ⁺ 1,7	See. atra	ε; β ⁺ 1,1 γ(1347; 1631)			16-2.2	β ⁻ 0.9 γ.(742)	ly 59 p	IT-1.8	0-4.1_	β*2,1:2,7 y 315:641:	0 0 47;
γ 837; 434; 514; 160; g	1038: (668; 303. 1551)	9) β ⁺ 2,4 γ (1596)	03,9+7,6	by (4) 7 1576. € 0.20	o 89	814_1 (2186_)	y (748: 676)	y 454; 1525	578, 78	451 302 698 - 1358
Ce 136 0,19	Ce 137 34,4 h 9,0 h	Ce 138 0,25	Ce 139 56,5 s 137,6 d	Ce 140 88,48	Ce 141 32,50 d	Ce 142 11,08	Ce 143 33,0 h	Ce 144 284,8 d	Ce 145 2.98 m	Ce 146 13.5 m	Ce 147 57 s
	¹ η 254 «" β ⁺ « γ.447, γ.(825; (437)				β ⁺ 0,4; 0,6 γ 145		β ⁻ 1.1; 1.4 γ 293; 57; 665; 722	рто.з., т 134:80 9	β ⁻ 1,7; 2,1 γ724;63,1148,	β ⁺ 0,8. γ 317: 218;	β ⁻ 3,3 γ 269; 93; 580;
o 0.95+6.3 La 135	V(825. (437) 169) e" La 136	00.015+1.1	1754 7166 La 138	۵0.57 La 139	La 140	σ0,95 La 141	6,0 La 142	La 143	285:440 La 144	265, 134 La 145	374 La 146
19,4 h	9,9 m	La 137 6 · 10 ⁴ a	0,09	99,91	40,272 h	3,93 h	92,5 m	14,23 m	40,9 s	24,8 s	6,2 s 10 s
ε; β ⁺ γ 481; (875; 588); g	ε; β* 1,9 y 819; (761; 1323)	ε noγ g	1,35 · 10 ¹¹ a ε;β ⁻ 0,3 γ 1436,789	σ 9 ,0	β ⁻ 1.4; 2;2 γ 1596; 487; 816; 329 σ 2,7	β ⁻ 2,4 γ 1355	β ⁺ 2.1:4.5. γ 641:2398: 2543.	β ⁻ 3.3. γ621; 644	β ⁺ 4,1;4,4 γ 397:541: 845	f ⁻ 4.0; 4.1 у 70; 356; 118; 170;447; 1819	β ⁺ 6.9 y 259, y 259; 410 925 503
Ba 133	Ba 134	Ba_135	Ba 136	Ba 137	Ba 138	Ba 139	Ba 140	Ba 141	Ba 142	Ba 143	Ba 144
38,9 h 10,5 a ly 276; 12 r	2,417	28,7 h 6,592	7,854	2,55 m 11,23	71,70	83,06 m	12,75 d β ⁻ 1,0 χ 537; 30; 163;	18,3 m	10,7 m	14,5 s	11,9 s
12 ε ε γ 356; ε 81; γ (633) 303	σ 0.158 + 1.8	lγ 268 e σ 5.8	σ 0,010+~0,4	₩ 662 o 5,1	σ 0.35	β ⁻ 2,4 γ 166; (1421) σ 6	γ 537; 30; 163; 305 σ 1,6	β ⁺ 2,8; 3,0 γ 190; 304; 277; 344	β 1.0; 1.7 γ 255; 1204; 895	β 4,2 γ 211; 799; 980; 1011	β ⁻ 2,4; 2,9 γ 104; 431; 388; 157; 173
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Er 154 3,75 m Er 156 18,6 m

35; 30.

Er 157 ~ 25 m

β⁺ γ 121; 391...

Ho 156

3 p-spallation ~1 GeV p / Ta

2 Light particle induced reactions

HI induced reactions

1

G.J.Beyer, J.Comor et al. Radiochimica Acta 90, 247-252 (2002)