Photodissociation of neutron deficient nuclei

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• *p*-Process Nucleosynthesis

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- The Photoactivation Technique @ S-DALINAC

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- Summary & Outlook

Reaction rates in the $A \approx 100$ region at $T_9 = 2.5$

Rh 93	Bh 94	Bh 95	Bh 96	Bh 97	Bh 98	Bh 99	Bb 100	Bh 101	Bb 102	Rh 103	Rh 104	Ph 105	Dh 106
	70,6 8 25,8 8	1,96 m 5,0 m	1,5 m 9,9 m	44 m 31 m	3,5 m 8,7 m	4,7 h 16 d	4,7 m 20,8 h	4,4 6 3,3 8	2.9 a 207 d	56,1 m 100	4.4 m 42 s	45 s 35.4 h	22h 30
	7.5. 11431;		B*4.7 B*3.3	1 26. 3121.		1 0.7 A. 0.7:	1 32:74 B+ 2.6.		1475 B+1.8	1000	h 61 5- 2.a	p*a.s	8" Q.9: 1.7.
	758 312; 1075;\$0 146	9" 7542. 5784. 1382.	1099, 585, 1992, 532,	422. 840. h 258 879	7 652; p* 0.5	558 7528	7 (540, 2338, 467 1 1583	Y 367; + 122; 545 198; 545 198;	601; 8° 12 667	H (40) - 11-	5"	lh 130 = 5000 =	γ 612: β= 3,8 1648: γ 512
Ru 92	Ru 93	Ru 94	Ru 95	Ru 96	Bu 97	Bu 98	Bu 99	Bu 100	Bu 101	Bu 102	Bu 103	Bu 104	Ru 105
3,65 m	10,8 s 59,7 s	51,8 m	1,65 h	5.52	2,9 d	1,88	12,7		17,0	31,6	39,35 d	18,7	4,44 h
β*	7 1296; p* 5,3 1191;m 1681;		 ε; β⁺ 1,2 γ 336; 1097; 								8-0.2:07		β 1,2; 1,8 7724: 469
y 214; 259; 135	19734 1435 BD 2.48 0	γ367; 891 m	627 9	ar 0,25	y210; 324 9	248	π 4	σ 5.8	a 5	a 1,3	γ497; 610 m		676; 316 g; m; c 0.30
Tc 91	Tc 92	Tc 93	Tc 94	Tc 95	Tc 96	Tc 97	Tc 98	Tc 99	Tc 100	Tc 101	Tc 102	Tc 103	Tc 104
3,3 m 3,14 m 8* 5.2	4,4 m	43,5 m 2,7 h	53 m 4,9 h	60 d 20 h	52 m 4,3 d	92,2 d 4,0 -	4,2 · 10 ⁶ a	6,0 h 2,1-	15,8 s	14,2 m	4,3 m 5,3 s	54,2 s	18,2 m
g* 1642	B+ 4.2	* 3 1303.	8*0.8 y 871;	7 204: * 582: rop!	e" no #* 4 y 770;		B= 0.4	h 141	β 3,4		3.2 × 475:	β ⁻ 2.2	β 5,1
m 9	329; 148	y2045 1085	y 871 850	835 y 188; hy (38) 9074	3 778; 850; 1200 813	e" re y	y 745; 662 σ 0,9 + 1,67	8" 7 13221 0 20	γ 540; 591	β ⁻ 1,3 γ 307; 545	631; 628; hy y 475	y 346; 136; 210	y 358; 531; 535; 884; 893
Mo 90	Mo 91	Mo 92	Mo 93	Mo 94	Mo 95	Mo 96	Mo 97	Mo 98	Mo 99	Mo 100	Mo 101	Mo 102	Mo 103
5,7 11	60 S 15,5 M	14,04	6.9 h 3.5 ·	9,25	15,92	16,68	9,55	24,13	66,0 h	9,63	14,6 m	11,2 m	67,5 s
β ⁺ 1,1 γ257	4.0. \$*3.4		263						y 740; 182;	1,15-10-8	β ^{-0,8} ; 2,6	y212: 148:	B-
m; g	/1208; n g		p n		o 13,4	σ0,5	a2,5	or 0,14	m; g	0 0,19	1013; 508	9	y 83; 424; 688; 519
Nb 89	Nb 90	Nb 91	Nb 92	Nb 93	Nb 94	Nb 95	Nb 96	Nb 97	Nb 98	Nb 99	Nb 100	Nb 101	Nb 102
66 m 2,0 h 8*3.3 26 - 1977	10,0 8 19,0 n	e0,9 0 680 a	10,15 d 3,6 · 10 ⁷ a	16,13 8 100	6,26 m 2-10* a p=0,5	85,5 h 34,97 d	23,4 h	53 s 74 m	51 m 2,9 s 5" 2,0;	2,8 m 15 s	3,1 s 1,5 s	7,1 s	4,3 s 1,3
y 588; 1835; 507, 3005,	y 122. 2019	5.8*	1. 1. MAR	h (11)	e ⁻ 703	6 238 B-0.2	β ^{-0,7}		29 2787: BT 4.8	γ 38; 254 2642; F 3,1	F 4.2 1.538 7.835	β- 4,3	3"-4.0 \$".7,5 1/256; 1/296
n g	a ⁻ 141	y 1205 84	7 534 234	e ⁻ 1.0	Y (875) 54.4	1254. 0<7	1091	Py 743 7658	1160 1004	hy 3057 88	1280 159	450; 441; 467	1633; 551; 551 401
Zr 88	Zr 89	Zr 90	Zr 91	Zr 92	Zr 93	Zr 94	Zr 95	Zr 96	Zr 97	Zr 98	Zr 99	Zr 100	Zr 101
00,40	hy 588	31,43		17,15	1,5 . 10. a	17,35	64,0 d	2,80 3.9 · 10 ¹⁹ a	16,8 h	30,7 s	2,1 \$	7,1 s	2,1 s
	5*0.9 5*0.5 24 1(1713)				β 0,06 m		β ⁺ 0,4; 1,1 v757; 724	207	y 508: 1148: 355	β 2,3	γ 469; 546; 594	BT 2.8: 3.0	y 119; 206;
y 393	y 1507;g m	σ = 0,014	at 1,2	0.0,2	σ-2	or 0,049	9	0.020	m	9	g; m	9	2010; 598
13h 803h	106.6 d	Y 89	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96	Y 97	Y 98	Y 99	Y 100
h 381	,o a		h 238	40,0 m 00,0 0	0,04 11	10,111	10,7 111	β ⁻ 4.4	8,9 8 5,34 8	1,2 5 3,75 s (F 5,1; (F 6,7	2,0 \$ 0,55 8 8"4.8: 8"8.8.	1,4/ S	0,94 s 0,73
p*	β*	- 0.001 +	480 87	\$*1.5. v (1209)	β ⁼ 3,6 γ 934; 1405;	ρ ⁻ 2,9 γ267; 947;	β ⁻ 4,9 γ 919; 1139;	y 954; 2176; 3577; 1324;	γ1751 9'0:017: 5"7.1	7 1123: 3401 101.975. 1997.	7 1223; 2941; (01. 1541	β 6,8; 7,5 γ 122; 724	1212 1213
0 11	A 1020: 080'	12 809 1200	Y (2319) 1 (2198)	h 556 a 1,4	561; 449	1918	551	2633	1107. × 1750.	In (898) 80	80 80	Bn	970 04

Reaction rates in the $A \approx 100$ region at $T_9 = 2.5$

Rh 93	Rh 94	Rh 95	Rh 96	Rh 97	Rh 98	Rh 99	Rh 100	Rh 101	Rh 102	Rh 103	Rh	ν.n) 🚽	
	β* 6.4, β* 7.4., γ 1431; 1431; 798, 312, 1073, β¢ 148.,	1,543 B ⁺ 3.2 3 ² 1,784 1362	hr (53): e p* 4.7 p* 3.3 y 850: 1.833 1220. 685; 1222 432	μ ⁺ 2,6 γ 168: γ 422 422 840; 1γ 259 878	3* 7 652 p* 3.5 745	β*0 β*0.7; γ.54 [.1. 618; γ.528; 1201, 203,90.	hy 32; 7 R ⁴ y (542) 1653	1 4 7 307: 1 127: 545 128: 128: 129:	4 1.470; A10 631; A10 631; A10 1.475;	h (40) e 11 a	γ 51 3 1 (598)	,,,.,	`
Ru 92 3,65 m	Ru 93	Ru 94 51,8 m	Ru 95 1.65 h	R 6	R∖ J7 ≎⊌d	ú 98 1.88	R 99	R 100	Ru-101	Ru 102	Ru 39,1	γ,p)	
β ⁺ γ214: 259: 135	y 1396: 1191m y 531 19734 192,45 g	ς γ.357; 8:1 m	 β⁺ 1,2, γ 338; 101 827 9 	10.25	s 216; 324	1<8	4		5	σ1.3	8 0,2; γ.497; 6 m		▼,
Tc 91	Tc 92 4,4 m	TC .3 43.5 m 27 h	TC 5 53 m Joan	To 25	TC 96	TC 57	Tc 98 42.105 a	Tc 99	Tc 100 15,8 s	Tc 101 14,2 m	TC 4,3 m	(γ, α)	
8* 12451; 1542; 1605 m 2	β ⁺ 4,2 γ 1510; 773; 329; 148	hy 392 1* 6.8. 1 1883 1 2045 5281 1 5281 1 5281	2.2.5 15 8 1871 10	1,204 500 5,000 5,000 5,000	100 JT 7778 850: 812.	200	β ⁻ 0.4 γ 744, 652 σ 8,9 + 1,67	h 141 	β ⁼ 3,4 ^e γ 540; 591	β 1,3 γ 307; 545	8" 1.6: 3.2 y 475; 601; 608; h		
Mo 90 5,1 n	Mo 91	Mo 92	Mo 9.	Mo.94 9,29	Mc 95	Mo .6 16,68	Mo 97	Mo 98 24,13	Mo 99 66,0 h	Mo 100 9,63	Mo 101 14,6 m	Mo 102 11,2 m	Mo 103 67,5 s
ε β* 1,1 γ257 m; g	8*2.8: 4.9		685; 283; e y(550) g		13,4	10.5	125	0.14	β 1,2 γ 740; 182; 778 m: g	1,15 · 10 ¹⁹ a	β 0.8; 2,6 y 192; 591; 1013; 506	β ⁻ 1,1 γ212; 148; 224	β" γ 83; 424; 000: 519
Nb 39	NL /0	Nb /1	Nb 9.	Nb 93	Nb 94 8,28 m 2 10 ⁴ a	Nb 95	Nb 96 23,4	Nb 97 53 s 74 m	Nb 98 51 m 2,9 s	Nb 99 26 m 15 s	Nb 100	Nb 101 7,1 s	Nb 102
2,5 y 568 833 507 Ti	hr 122 er	hy (108) e < β ⁺ γ 1206 - Γ ⁺	3 3 334 954	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	17 (41) 5 (41) 5 (41) 705 705 14.4	h 235 of 1.4 1 236 1 236 1 236 0 < 7	β ⁺ 0 7 278; 569; 091	fy 743 g ^{+−} 1,3, y 550,	8" 2.8. 2,2 9 787. 8" 4,6 723. 9 787. 1 109 1024	6"3.2. 7 99, 254; 2642: p 3,1 2684. y 138; 1y 3857: 58	μ 5.5; 1.535; γ.535; 600; 538; 1280 158	β ⁺ 4.3 γ278; 158; 480; 441; 467	β ⁺⁺ 4.8 β ⁺⁺ 7.3 γ.296; γ.296; 1633; 551; 551 401.
Z, 12 83, d	Z. 3 4,16 m 78,4 h	ZI 51,15	Zr 91 11,22	Zr 92	Zr 93	Zr 94	Zr 95 64,0 d	Zr 96 2,80	Zr 97 16,8 h	Zr 98 30,7 s	Zr 99 2,1 s	Zr 100 7,1 s	Zr 101 2,1 s
* γ393	8*8.8; 2.4 5 1907; p	ır - 0,014	1.2	<i>σ</i> 0,2	μ 0,06 m σ ~ 2	170,049	β ⁼ 0,4; 1,1 γ 757; 724 9	3,9 · 10 ¹⁹ a	β 1,9 γ508; 1148; 355 m	β 2,3 no γ 9	β ⁼ 3.5; 3.6 γ469; 546; 594 g; m	β 2,8; 3,0 γ504; 401	β γ 119; 208; 209; 1958; 2010: 598
Y & 7 tah 10.3 h	Y 8 <mark>8</mark> 106,5 d	Y 8 9	Y 90 3,19 h 64,1 h	Y 91 49,7 m 58,5 d	Y 92 3,54 h	Y 93 10,1 h	Y 94 18,7 m	Y 95 10,3 m	Y 96 8,6 s 5,34 s	Y 97	Y 98 2,0 s 0,55 s	Y 99 1,47 s	Y 100
hy 381 s p* y 468 p m	β ⁺ γ 1836; 898	+ 0.001 +	h 208; 480 β γ (2319) β 2.3 γ (2108)	p=1,5 y (1205) # 1,4	β 3,6 γ 934; 1405; 561; 449	β 2,9 γ267; 947; 1918	β 4,9 γ919; 1139; 551	β 4,4 7 954; 2176; 3577; 1324; 2633	β ⁺ 2.8 γ 1751; 916; 617; 1107 γ 1750	μ λ,τ. μ 6,2 5,0 γ 32388 γ γ 1102; 3401; 1907 16 %; 970 1907 1907	β 4.9; β 8.8 7,4 γ 1223; γ 1223; 2941; 621 1591 60 M0	β 6,8; 7,5 γ 122; 724 80	8" 8" 8.1 7 213; 7 213; 355; 715



Gamow window for (γ, n) reactions

• Planck distribution:
$$n_{\gamma}^{\text{Planck}} dE = \frac{1}{\pi^2 (\hbar c)^3} \frac{E^2}{\exp(E/kT) - 1} dE$$



Gamow window for (γ, n) reactions

- Planck distribution: $n_{\gamma}^{\text{Planck}} dE = \frac{1}{\pi^2(\hbar c)^3} \frac{E^2}{\exp(E/kT) 1} dE$
- Cross section $\sigma(E)$ with typical threshold behaviour



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- Planck distribution: $n_{\gamma}^{\text{Planck}} dE = \frac{1}{\pi^2(\hbar c)^3} \frac{E^2}{\exp(E/kT)-1} dE$
- Cross section $\sigma(E)$ with typical threshold behaviour
- Reaction rate: $\lambda(T) = \int c \cdot n_{\gamma}^{\text{Planck}} \cdot \sigma(E) \cdot dE$



First step: Activation





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First step: Activation



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Second step: γ -spectroscopy



Second step: γ -spectroscopy



• Isotopic abundance of ¹⁹⁶Hg: 0.15%

(γ,n) reaction rates for the *p*-process

Groundstate reaction rates at $T = 2.5 \cdot 10^9$ K

isotope	λ_{e}	_{<p< sub=""> [s⁻</p<>}	$^{-1}]$	$\lambda_{\rm NONS}~{\rm [s^{-1}]}$	$\lambda_{\rm MOST} \ [{\rm s}^{-1}]$
⁹⁶ Zr	6.2	±	0.3	6.1	_
^{186}W	314	±	44	257	250
¹⁸⁵ Re	19	\pm	9	12.8	
¹⁸⁷ Re	94	\pm	5	70.5	74.9
¹⁹⁰ Pt	0.4	±	0.2	0.18	0.29
¹⁹² Pt	0.5	\pm	0.2	0.58	0.56
¹⁹⁸ Pt	80	\pm	19	50	110
¹⁹⁷ Au	6.2	±	0.8	4.8	5.6
¹⁹⁶ Hg	0.42	\pm	0.07	0.32	0.58
¹⁹⁸ Hg	2.0	\pm	0.3	1.4	2.1
²⁰⁴ Hg	57	\pm	9	73	170
²⁰⁴ Pb	1.9	±	0.3	1.5	3.0

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Coulomb dissociation at GSI/LAND

Photodissociation in inverse kinematics





E~500 MeV/u

Photodissociation in inverse kinematics



²⁰⁸Pb(^{100,94,93,92}Mo,^{99,93,92,91}Mo+n)²⁰⁸Pb

Absorption of

'Virtual' Photons

Coulomb dissociation at GSI/LAND



Coulomb dissociation at GSI/LAND



Summary & Outlook

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 $\bullet~{\rm Experiments}$ on $^{92,93,94,100}{\rm Mo}$ @ LAND $/~{\rm GSI}$

- Photoactivation @ S-DALINAC
- Coulomb Dissociation in Inverse Kinematics @ LAND / GSI

- $\bullet~{\rm Experiments}$ on $^{92,93,94,100}{\rm Mo}$ @ LAND $/~{\rm GSI}$
- Photoactivation of $^{92}\mathrm{Mo}$ @ ELBE

- Photoactivation @ S-DALINAC
- Coulomb Dissociation in Inverse Kinematics @ LAND / GSI

- $\bullet~$ Experiments on $^{92,93,94,100} Mo$ @ LAND / GSI
- Photoactivation of ⁹²Mo @ ELBE
- Photoactivation of ¹⁰⁰Mo @ S–DALINAC

Collaboration for Experiment S295

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• Reaction rate: $\lambda(T) \propto \sum a_i(T) \cdot Y_i$