Gamma-induced reactions in explosive nucleosynthesis

- The p-process
- Direct measurements with photons
- "Indirect" measurements: Optical potentials
- Outlook



Andreas Zilges Institute for Nuclear Physics TU Darmstadt from October 1st, 2007:



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The p-process: Nuclear reaction network

Pb 188 25,5 s	Pb 169 51 s	Pb 190 1,2 m	Pb 191 2,2 m 1.4 m	Pb 192 3,5 m	Pb 193	Pb 194 12,0 m	Pb 195	Pb 196 36,4 m	Pb 197 43 n a n	Pb 198 2.40 h	Pb 199	Pb 200 21,5 h	Pb 201	Pb 202	Pb 203	Pb 204
α 5.960 γ 165: 758 φ	* # 5,72 7 271 1107 * → m	e: 3* e 5,577 y 942; 142; 151; g	* 287 712: α, 223 614 γ%27 18	c: 9* a 5,112 9 1195: 508; 168; g	5 302 e 348, y 368, 716, 211, 1 9	c u 4,64 ⇒ 592: 1619; 204g	a. 2" 4 17354 + 334; 576; 382 753;11 9	s67; 192 9	223 77 223 7392 19 25 751; 19 25 751; 1725	* γ 290; 865; 178 0	A - 307 - 307 - 46 - 1155 - 304 - 307 - 307	* > 148; 257 238; 288	5" 5-23" 361, 361, 346,	422 1574 1424 1451 32010 1 1252.	H- 52% 1,1273 - 881	1× 8%; 912: 375
TI 187	TI 188	TI 189	TI 190	TI 191	TI 192 10,8 m 8,6 m	TI 193	TI 194 33 m	TI 195 36s 1,13h	TI 196 1.4h 1,8h	TI 197 2,84 h	TI 198	TI 199 7,42 h	TI 200 26,1 h	TI 201 73,1 h	TI 202 12,23 d	TI 203 29,524
10 0.00 10	() ⁴ () ⁴ (12) 552 555 () ⁴ (3)	y 216. 1 318 1 234 223 342 9 3	р ⁴ 42 к у 416: 37.5,7 625 у 415 731 525	9 216 365 265 3552	4; ju ⁴ 4; 21 14 423; 17 423 638; 11 13; 787; 281	(γ,r	μ ^ι γ*28.	+ 500; 065 1561 1564 0	γ 428 636 636 956 γ 225 1056 1056 1	D+ V-120	61716011 6 472 pt. 687 y412. by 382 678 C ⁺⁺ 627	e 5 455: 208; 247: 158 9	6 β ⁺⁺ 5 369: 1206; 579: 826	v 167; 135	v ∽ 440; (520)	er 11
Hg 186 1,4 m	Hg 187	Hg 188 3 ² m	Hg 189 8.7 m 7,7 m	Hg 190 20,0 m	Hg 191 50.8 m ~ 50 m	4,9 h	11.1 h 193	Hg 194 520 a	Hg 195	Hg 196 0,15	Hg 197	Hg 198 9,97	Hg 199 42,6 m 16.87	Hg 200 23,10	Hg 201 13,18	Hg 202 29,86
*: [11 n 5.098 n 112; 252; 192: 228	14,17 1977 - 19704	4,0 × 67 90.	1.021: 37 72.962; 4.132 425 246 71 4	143; 17.	8 ¹ 7 (20) (20) 575 (20) 7 (20) 7 (20) 1 (20) 1 (20)	* γ 275: 157; 307	- 438 072, 1 168 1- 130, 1 238 10	*	7.9 1991 9.081 #8. 61. 1 9	a 110 - 3000	A A A A A A A A A A A A A A A A A A A	 < 0,017[°] + 2 	n 158; 374 67 - e 2100	ar< 60	ir < 80	
Au 18 4,2 m	(γ, \mathbf{p})	A 187	Al d	Au 189	Au 190 12,8 m	Au 191	Au 192 5,0 h	Au 193	Au 194 38,0 h	Au 155 30,5 s 100,1 d	Au 196 87h 825 82d	Au 197 7,73 s 102	Ati 198 230 d 2,6948 d	Au 199 3,139 d	Au 200	Au 201 26,4 m
5:3' 5:5,059 7:310: 243; 332	y 192; 256; 765: 416	4831 91001 (1458) 40101 (1458)	* 296 4 606		β 3.4 3 √ 296; 30 598.	1-20- 	ρ ⁺ 2,5 γ 317: 295. 612	h 258. 1 155 or 258. e 258. n 2	9* 1,5 9 328; 294; 1469	1, 122 1. 20. 	1 1 vieta 148: 201 202 168: 41 400	19275 9 1917	1+212 (***12 97 14. 183 1415. 254. 15000	810,3; 0,5 9158; 208 9 10 30	4 14 p. 28. - 388 64 p. 58. 398 54 159 - 393 183	p 1.3. 7 543: 517 813: 167
Pt 184 17,3 m	Pt 185 33 m 1,2 h	1, 1,0 2, 1, h	Pt 2,3	,u)	Pt 189 11 h	21 190 0.01	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d - 30 h	Pt 194 32,9	Pt 195	Pt 196 25,3	Pt 197 94,4 m 18,3 h	Pt 198 7,2	Pl 199 13,8 a 30.8 m	Pt 200 12,5 h
α 4,50 γ 166; 192; 548; 731	4(13-4)44-5 9(230) 108 107 107 107 107 104 107 104 107 104 104 104 104 104 104 104 104	ς α 4,23 γ 689; 612 m	* 7 106: 202; 110; 285 709	s 8,92 v 188, 195; 382, 424	* 721, 806. 589, 243; 545	6,5 a 3,17 o 150	10. A	+ 20 - G	M (128) M ²	o 0,1 + 1,1	15 22; 136 4	ar 0.045 + 0.55	1-246. 57 67 17 17 18 18 10 10 10	σ 0,027 − 4 0	1-362 (5.17 35 (7.168) 6 (1.16)	0 0.6: 0.7 y 78: 136: 244; 60: 227 5 0
Ir 183 55 m	Ir 184 3,0 h	lr 185	Ir 186	Ir 187 10,5 h	Ir 188 41,5 h	13,3 d	lr 190 3.16 1,26 11,86	Ir 191 4,94 s 07,3	Ir 192 211a 1/4 17.000	Ir 193 10,61 d 62.7	Ir 194 171 d 19,15 h	Ir 195 28h 2,5h	ir 196 1,40 h 52 s	ir 197 a.a.m 5.8m	lr 198 8 s	
y 393; 229 86; 203 m; g	p ⁺ 2.9 ∨ 264; 120; 360	β+	7: (E. 117: 117: 115:	* y 918; 427; 401; 611	8 ⁴ y 155, 2215; 633, 478.	y 9 245, 70; 69 g; m	THE REAL PROPERTY OF	5 180	1 150 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	hy (80) - 105 A ⁻¹¹ - 105	(*************************************	10. 1,1 , 190 412 - 56 210 512. 911 14 2 17 0	F 15 31 50 1 394 501 - 362 332 467 778 462 647 383	(*************************************	p=4.0 y507; 407	
Os 182 22,1 h	Os 183 99h 130h	0,02	Os 185 94 d	s 186 \.58	Os 187 1.6	Os 188 13,3	Os 189 6h 16,1	Os 190 8.9 m 28.4	Os 191 13,10 h 15,4 d	Os 192	Os 193 30,11 h	Os 194 6.0 a	Os 195 6,5 m	Os 196 34,9 m		
n 510; 180. 263. 56 m	97882, 974, 1988, 9682, 1968, 194, 9607, 67, 188,	··· 3000	c 1 646; 875 880; 717	α 2,76 α - 80	e 200	σ - S	is (84) 6	5 508 917; 301; 187; 5 12	γ ⁽⁷⁴⁾ μ ⁽⁷⁰⁾ σ ⁽⁷⁾ σ ⁽²⁰⁾	208, 458, 332, 455,	рто, 1 5 129: 460; 73 р и 40	β ⁺ 0,1 943 9	р-2 9	p= 0.8 5408; 128. 9		122
Re 181 20 h	Re 182	Re 183 71 d	Re 184	Re 185 37,40	Re 186 2 · 10 ⁵ a 39,25 h	Re 187 62,60	Re 188 18,8 m 16,58 h	Re 189 24,3 h	Re 190	Re 191 9,8 m	Re 192 16 s					
(9 366; 361; 639	+728 1051; + 328; 551: 06; 105: 1131 00: 1531	\$ 182:46;292; 209:110:99 9	1982 - 1933; 1982 - 750 - 11; 217; - 658 121 9000	ir 0.54 + 114	1,52 374 42 82 157.	5 - 10 ¹⁰ а в 0.0000 по у н 2.0 + 72	H-54, 5-21, 105, 152, 0 338	γ217:218; 245. g m	9 1177 1 182 9 197, 598 988, 522, 883, 9	3-1,9	β ⁻¹ + 4 9 467; 761; 206 8	118		120		
W 180 0,13	W 181 121,2 d	W 182 26,3	W 183	W 184 30,67	W 185	W 186 28,6	W 187 23,72 h	W 188 69 d	W 189 11 m	W 190 30,0 m						
	* 7_[5] e	-7 20	h 108 91 88 48. e 105	» C,002 + 2,0	(102) (102) (74) (74) (75) (74)	ur 36	p= 0.6; 1,3 v 686; 480, 72 r 70	β= 0.9. γ(291: 227)	p= 2.5 y256; 417; s50	97 1.9 7158; 162						

For lighter nuclei there may be competing reactions: (n, γ), (p, γ), (α , γ), ν p-process

Abundance of p nuclei: Prediction vs. observation



M. Arnould and S. Goriely, Phys. Rep. **384** (2003) 1 S. Goriely et al., Astronomy & Astrophysics **444** (2005) L1

Nuclear Physics input for the p-process

- Groundstate masses
- Properties of excited states
- Level densities
- Photoresponse (γ,γ'), (γ,n), (γ,α), (γ,p)
- Optical potentials (e.g. α nucleus)

Photon sources for direct measurements

- Bremsstrahlung (untagged and tagged)
 - Production of a quasi-thermal spectrum
 - Photon Tagger System NEPTUN
- Laser Compton Backscattering
 - AIST at Tsukuba/Japan → next talk
- Virtual photons from Coulomb interaction
 - SUPER**FRS/**NEU**LAND setup at GSI/**FAIR → talk by Konstanze Boretzky on Thursday

The photoactivation setup at S-DALINAC



- (1) Photon flux ~ $10^5 \gamma$ / (keV s cm²) Calibration of the photon flux via ${}^{11}B(\gamma,\gamma')$
- (2) Photon flux ~ 10⁷ γ / (keV s cm²)
 Calibration of the photon flux via ¹⁹⁷Au(γ,n) and ¹⁸⁷Re(γ,n)

Energy region of interest: Gamow window for (γ, n)



Energy [keV]

Production of a quasi-thermal spectrum



A. Z. *et al.*, Prog. Part. Nucl. Phys. 44 (2000) 39 P. Mohr *et al.*, Phys. Lett. B **488** (2000) 127

Groundstate reaction rates @ 2.5x10⁹ K

Isotope	λ _{exp,gs}	Reference	λ _{NONS,gs}	λ _{MOST,gs}	
¹⁸⁶ W	310(40)	K. Sonnabend et al., ApJ 583 (2003) 506	260	250	
¹⁸⁵ Re	19(7)	S. Müller et al.,	19	44	
¹⁸⁷ Re	76(7)	Phys. Rev. C 73 (2006) 025804	72	70	M. Arnould and
¹⁹⁰ Pt	0.4(2)	K. Vogt et al	0.18	0.29	S. Goriely,
¹⁹² Pt	0.5(2)	Phys. Rev. C 63	0.58	0.56	Phys. Rep. 384 (2003) 1
¹⁹⁸ Pt	87(21)	(2001) 055802	50	110	(2000) 1
¹⁹⁷ Au	6.2(8)	K. Vogt et al., Nucl. Phys. A 707 (2002) 241	4.81	5.6	T. Rauscher and FK. Thielemann, ADNDT 75 (2000) 1
¹⁹⁶ Hg	0.42(7)		0.32	0.58	<u> </u>
¹⁹⁸ Hg	2.0(3)	K. Sonnabend et al.,	1.36	2.1	
²⁰⁴ Hg	57(21)	(2004) 035802	73.3	170	
²⁰⁴ Pb	1.9(3)		1.53	3.0	
¹⁹¹ lr	4.3(5)	J. Hasper,	4.6	-	
¹⁹³ lr	13.5(16)	submitted	14.6	-	

Groundstate reaction rates @ 2.5x10⁹K



DNDT 75 (2000) AIP 769 (2004) 1154 F.-K. Thielemann, Koning et al., Rauscher and $\Sigma \vdash A$

Photodissociation of Er isotopes



From integrated reaction rates to $\sigma(E)$

Untagged photons from bremsstrahlung measure always INTEGRATED reaction rates:

$$\lambda(T) = c \int n_{\gamma}(E) \sigma(E) dE$$

Additional information can be deduced from the shape of the cross section $\sigma(E\gamma)$

\rightarrow use photons with "known" energy

- Tagged bremsstrahlung photons
- Laser Compton Backscattering

Photon tagger NEPTUN @ S-DALINAC



Energy range: $6 \text{ MeV} \le E_{\gamma} \le 20 \text{ MeV}$ Energy resolution: $\Delta E = 25 \text{ keV}$ @ 10 MeVPhoton intensity: $\approx 10^4 \text{ keV}^{-1}\text{s}^{-1}$



"Indirect" measurements: α -nucleus potentials

α – nucleus potential in Sn isotopes from (α , α)



D. Galaviz et al., PRC 71 (2005) 065802

α - capture cross sections



ATOMKI – NOTRE DAME - Collaboration

α - capture cross section

 112 Sn(α,γ) 116 Te



N. Özkan et al., PRC 75 (2007) 025801 <u>Overview:</u> P.Demetriou, C. Grama, S. Goriely, NPA **707** (2002) 253

Accelerator Mass Spectrometry



High sensitivity: isotopic ratios down to 10⁻¹⁵

High <u>efficiency</u>: amounts of 10⁵ nuclei

The existing 10 MV Tandem Accelerator (1st basement) Institute for Nuclear Physics, University of Cologne



The new 6 MV Tandem AMS machine (2nd basement)





M. Büssing*, M. Elvers*, J. Endres*, M. Fritzsche, <u>J. Hasper</u>*, L. Kern, K. Lindenberg, S. Müller, <u>D. Savran</u>, V. Simon, <u>K. Sonnabend</u>

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