The photoresponse of heavy nuclei – some implications on nucleosynthesis

- Nuclear physics and the p-process
- Photoresponse of atomic nuclei
- Structure of the Pygmy Dipole Resonance
- Outlook



Andreas Zilges Institut für Kernphysik TU Darmstadt



The p-process of nucleosynthesis

Pb 188 25,5 s	Pb 189 51 s	Pb 190 1,2 m	Pb 191 22m 1Am	Pb 192 3,5 m	Pb 193	Pb 194 12,0 m	Pb 195	Pb 196 36,4 m	Pb 197	Pb 198 2.40 h	Pb 199	Pb 200 21,5 h	Pb 201 61: 0.4 h	Pb 202	Pb 203	Pb 204	
с: р « 5.960 ү 185: 758 д	α 5,72 γ 271 - 1107 ≠ → m	α 5,577 φ 942; 142; 161; g	× 357 712. 0.523 614	c: 9 a 5,112 9 1195: 908; 168; g	5 502 * 3465 Y 3655 776. 871 1 9	c u 4,64 ⇒ 592: 1619; 204g	8.2" 4 1354 335; 578, 382 753;11 9	v 253; 502 867; 102 9	1227 1299 1227 1299 147 45; Nil; 147 1775	* 290; 865, 178 0	- 307 - 302 - 302 - 303 - 1155 - 750	* > 140; 257 208; 285	37 5 32 361, 361, 348,	422 1974 19.42 462 39.0. 10 1 282.	H- 525, 1,1273 - 821	is 88; 912; 375 ± 0/25	
TI 187	TI 188	TI 189	TI 190	TI 191	TI 192	TI 193	TI 194	TI 195	TI 196 1.4h 1,8h	TI 197 2,84 h	TI 198 1.87+ 5,31	TI 199 7.42 h	TI 200 26.1 h	TI 201	TI 202 12 23 d	TI 203 29,524	
1: 3 6.55 y 148. + 591 162 - 197 1520 J	р* 1,415: с 582: 3* 556., о.413.,	y 216. 1 518 y 334 123 342 9 3	94160 94160 8625 7210	- or	γ -pr	oce	SS	+ 594; 665 1561 1561	γ 429 635 635 635 635 911 911 915 915 915 915 915 91	D+ 5 422	612 pt., 687., y412, by 288., 648 c ⁺ 627.,	\$ 455 247: 9	-pro	ces	S 5201	er 11	
Hg 186 1,4 m	Hg 187	Hg 188 3 7 m	H 8.7 m 7,7 m	20,0 m	50.8 m ~ 50 m	4,9 h	11.1 h 35h	Hg 194 520 a	Hg 195 40h / 95	Hg 196 0,15	Hg 197	H(9,97	42,6 m 16 87	23,10	201 13,18	Hg 202 29,86	
 ∧ 5.098 ∧ 112; 252; 192; 228 	***,17 .553 0 5.04 176. +200.	α 4,61 × 67; 190; 83; 115	1.321. 3 ¹¹ 72.992; +733; 425 3 ¹⁴ 71 4	43; 151 155	β ¹ 7.1983 (* γ 275, 157, 307	- 438 078, y 168, 14 (30, 1) 79	* 10.7	7.19 1552 9.782 8%. 61 1 9	a 110 - 3000	A.	⇒ C,017 + 2	n 158 274 aftir - 2100	a < 60	ir < 80		
Au 185 4,2 m	Au 186 10,7 m	Au 187	AU	Au 189	Au 190 12,8 m	Au 191	Au 192 5,0 h	Au 193	Au 194 38,0 h	Au 100 30,5 s 100,1 d	Au 196 87h 826 82d	Au 197	Au 198 2,3. 1 2,6943 d	Au 199 3,139 d	AU 200	Au 201 26,4 m	
, 5 5,059 9 310: 243; 332	a 4,653 y 192; 296; 766; 416	4 4881 17 (101) 47 (102.) 1454 515	- 256: 340; 506	φ ¹ φ ¹ φ ¹ φ ¹ φ ¹ φ ¹ φ ¹ φ ¹	β 3.4 598, 30 598.	1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1	p ⁴ 2,5 7 317; 298 612	H 258 1 155 0° 258. 4 258. 01 2	9 1,5 9 328; 264; 1468	1) 192	1 1 1 125 148; 251 253 168; 6 455.	19.275 8 19.	87 14. 183 14. 224. 22520	в п.3; 0.5 у 158; 208 9 30	3 1.9 5 28. -388 69 158. 378 38 189 -383 189	p= 1.3. 7 543; 517 813: 167	
Pt 184 17.3 m	Pt 185	Pt 116 20h	Pt 187 2,35 h	Pt 188 10,2 d	Pt 189 11 h	01 190 0.01	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d - 30 n	Pt 194 32,9	Pt 195 4,02 d 33.8	Pt 196 25,3	Pt 197	Pt 198 7,2	Pl 199 1 88 50.8m	Pt 200 12,5 h	
ο 4,50 γ 106; 192; 548; 731	41 3 4945 8 9 2001 - 5 4946 7 108 - 3 480 157	G 4,23 γ 689; 612. m	* 	5 8,92 9 188, 195; 382, 424,	, , 721, 808, 589, 243; 545	0,5 a 3,17 o 150	5, 599; 45 10. 4	# 20 6	14 (128) 15 -	o 0,1 + 1,1	1528 1381. 4	ir 0.045 + 0.55	μ ² μ ² μ ² μ ² μ ² μ ² μ ² μ ²	σ 0,027 − 4	7-42 (1-17) 1-16(-144) 3-1(-14) 4-16	0 0.8: 0.7 y 78: 136: 244; 60: 227 5 0	
Ir 183 55 m	Ir 184 3,0 h	lr 185 14,4 h	Ir 186	Ir 187 10,5 h	Ir 188 41,5 h	13,3 d	Ir 190 3.16 1.26 11.80	Ir 191 4,94 s 37,5	Ir 192 2016, 14 m 1980	Ir 193 10.65 1 527	Ir 194 17, 1 19,15 h	Ir 195	196 ,45 52 s	n 107 8,9 m 5.8 m	* 198 s		
y 380; 229 86; 200 m; g	p ⁺ 2.9 ∀ 264; 120; 360	ς γ 264; 1829. 60; 97; 1658	· (F) (K2., (F) (45.)	* 7 918: 427; 401: 611	8 ¹ y 155, 2215; 633, 478.	y 245, 70; 59 g. m	n de la contra de	110. 14 2.	7 1334 6 1 7 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	MIBEL IS	β ² - 120 γ40 - 220 γ40 - 234 231	10 1300 412 1300 412 1300 512 10 10 10 10 10 10 10 10 10 10 10 10 10	F 13 1 301 DH 332 407 D7 331	(* 27)r > 470; 431; 816	0 ^{4.0} 7507; 407		
Os 182 22,1 h	Os 183	Os 184 0,02	Os 185 94 d	s 186 .58	Os 187 1.6	Os 188 13,3	Os 189 6h 16,1	Os 190 8,9m 28,4	Os 191 13, 14 15, 6	Os 192	Os 193 30,11 h	Os 194	Os 195 6.5 m	Os 196 1.9 m		100	
n 510; 180, 263, 58 m	5182, 54, 188, 9882, 108, 114, 51071, 61, 188, .	11 30CC	с у 646; 875 880; 717	α 2,76 α - 80	æ 200	e - 5	is (24) 6 - 0 - 0	917 301 187	2174) 1 ⁷⁷⁰ 7 250	208. 458. 312. 433.	189: 460; 3 g ar40	p 49 9 49 9	р-2 9	β 0.8 5408; 128. 0		122	
Re 181 20 h	Re 182	Re 183 71 d	Re 184	Re 185 37,40	Re 186 2 · 15 a 89,25 h	Re 187 62,60	Re 188 18,8 m 16,98 h	Re 189 24,3 h	Re 190	9,8 m	Re 192	440		100			
(+ 356; 361; 639	+78 1921 + 296 521 - 66 165 - 1121 60, 1521	\$ 182:46; 292; 209:110:99 9	1 282 750; 111; 277; 288; 221 c - 9000	ii 0.54 i 114	1,5% 7.4 4% 8% 157.	р 0.0096 10 7.1 2.6 + 72	H-84, 5-21, 106, 152 0 558	7 217: 218; 245 g: m	19177 138 9187 538 588 522. 883. 5	37 1,9	р та 9467; 79 206 Я	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							
<i>σ</i> − 1	γ_(6) σ	i n 20	9.7% 20 20. c 10,5	» C,002 + 2,0	(12) (74), (121) (74), (7-0,1)	ır 36	72 1770	γ(291: 227) Ω	y258; 417; 550	7 158; 162 g		r-process					

Nuclear reactions and decays during p-process

Pb 188 25,5 s	Pb 189 51 s	Pb 190 1,2 m	Pb 191 2,2m 1/4m	Pb 192 3,5 m	Pb 193	Pb 194 12,0 m	Pb 195	Pb 196 36,4 m	Pb 197 43 n 3 n	Pb 198 2.40 h	Pb 199	Pb 200 21,5 h	Pb 201	Pb 202	Pb 203	Pb 204
с. р* « 5.960 у 165; 758 g	* ir 5,72 γ 271 1107 ≠ → m	e: β* e 5,577 γ 942; 142; 151; g	4 3 287 712. 0.523 614 γ927 18 6.⇒§	c: 9* a 5,112 9 1195: 906; 168; g	5 348, y 365, 776, 771, 1 9	c u 4,64 > 592: 1619; 204g	a. 27 4 § 354 9 334; 578, 382 753; 11 g	ς γ 253; 502 867; 102 θ	7: 122 223 17: 223 17: 223	* γ 290; 865; 178 9	A - 307 - 307 - 307 - 307 - 307 - 155 - 155 - 300 - 155 - 300 - 155	* > 148: 257 208: 286	t 27 3 23 361, 348,	422 1874 948: 1 463 39610 1 282.	H- 6254	1× 895; 912; 375
TI 187	TI 188	TI 189	TI 190	TI 191	TI 192	TI 193	TI 194 33 m	TI 195 36s 1,13h	TI 196 1.4h 1,8h	TI 197 2,84 h	TI 198 1.87 + 1 5,3 h	TI 199 7,42 h	TI 200 26,1 h	TI 201 73,1 h	TI 202 12,23 d	TI 203 29,524
1: 3 5.98 y 168. 5 591 162. 197 1220 9	() ⁴ () ⁴ (2) 582 556 () ⁴ (3	y 206. 1 Ste 1 534 103 942. 9 1	р ⁴ 42., с у-416: 37.5,7 625 у 415 721., 625,	1. p 9.216; 365; 385; 385;	6.6 ⁴ 6.2 ⁴ 9.423 9.453 628: 1113 787., 591.,	(γ, r	în Tar	7 594; 665 1564 1564 9	1 429 535 535 535 7 438 911 915 955 955 955 955 955 955	R+	6.176.01 612 567	е 5 455: 200; 247: 188 9	6 β ⁺⁺ × 369: 1206; 579: 828	v ⇒ 197; 135	s 5 440; (520)	er 11
Hg 186 1,4 m	Hg 187	Hg 188 3 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 25h	Hg 194 520 a	Hg 195 40h / 95	Hg 196 0,15	Hg 197	Hg 198 9,97	Hg 199 42,6 m 16.97	Hg 200 23,10	Hg 201 13,18	Hg 202 29,86
*: [1" n 5.098 x 112; 252; 192: 228	50,17 577 0 5 D4	4.0 × 67 90	γ.321: 3 ⁷ 72.962; +133 425 2 ³ € 71 - 4	, 143; 172 155	β ¹ 7.1981; (.853) 5754; (.965) 17.0; 3.00	* γ 275; 157; 307	- 498 078, 1- 130, 1 1- 130, 1 1- 130, 1 1- 130, 1 1- 148	4 30 7	7.4 5.551 9.752; 555, 551, 4 9	a 110 - 3000		 < 0,017⁺ + 2 	5 158 374 6 e-2110	n < 60	ur < 80	or 50
Au 18 4,2 m	(γ, \mathbf{p})	A 187	AU	Au 189	Au 190 12,8 m	Au 191 19 3.18 h	Au 192 5,0 h	Au 193	Au 194 38,0 h	Au 100 30,5 s 100,1 d	Au 196	Au 197	Au 198 2,30 d 2,6943 d	Au 199 3,139 d	AU 200	Au 201 26,4 m
κ: 3 ¹ 5 5,059 γ 310; 243; 332	y 192; 298; 766; 416	2000 1 1428 1428	* 296 S		β 3.4 598, 30 598.	1 1-2 1-2 1-2 2 2 2 2 2 2 2 2 2 2 2 2 2	ρ ⁺ 2,5. γ 317; 298: 612	H 258. 1 188 0° 258. 4 258. 01 4	e 9* 1,5 9 336; 264; 1469	1 222 4 ⁻ 1	1 1 425 1425 3051 322 1385. 47 425.	19275 9 ⁻¹ 1917	1+215 (****12 97 14. 183; v415. 254. ******	87 0,3; 0,5 9 158; 208 9 30	1 () - 38 6+ 158 38 8+ 158 38 181 - 38 181	p=1.3. 5543; 517 813, 167
Pt 184 17.3 m	Pt 185	h 1 ó 2 j h	Pt 2,3	,	Pt 189 11 h	21 190 0.01	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d - 50 m	Pt 194 32,9	Pt 195	Pt 196 25,3	Pt 197 94,4m 18,3 h	Pt 198 7,2	Pl 199 13,6 s 50.6 m	Pt 200 12,5 h
s 6 4,50 7 166; 192; 648; 731	4(13.4,44.7) # 9.2001 (3.4,44.7) (125 (3.480) (137 (341	ς α 4,23 γ 689; 612 m	* 	* 8,92 * 188, 195; 382, 424.	* 721, 808. 589, 243; 545	6,5 a 3,17 o 150	2 199; *** 10.		14 (128) 15 - 5 - 5 15 - 5	er 0,1 + 1,1	15 22; 155 4	ır 0.045 + 0.55	1-326 φ ⁺ 1.77 β ⁺ 1.7 β ⁺ 1.7 180 π φ ⁺ 0	σ 0.027 − 4 0	(+.362) (5 - 17) (362) (5 - 17) (5 - 372) (6 - 3 (16) (16)	11 0,8; 0,7 y 78; 136; 244; 90; 227 97: 0
Ir 183 55 m	lr 184 3,0 h	lr 185	Ir 186	Ir 187 10,5 h	Ir 188 41,5 h	13,3 d	Ir 190 316 1,25 11,80	Ir 191 4,94 s 37,3	Ir 192 211a 14 n 15/10 d	Ir 193 10,53 d 52.7	Ir 194 171 d 19,15 h	Ir 195 28h 2,5h	ir 196 1,40 h 52 s	lr 197 8,9 m 5.8 m	lr 198 8 s	
м р 7,393; 229 86; 203 m; g	с р* 2.9 у 264; 120 260	β+		* 7 918; 427; 401; 611	8 ¹ y 155, 2215; 633, 478.	y 245 70: 59 g. m	A REAL REAL REAL REAL REAL REAL REAL REA	5, 120	1 154 C 151 C 154 F 154 F 154 F 154 F 155 F 155	ły(83) - 125	(*************************************	10. 1,1 13. 1,1 1300 430 + 595 500 572. 511 14 5 70 0	F 15 8133 1384 (201) - 360 202 407 778 462 647 383	(* 24) ** > 470; 431; 816	р ^{4.0} ү507; 407	
Os 182 22,1 h	Os 183	0,02	Os 185 94 d	s 186 158	Os 187 1.6	Os 188 13,3	Os 189	Os 190 89m 25,4	Os 191 13,10h 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, 58 M	105 94. 105 9824 105 114 5 1071 67 158.	ii 3000	c 1 646; 875 680; 717	2,0 - 10* a σ 2,76 σ - 80	er 200	σ - 5	is (24) 6 - 0 - 20	5 538 915) 301) 181)	γ074) μ ^{(**} 0,1 α ^{**} α ^{**} 230	206, 453, 332, 485 + 21.	β ⁻¹ , 1 5 139: 460; 73g π40	8=0,1 943 9	р-2 9	β 0.8 5 408; 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 89,25 h	Re 187 62.60	Re 188 18,8 m 18,98 h	Re 189 24,3 h	Re 190	Re 191 9,8 m	Re 192 16 s					
(9 300, 361; 639	+ 78 1925 + 396; 591 - 66; 105 - 1175 00, 457	5 182: 46; 292; 209: 110: 99 9	1923 750 11; 277; 855 221 9000	ir 0.54 + 114	1,5% 7 / · · · · · · · · · · · · · · · · · ·	β 0.0096 no g = 2.6 + 72	H-84, 5, 21, . 106., 5, 155 0, 558	γ217:218; 245 g.m	Hy 177 (182) Y 197, 598 588, 521, A82, 5	37 1,9	9 4 467; 761; 206 R	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						
7-4	່າ γ_(5)	- 20	h 108 70 88 48. c 105	» C.002 + 2.0	1,62; 070,4. 132; -(155) 174; -(155)	ir 56	p 0.6; 1,3 5 686; 480, 72 # 70	β=0.9. γ(291:227)	07 2.5 y258; 417; 550	0 1.9 7158; 162						

In addition (n,γ) and (p,γ) reactions and the vp-process may become important.

Nuclear physics in the p-process network

Ground state masses

Properties of excited states

Nuclear level densities

Photoresponse (γ , γ '), (γ ,n), (γ ,α), (γ ,p)

Optical potentials

The photoresponse of atomic nuclei – E1 strength



- Two Phonon Excitation: $E_x \sim 3$ MeV, B(E1) $\sim 10^{-2}$ W.u.
- Giant Dipole Resonance: $E_x \sim 18$ MeV, B(E1) ~ 10 W.u.
- Pygmy Dipole Resonance ?
 - F. lachello, PLB 160 (1985) 1
 - G. Colò et al., PLB 485 (2000) 362
 - D. Vretenar et al., PLB 487 (2000) 334

Experimental tools



<u>Real</u> and <u>virtual</u> photons can be used for excitation!

E1 strength above threshold in exotic nuclei



(Results on ^{18,20}O: *E. Tryggestad et al., PRC <u>67</u> (2003) 064309)*

Photoresponse below threshold of stable nuclei: Real photon scattering - NRF



Review: U. Kneissl, H.H. Pitz, and A.Z., Prog. Part. Nucl. Phys. 37 (1996) 349

Photon scattering off ¹³⁸Ba



A. Z. et al., Phys. Lett. B 542 (2002) 43

Photon scattering using bremsstrahlung

- Excitation with "white" photon spectrum
- γ decay from bound states measured with very high energy resolution
- → Complete photoresponse <u>below</u> the particle threshold, i.e. B(E1), B(M1), B(E2) strength
- + Model independent
- + One experiment covers wide energy range
- Increasing background at small energies
- Studies of radioactive nuclei impossible
- Limited information about nuclear structure

E1 strength below threshold in N=82 nuclei



E1 strength below 9 MeV in N=82 nuclei



A. Z. et al., Phys. Lett. B **542** (2002) 43, and S. Volz et al., to be published

Substructure within the PDR ?



Investigating the PDR with α -particles



for detection of γ decays

for detection of α -particles, **∧E ~ 100-200 keV**

This setup combines isospin selectivity and skin sensitivity of α -particles with spin selectivity and energy resolution of γ -spectroscopy

D. Savran et al. submitted to NIM A

The new ISOSPIN setup at KVI

Total photopeak efficency: ~0.1% at 9 MeV

2D-energy matrix: (α , α ' γ) on ¹⁴⁰Ce



E1 strength in ¹⁴⁰Ce: ($\alpha, \alpha' \gamma$) vs. (γ, γ')



Summary

- An E1 resonance exhausting up to 1% of the EWSR is observed in all examined stable nuclei around about 7 MeV
- The strength seems to split up into two parts with different underlying isospin structure and/or different nuclear surface content
- More resonance like strength is found above the particle threshold in n-rich systems
- We do not understand the connection between the strength <u>below</u> and <u>above</u> the threshold and between the strength in <u>stable</u> and <u>exotic</u> nuclei

Connection to E1 strength above the threshold in stable nuclei

Low Energy Photon Tagger @ S-DALINAC NiederEnergiePhotonenTagger



High resolution measurement (<0.25 %) of photon induced reaction rates in the energy range 8 MeV < E_{γ} < 20 MeV

NEPTUN at S-DALINAC



The photoresponse of heavy nuclei – some implications on nucleosynthesis



- Complete photoresponse (γ,γ'), (γ,n), (γ,α), (γ,p)
 can be measured in stable nuclei at S-DALINAC
- Additional information about structure from (α,α'γ) and (e,e') experiments

The photoresponse of heavy nuclei – some implications on nucleosynthesis

M. Elvers, J. Endres, M. Fritzsche, J. Hasper, L. Kern, K. Lindenberg, S. Müller, D. Savran, C. Siegel, K. Sonnabend, S. Volz (Institut für Kernphysik, TU Darmstadt)

M.N. Harakeh, A.M. van den Berg, H.J. Wörtche (KVI Groningen)

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More information and references: www.zilges.de