

Experimental techniques to investigate the p process of nucleosynthesis

- The „exotic“ p process
- „Direct“ measurements with real and virtual photons
- „Indirect“ measurements:
Radiative capture



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p nuclei

Er 156 18.6 m	Er 157 18.65 m	Er 158 2.25 h	Er 159 36 m	Er 160 28.6 h	Er 161 3.24 h	Er 162 0.139	Er 163 75 m	Er 164 1.601	Er 165 10.3 h	Er 166 33.503	Er 167 2.3 s
$\epsilon; \beta^+ ...$ $\gamma 35; 30...$ e^-	$\epsilon; \beta^+ 2.5$ $\gamma 53; 391;$ $121...$	$\epsilon; \beta^+ 0.8...$ $\gamma 72; 387...$ m_1	$\epsilon; \beta^+ 1.1...$ $\gamma 624; 649...$ $g; m$	$\epsilon; \gamma 7; e^-$ m_1	$\epsilon; \beta^+ ...$ $\gamma 827...$ $g; m$	σ_{19} $\sigma_{n, \alpha} < 0.011$	$\epsilon; \beta^+ ...$ $\gamma 114...$	σ_{13} $\sigma_{n, \alpha} < 0.0012$	$\epsilon; \beta^+ ...$ $\gamma 114...$	$\sigma 3 + 14$ $\sigma_{n, \alpha} < 7E-5$	$\gamma 208$ e^-
Ho 155 48 m	Ho 156 7.8 m 9.5 s 56 m	Ho 157 12.6 m	Ho 158 21 m 27 m 11 m	Ho 159 8.3 s 33 m	Ho 160 3 s 5.0 h 26 m	Ho 161 6.7 s 2.5 h	Ho 162 68 m 15 m	Ho 163 1.1 s 4570 a	Ho 164 37 m 29 m	Ho 165 100	Ho 166 1200 a 26.80 h
$\epsilon; \beta^+ 1.8$ $\gamma 240; 136...$	$\epsilon; \beta^+ 366;$ $266...; \gamma 136...$	$\epsilon; \beta^+ 1.2; 1.5...$ $\gamma 406; 99; 218;$ $839; 218; 99...$	$\epsilon; \beta^+ 1.3; 2.9...$ $\gamma 206...; 253...$	$\epsilon; \beta^+ ...$ $\gamma 121; 132; 107...$	$\epsilon; \beta^+ ...$ $\gamma 121; 132; 107...$	$\epsilon; \beta^+ ...$ $\gamma 728; 78...$	$\epsilon; \beta^+ ...$ $\gamma 26; 78...$	$\epsilon; \beta^+ ...$ $\gamma 58; 38...$	$\epsilon; \beta^+ 1.1...$ $\gamma 185; 120; 283; 1319...$	$\sigma 3.1 + 58$ $\sigma_{n, \alpha} < 2E-5$	$\beta^- 0.07...$ $\gamma 184; 810; 712...$
Dy 154 $3.0 \cdot 10^6$ a	Dy 155 10.0 h	Dy 156 0.056	Dy 157 8.1 h	Dy 158 0.095	Dy 159 44.4 d	Dy 160 2.329	Dy 161 18.889	Dy 162 25.475	Dy 163 24.896	Dy 164 28.260	Dy 165 1.3 m 2.35 h
$\alpha 2.87$	$\epsilon; \beta^+ 0.9; 1.1...$ $\gamma 227...$	$\sigma 33$ $\sigma_{n, \alpha} < 0.009$	$\epsilon; \beta^+ ...$ $\gamma 26...$	$\sigma 33$ $\sigma_{n, \alpha} < 0.006$	$\epsilon; \beta^+ ...$ $\gamma 3000$	$\sigma 60$ $\sigma_{n, \alpha} < 0.000$	$\sigma 600$ $\sigma_{n, \alpha} < 1E-5$	$\sigma 600$ $\sigma_{n, \alpha} < 0.000$	$\sigma 120$ $\sigma_{n, \alpha} < 2E-5$	$\sigma 1610 + 1040$	$\beta^- 0.9; 1.0...$ $\gamma 515...; \sigma 2000$
Tb 153 2.34 d	Tb 154 23 h 9.0 h 21 h	Th 155 5.32 d	Tb 156 24 h 5.4 h 5.4 d	Th 157 99 a	Tb 158 10.5 s 180 a	Tb 159 100	Tb 160 7.3 d	Tb 161 8.90 d	Tb 162 7.76 m	Tb 163 19.5 m	Tb 164 3.0 m
$\epsilon; \beta^+ ...$ $\gamma 212; 44...$	$\epsilon; \beta^+ ...$ $\gamma 248; 123; 1274...$	$\epsilon; \beta^+ ...$ $\gamma 347; 1420; 248; 123...$	$\epsilon; \beta^+ ...$ $\gamma 87; 105; 180; 262...$	$\epsilon; \beta^+ ...$ $\gamma 534; 199; 1222...$	$\epsilon; \beta^+ ...$ $\gamma 118; 110...$	$\epsilon; \beta^+ ...$ $\gamma 110; e^-$	$\beta^- 0.6; 1.1...$ $\gamma 879; 299; 966...$	$\beta^- 0.5; 0.6...$ $\gamma 26; 49; 75...$	$\beta^- 0.5; 0.6...$ $\gamma 260; 808; 888...$	$\beta^- 0.8; 1.3...$ $\gamma 351; 390; 494...$	$\beta^- 1.7; 3.0...$ $\gamma 169; 755; 215; 688; 611...$
Gd 152 0.20	Gd 153 239.47 d	Gd 154 2.18	Gd 155 14.80	Gd 156 20.47	Gd 157 15.65	Gd 158 24.84	Gd 159 17.48 h	Gd 160 21.86	Gd 161 3.76 m	Gd 162 8.2 m	Gd 163 68 s
$1.1 \cdot 10^{14}$ a	$\epsilon; \beta^+ ...$ $\gamma 97; 103; 70...$	$\sigma 60$	$\sigma 61000$ $\sigma_{n, \alpha} 0.000$	$\sigma 2.0$	$\sigma 254000$ $\sigma_{n, \alpha} < 0.0$	$\sigma 2.3$	$\beta^- 1.0...$ $\gamma 364; 58...$	$\beta^- 1.0...$ $\gamma 364; 58...$	$\beta^- 1.6; 1.7...$ $\gamma 361; 315; 102...$	$\beta^- 1.0...$ $\gamma 442; 403...$	$\beta^- 2.88; 214; 1562; 1685...$
Eu 151 47.81	Eu 152 96 m 9.3 h 13.33 a	Eu 153 52.19	Eu 154 46.0 m 8.8 a	Eu 155 4.761 a	Eu 156 5.2 d	Eu 157 15.18 h	Eu 158 15.16 m	Eu 159 11.1 m	Eu 160 12 s	Eu 161 26 s	Eu 162 10.6 s
$\sigma 4 + 3150 + 6000$	$\beta^- 1.9...$ $\epsilon; \beta^+ ...$ $\gamma 841; 963...$	$\sigma 300$ $\sigma_{n, \alpha} 1E-6$	$\beta^- 1.8...$ $\epsilon; \beta^+ ...$ $\gamma 122; 344...$	$\beta^- 0.17; 0.15...$ $\epsilon; \beta^+ ...$ $\gamma 87; 105; 1231...$	$\beta^- 0.5; 2...$ $\gamma 812; 89; 1231...$	$\beta^- 1.3...$ $\gamma 64; 411; 371; 619...$	$\beta^- 2.4; 3...$ $\gamma 944; 977; 898...$	$\beta^- 2.6...$ $\gamma 68; 71; 79; 96; 103...$	$\beta^- 4.1...$ $\gamma 173; 515; 412; 822...$	$\beta^- 72 - 314$	$\beta^- 71; 165$
Sm 150 7.38	Sm 151 93 a	Sm 152 26.75	Sm 153 46.27 h	Sm 154 22.75	Sm 155 22.4 m	Sm 156 7.9	Sm 157 0.7...	Sm 158 0.2...	Sm 159 0.9	Sm 160 1.6 s	Sm 161 4.8 s
$\sigma 102$	$\beta^- 0.1...$ $\gamma (22...); e^-$	$\sigma 206$	$\beta^- 0.7; 0.8...$ $\gamma 103; 70...$	$\sigma 420$	$\beta^- 1.5...$ $\gamma 104; 246; 141...$	$\beta^- 0.7...$ $\gamma 204; 88; 166...$	$\beta^- 2.4...$ $\gamma 198; 196; 394...$	$\beta^- 1.89; 364; 325...$	$\gamma 150; 682...$ $254; 797; 179...$	$\beta^- 110...$	$\beta^- 264$

s and r process

p nuclei

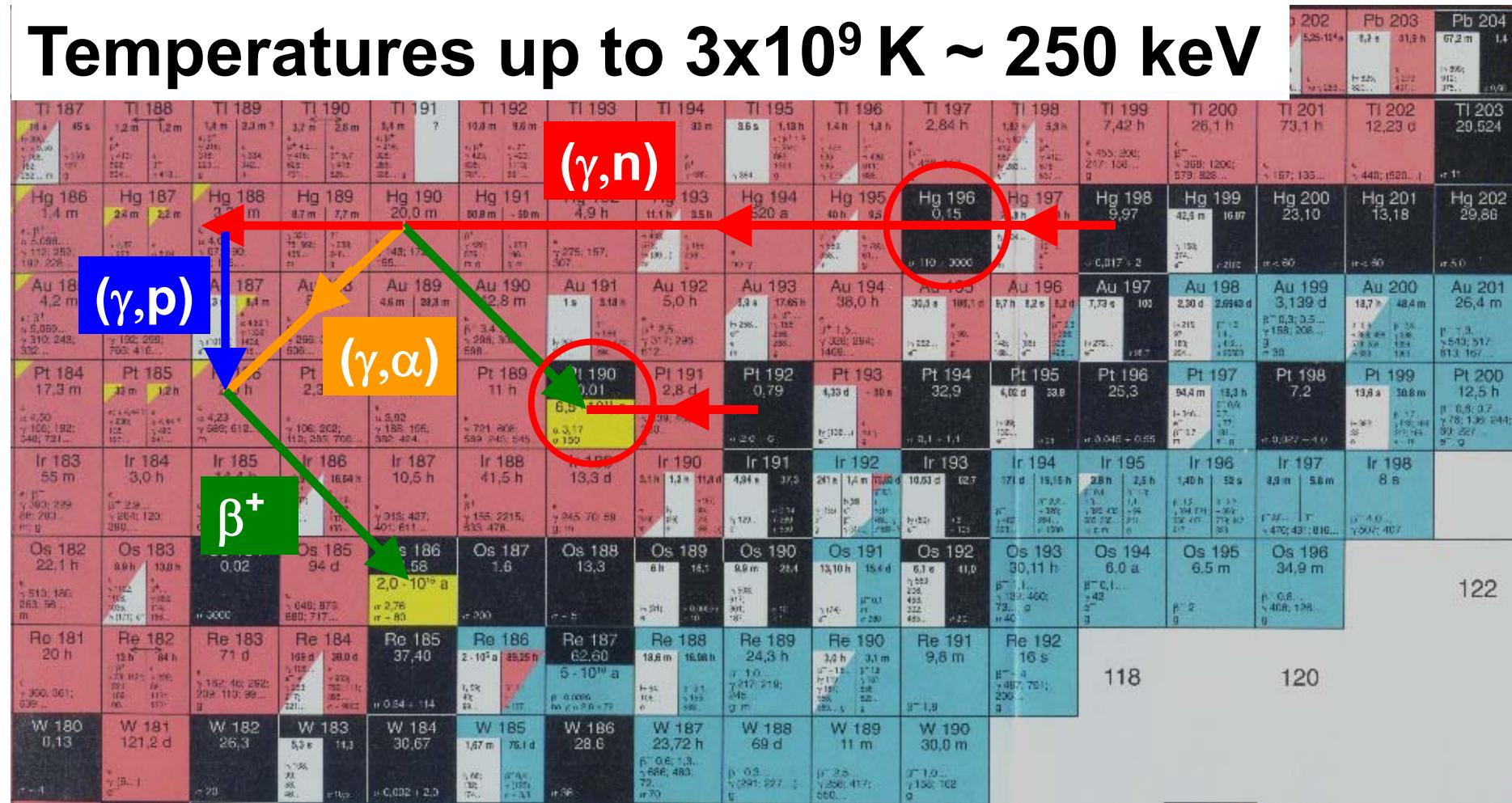
- 35 proton rich stable nuclei with $A > 70$
- typical isotopic abundance $< 1\%$
- typical abundance 5×10^{-4} ($\text{Si}=10^6$)

Ru 96	5.54
$\sigma_{\text{n}} 0.23$	

Dy 156	0.056	Dy 157	8.1 h	Dy 158	0.095
$\sigma_{\text{n}, \alpha} 33$	< 0.009	ϵ	$\gamma 326\dots$	$\sigma_{\text{n}, \alpha} 33$	< 0.006

The p process: Nuclear reaction network

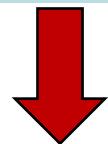
Temperatures up to 3×10^9 K ~ 250 keV



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

The p process: Nuclear reaction network

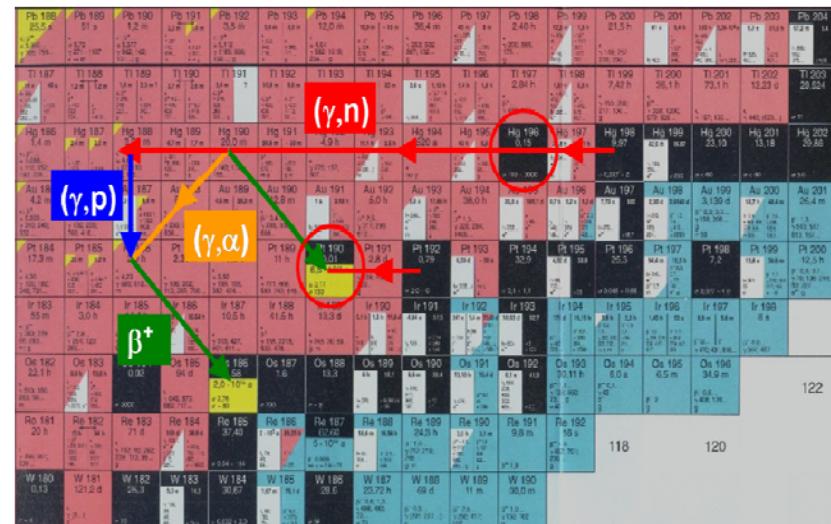
This network involves
about 20.000 reaction rates



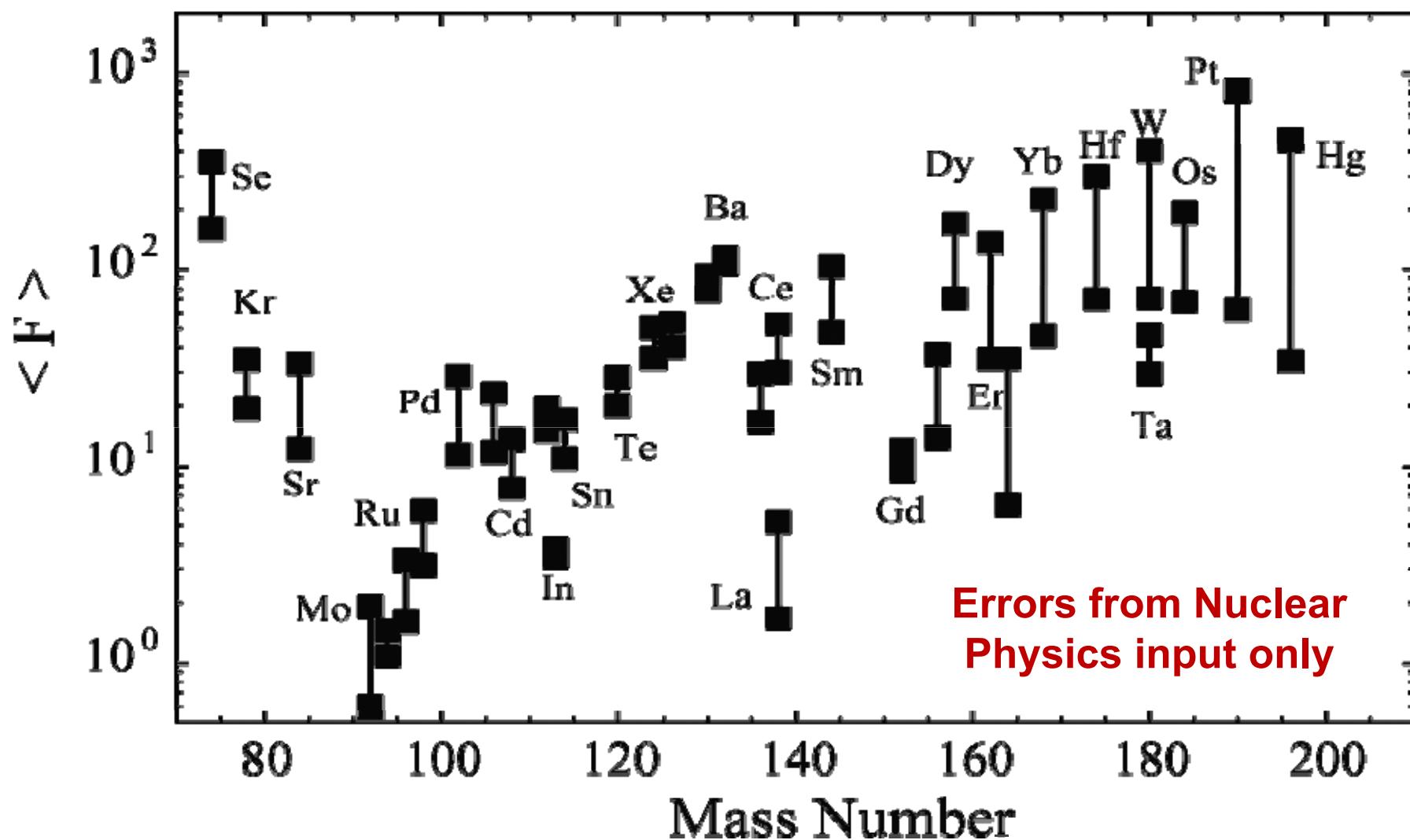
Statistical model calculations



Experiments are necessary
to check and to constrain
the model assumptions



Abundance of p nuclei: Prediction vs. observation



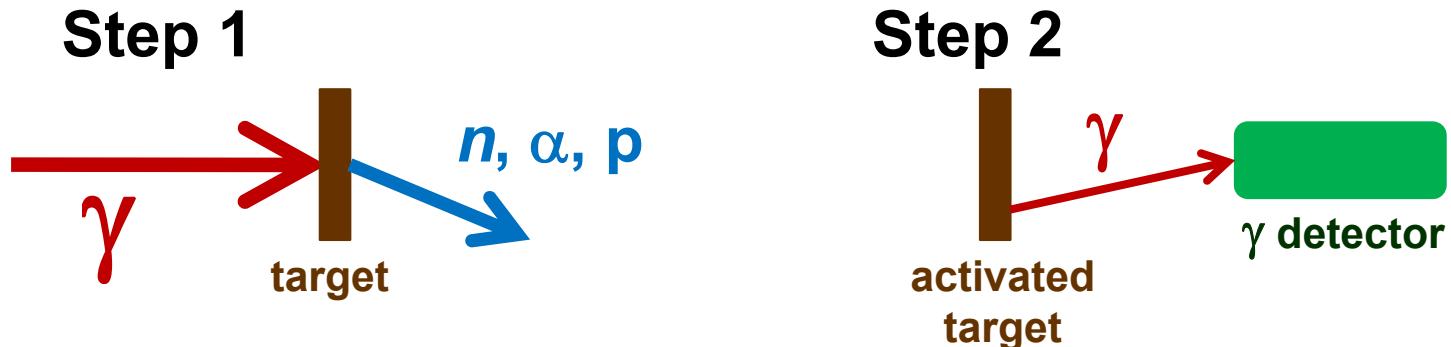
M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1

S. Goriely et al., Astronomy & Astrophysics 444 (2005) L1

Nuclear Physics input for the p process

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

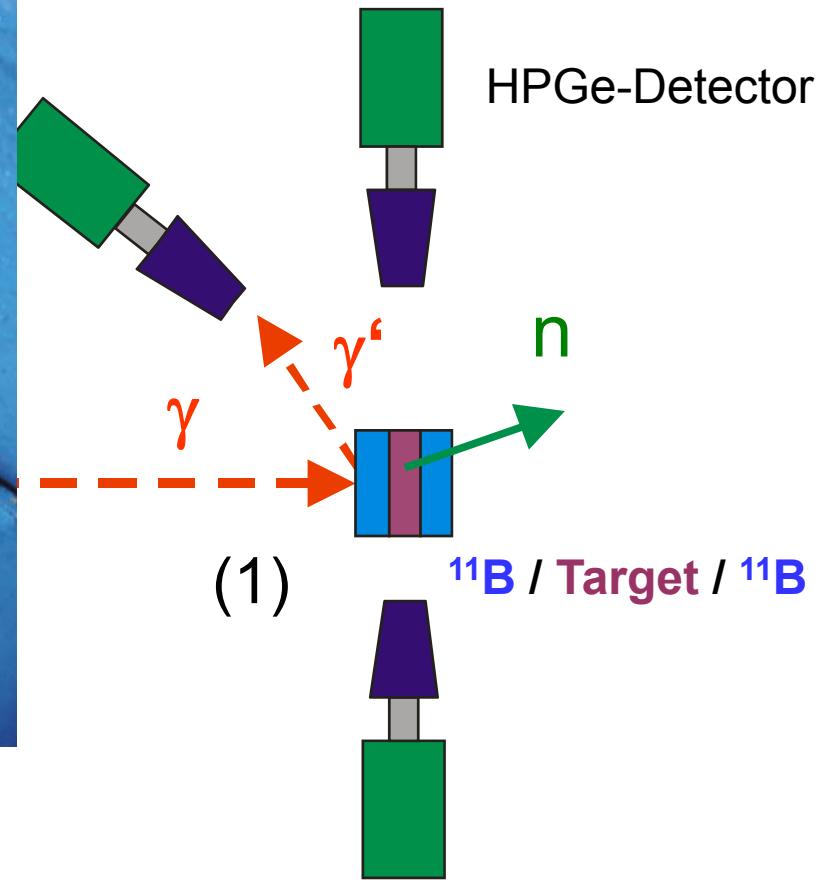
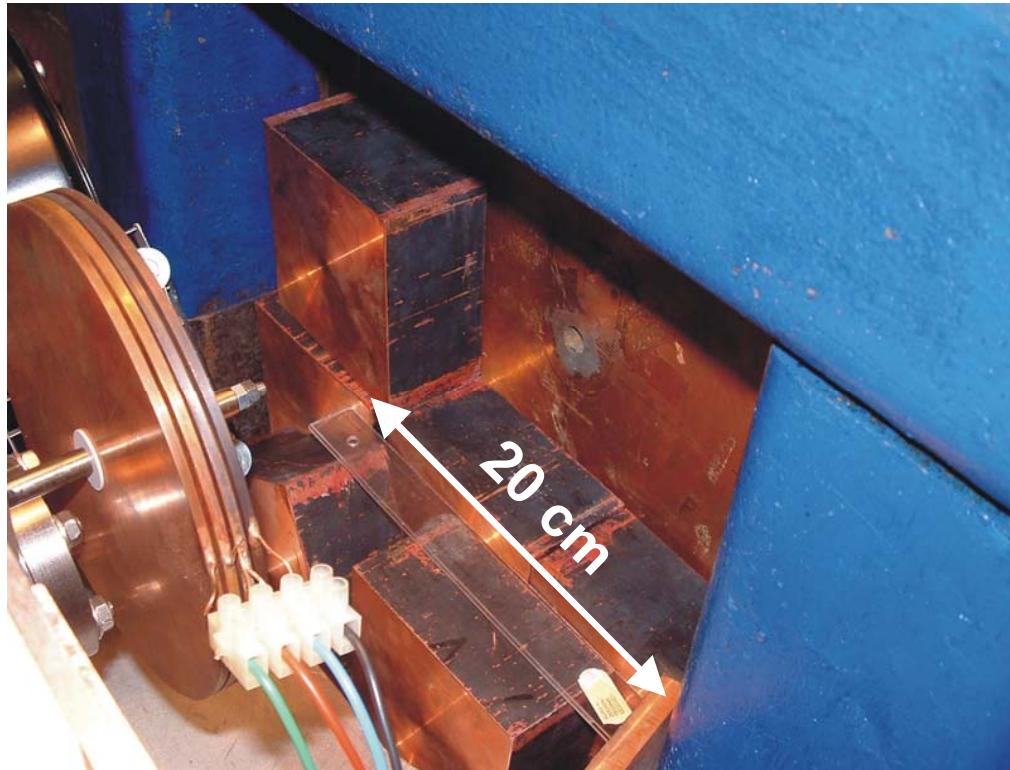
„Direct“ experimental techniques I: Activation of stable targets with real photons



Induce (γ, n) , (γ, α) , and (γ, p) reactions with real photons + measure activation

Er 161 3.24 h ϵ β^+ ... γ 827... g; m	Er 162 0.139 $\sigma 19$ $\sigma_{n, \alpha} < 0.011$	Er 163 75 m ϵ β^+ ... γ (1114...) g	Er 164 1.601 $\sigma 13$ $\sigma_{n, \alpha} < 0.0012$	Er 165 10.3 h ϵ no γ	Er 166 33.503 $\sigma 3 + 14$ $\sigma_{n, \alpha} < 7E-5$
Ho 160 3 s ly 118; 51; 107... e^- 2974	Ho 161 5.0 h ly (60); e^- ; β^+ ... 87 - 962...	Ho 162 26 m ly 211 e^-	Ho 162 6.7 s ϵ 26; 78... e^-	Ho 163 2.5 h ly 58; 38... e^- ; ϵ 185; 1220; 283; 937...	Ho 164 1.601 4570 a ly 298 e^- no γ
Dy 159 144.4 d ϵ γ 58; e^- $\sigma 8000$	Dy 160 2.329 $\sigma 60$ $\sigma_{n, \alpha} < 0.0003$	Dy 161 18.889 $\sigma 600$ $\sigma_{n, \alpha} < 1E-6$	Dy 162 25.475 $\sigma 170$	Dy 163 24.896 $\sigma 120$ $\sigma_{n, \alpha} < 2E-5$	Dy 164 28.260 $\sigma 1610 + 1040$

Photoactivation with bremsstrahlung

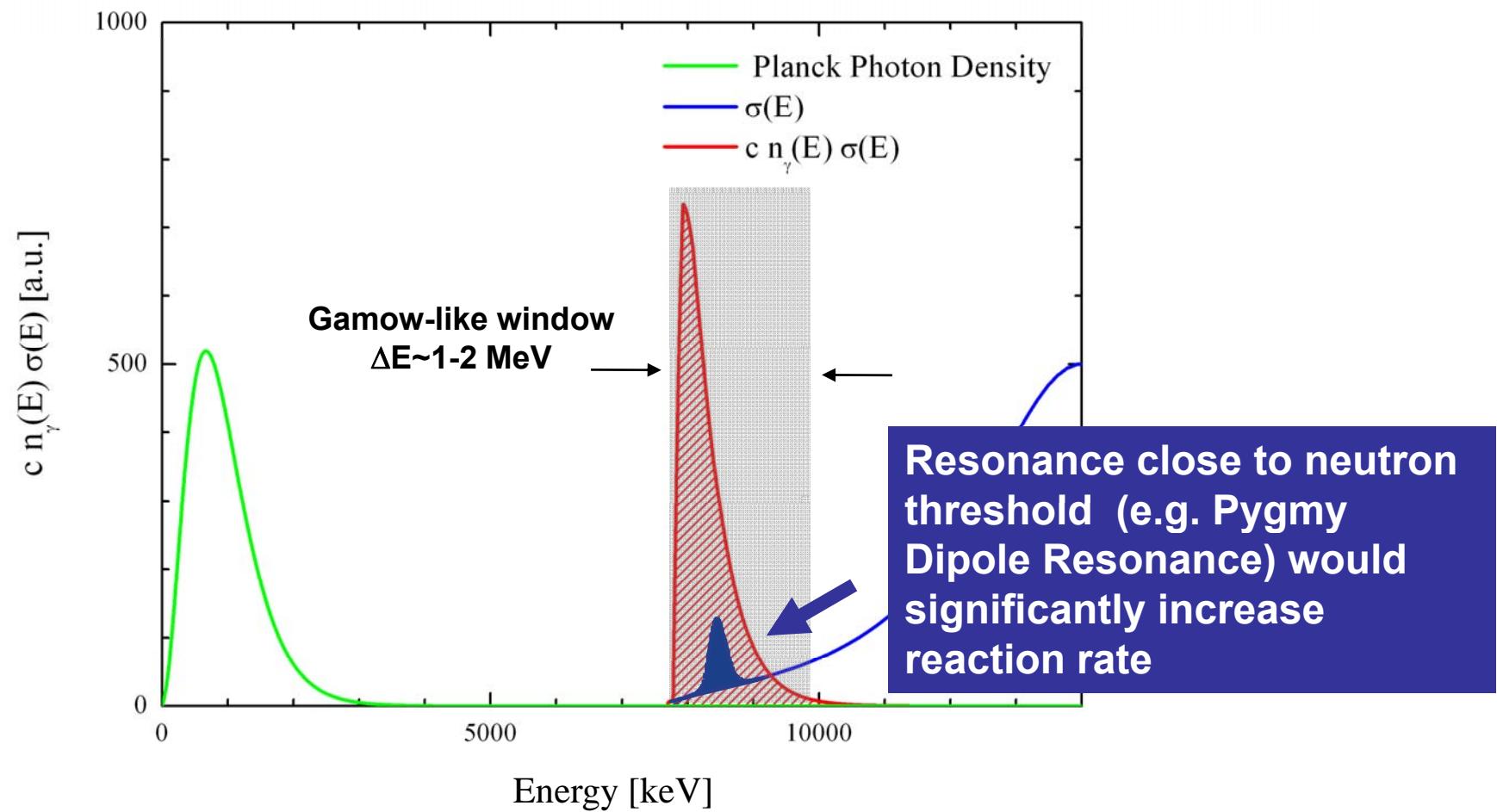


(1) Photon flux $\sim 10^5 \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{11}\text{B}(\gamma, \gamma')$

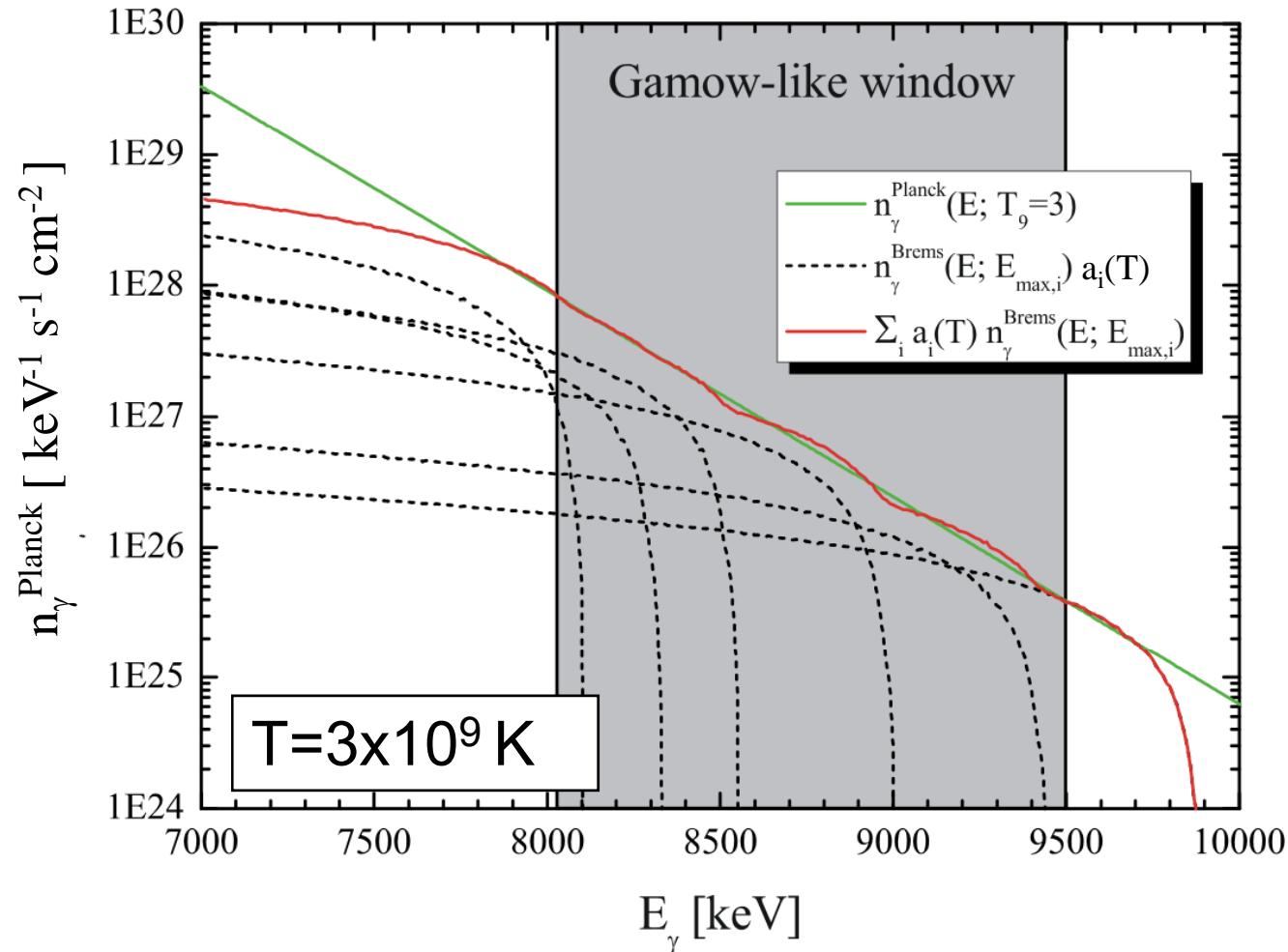
(2) Photon flux $\sim 10^7 \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{197}\text{Au}(\gamma, n)$ and $^{187}\text{Re}(\gamma, n)$

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

Reaction rate: $\lambda(T) = c \int n_\gamma(E) \sigma(E) dE$

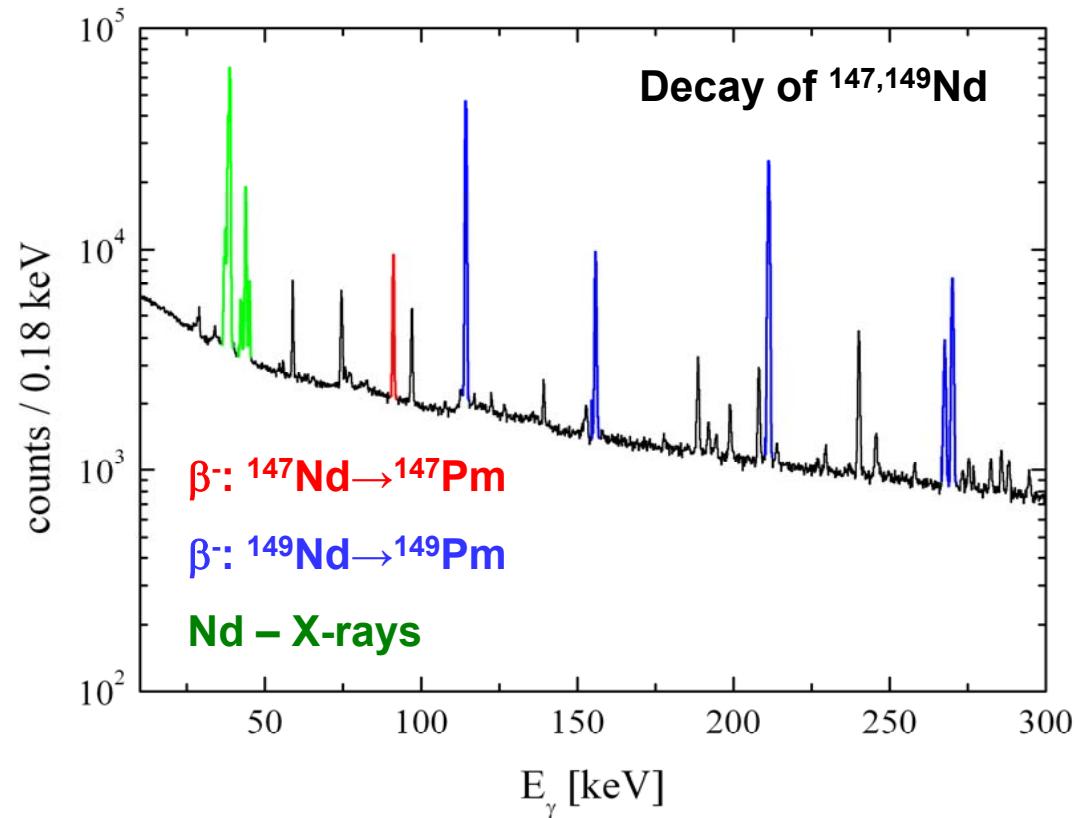
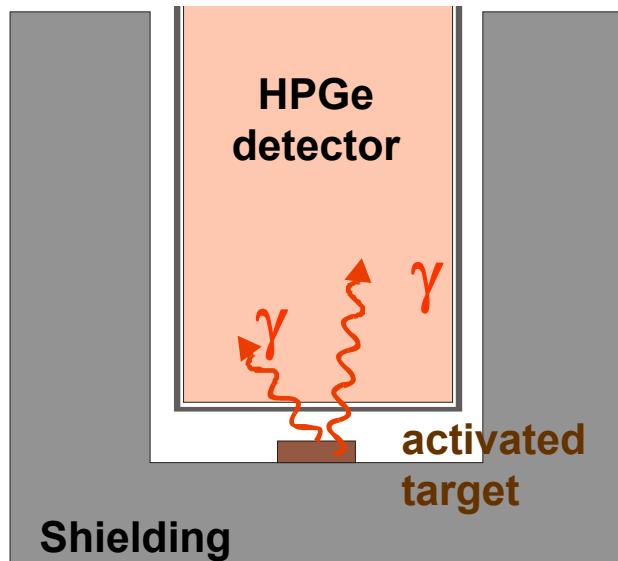


Production of a quasi-thermal spectrum



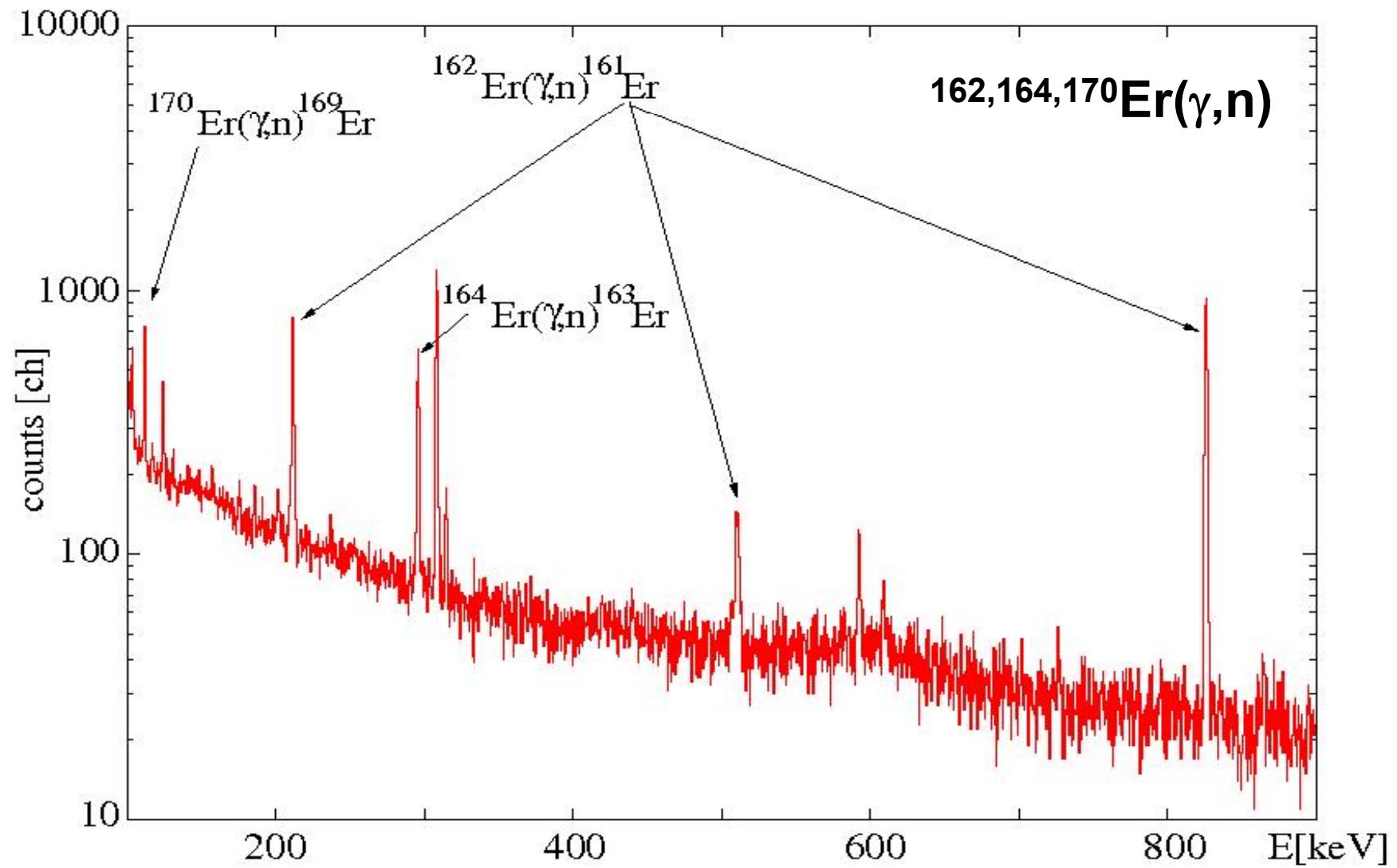
A. Z. *et al.*, Prog. Part. Nucl. Phys. 44 (2000) 39
P. Mohr *et al.*, Phys. Lett. B 488 (2000) 127

Activation measurement



Reaction Yield: $Y \sim \int n_\gamma(E) \sigma(E) dE$

Photodissociation of Er isotopes



J. Hasper and S. Müller, priv. comm.

Groundstate reaction rates @ 2.5×10^9 K

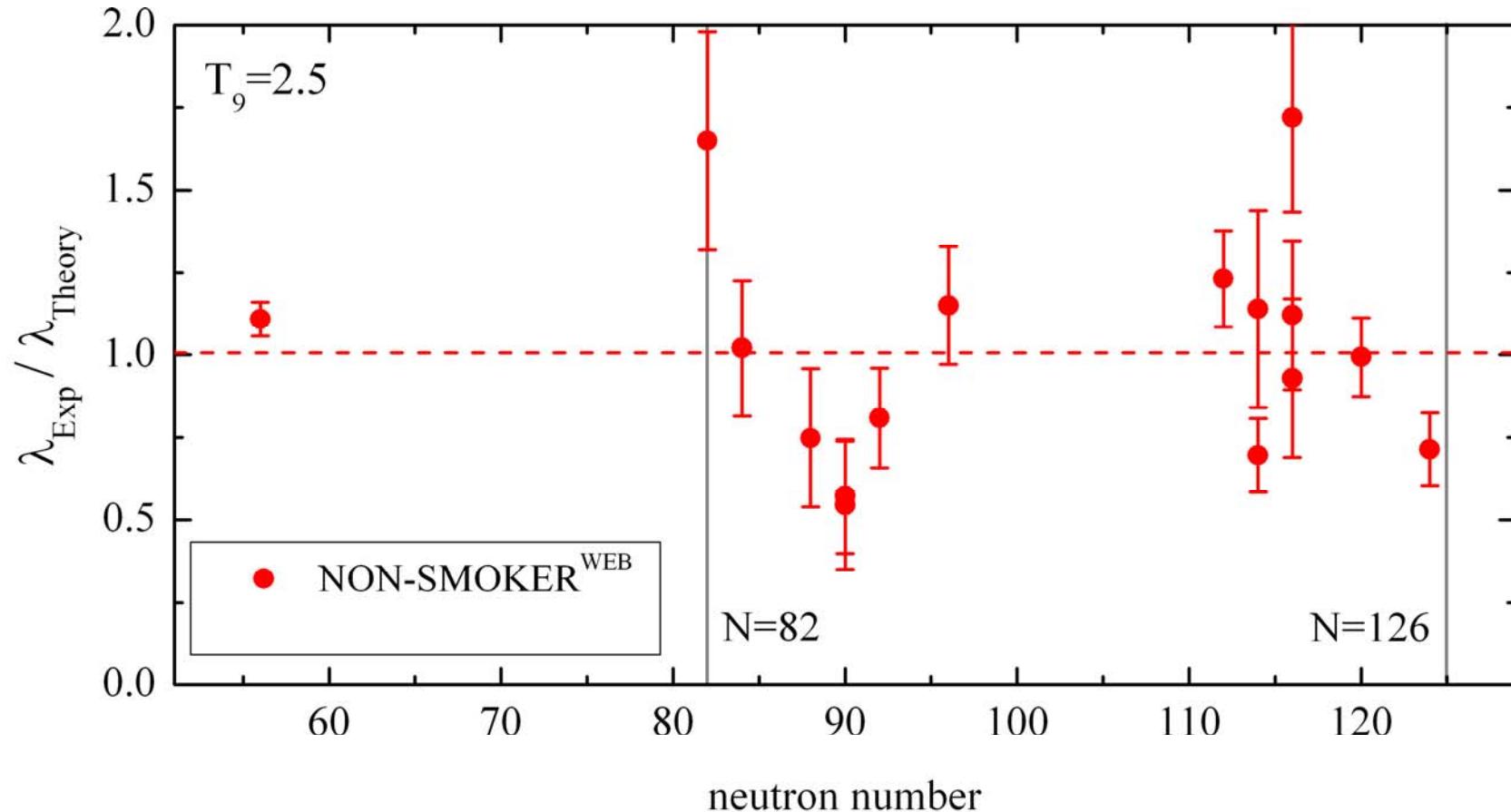
Isotope	$\lambda_{\text{exp,gs}}$	Reference	$\lambda_{\text{NONS,gs}}$	$\lambda_{\text{TALYS,gs}}$
^{148}Nd	65(18)	J. Hasper et al., PRC 77 (2008) 015803	86	82
^{150}Nd	41(12)		72	77
^{154}Sm	7.5(1.4)		9.2	11
^{187}Re	91(11)	S. Müller et al., PRC 73 (2006) 025804	74	99
^{190}Pt	0.6(2)	K. Vogt et al., PRC 63 (2001) 055802	0.14	0.20
^{192}Pt	0.4(1)		0.53	0.62
^{198}Pt	61(7)		61	80
^{197}Au	6.2(8)	K. Vogt et al., NPA 707 (2002) 241	5.3	7.5
^{196}Hg	0.43(7)	K. Sonnabend et al., PRC 70 (2004) 035802	0.25	0.36
^{198}Hg	2.0(3)		1.41	1.75
^{204}Hg	57(9)		80.1	108
^{191}Ir	4.3(5)	J. Hasper, submitted to PRC	4.5	4.6
^{193}Ir	13.5(16)		16	24

NON-SMOKER:
T. Rauscher and
F.-K. Thielemann,
ADNDT 75 (2000) 1

TALYS:
A. Koning et al.

(all reaction rates in s^{-1})

Groundstate reaction rates @ 2.5×10^9 K



NON-SMOKER^{WEB} and TALYS deviate by about 20%

NON-SMOKER^{WEB}, T. Rauscher, <http://www.nucastro.org>
TALYS, A. Koning et al., <http://www.talys.eu>

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

Untagged photons from bremsstrahlung
measure always INTEGRATED reaction rates:

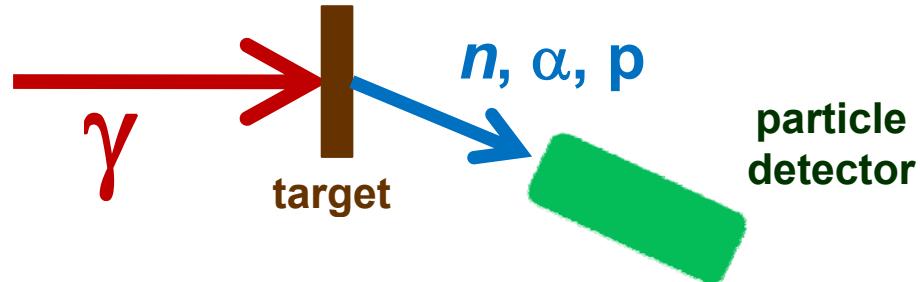
$$\lambda(T) = c \int n_\gamma(E) \sigma(E) dE$$

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

→ use photons with „known“ energy

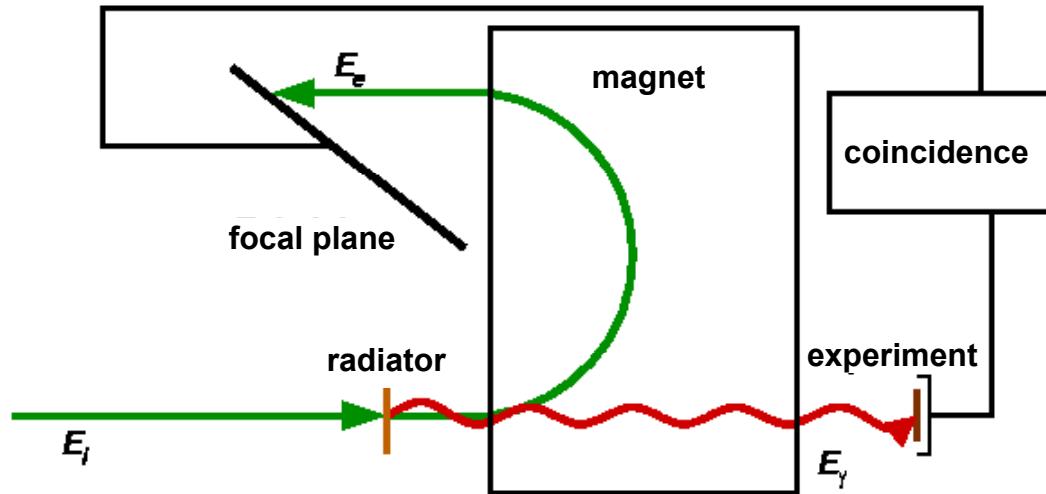
- Tagged bremsstrahlung photons
- Laser Compton Backscattering

„Direct“ experimental techniques II: Dissociation with monoenergetic photons



**Induce (γ, n) , (γ, α) , and (γ, p) reactions with real photons with known energy +
measure n , α , or p**

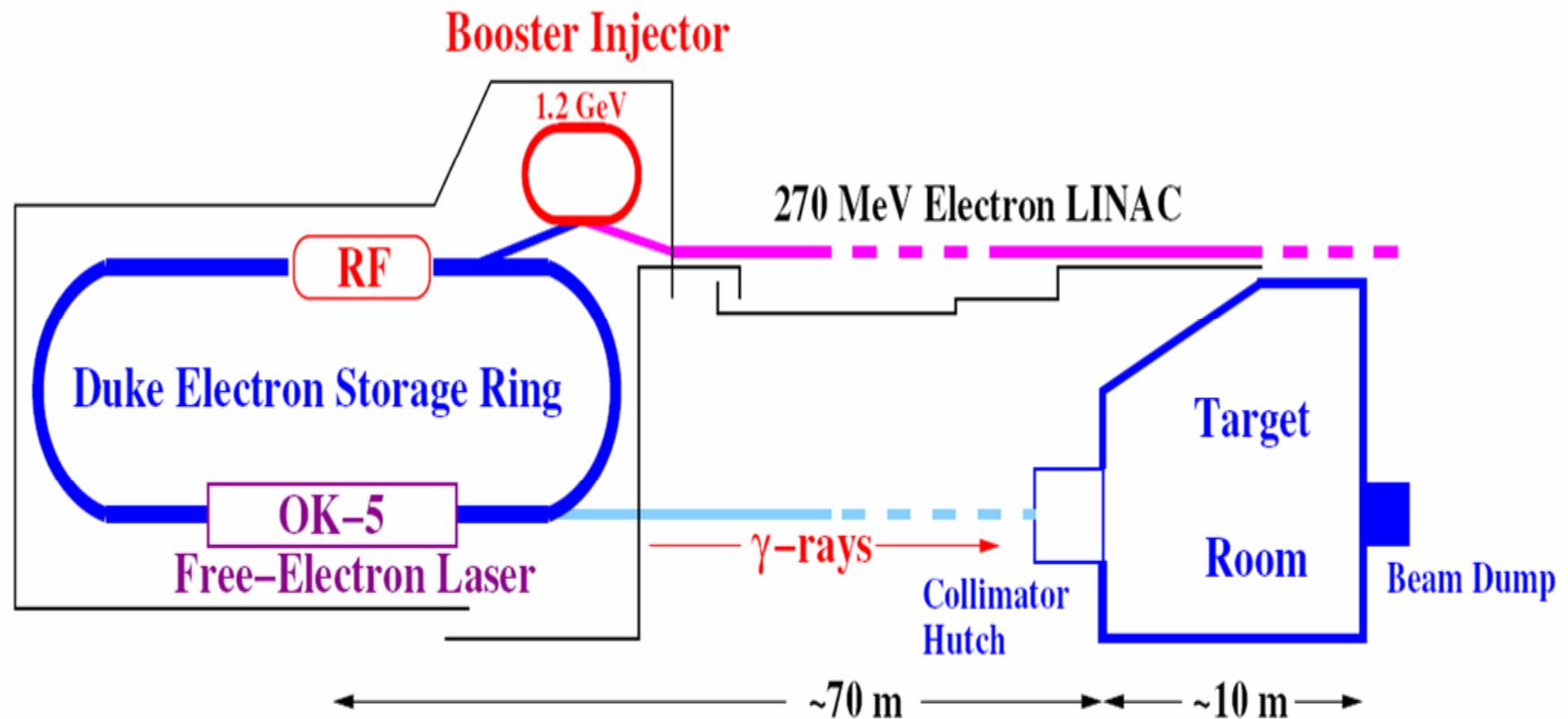
Photon tagger NEPTUN @ S-DALINAC



- $6 \text{ MeV} \leq E_\gamma \leq 20 \text{ MeV}$
 - $\Delta E = 25 \text{ keV}$ @ 10 MeV
 - Photon intensity: $\approx 10^4 \text{ keV}^{-1}\text{s}^{-1}$
- Measure (γ, γ') , (γ, n) , (γ, p) ,
and (γ, α) cross sections



Laser Compton Backscattering at H_I γ S (Duke)



→ see next talk by Anne Sauerwein

The limitations of real photon experiments

The above methods are limited
to „stable“ target nuclei, but:

(γ, n)

(γ, p)

(γ, α)

β^+

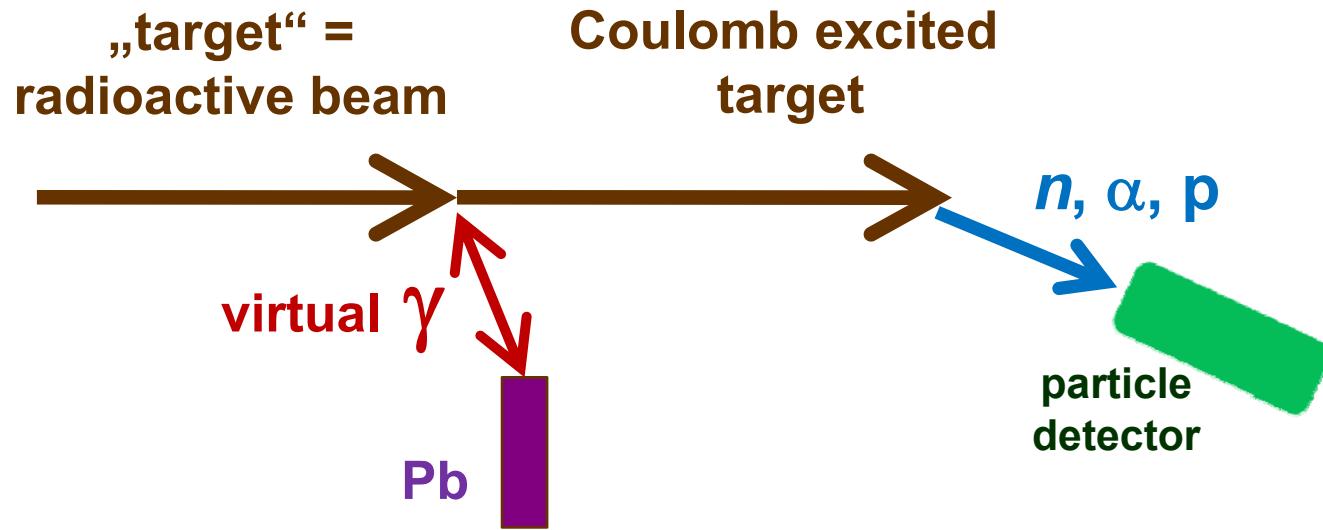
122

118

120

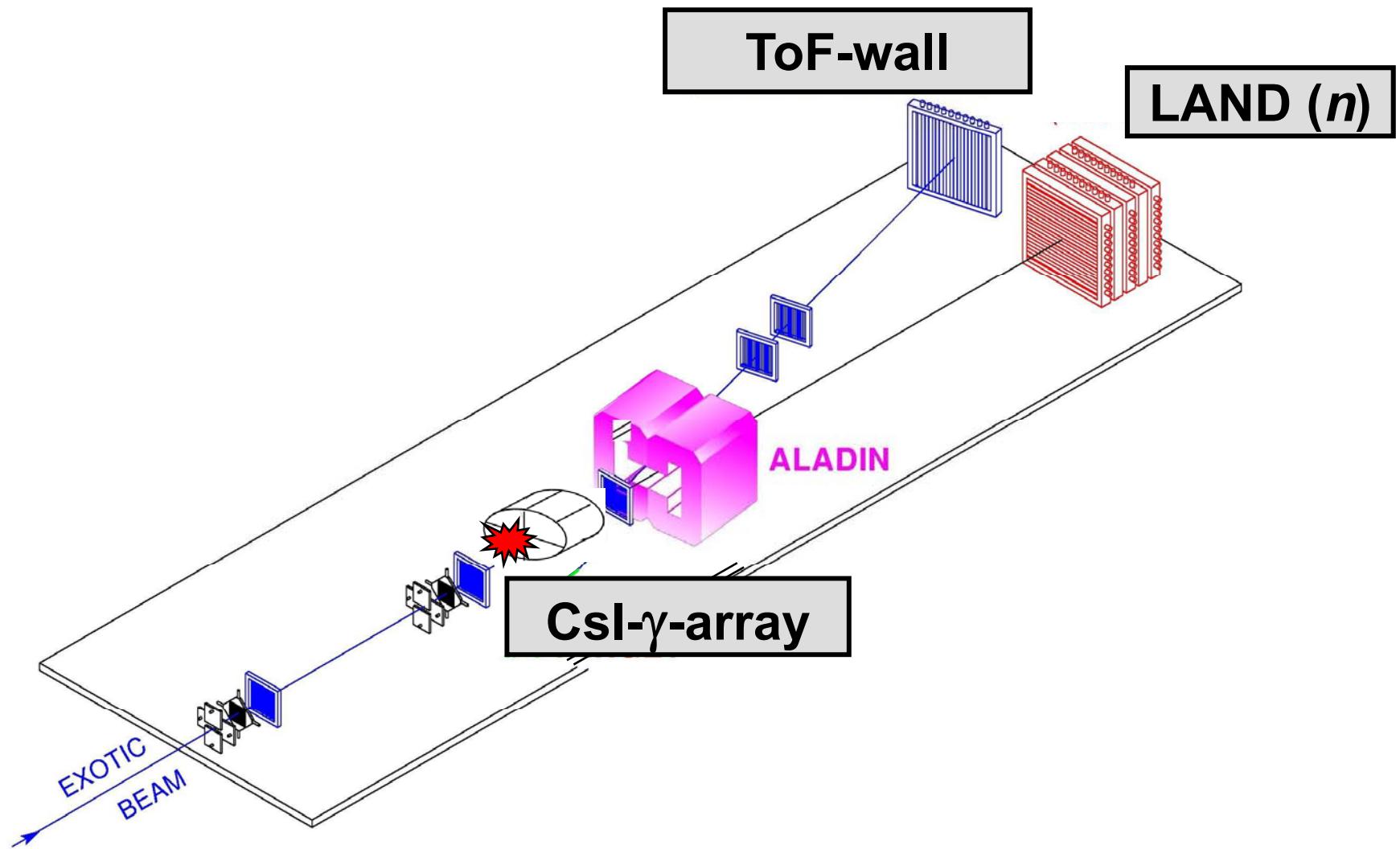
Pb 188 25,5 s	Pb 189 51 s	Pb 190 1,2 m	Pb 191 22 m	Pb 192 3,5 m	Pb 193 5,6 m	Pb 194 12,0 m	Pb 195 18,0 m	Pb 196 16 m	Pb 197 43 m	Pb 198 2,40 h	Pb 199 122 d	Pb 200 21,5 h	Pb 201 81 d	Pb 202 3,63 d	Pb 203 1,2 d	Pb 204 67,2 m
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Hg 186 1,4 m	Hg 187 24 m	Hg 188 22 m	Hg 189 3,7 m	Hg 190 10,7 m	Hg 191 20,0 m	Hg 193 60,8 m	Hg 194 50 m	Hg 195 40 h	Hg 196 0,15	Hg 197 0,15	Hg 198 9,97	Hg 199 42,6 m	Hg 200 16,87	Hg 201 23,10	Hg 202 13,18	Hg 203 29,86
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Au 186 4,2 m	Au 187 1,4 m	Au 188 1,4 m	Au 189 4,9 m	Au 190 29,3 m	Au 191 12,8 m	Au 192 1,8 h	Au 193 5,0 h	Au 194 1,8 h	Au 195 38,6 h	Au 196 32,4	Au 197 7,73 s	Au 198 2,30 d	Au 199 3,139 d	Au 200 14,7 h	Au 201 26,4 m	Au 202 14,7 h
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Pt 184 17,3 m	Pt 185 35 m	Pt 186 1,2 h	Pt 187 1,2 h	Pt 188 2,3	Pt 189 11 h	Pt 190 0,01	Pt 191 0,01	Pt 192 0,79	Pt 193 4,33 d	Pt 194 32,9	Pt 195 4,02 d	Pt 196 32,9	Pt 197 94,4 m	Pt 198 7,2	Pt 199 13,8 s	Pt 200 12,5 h
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Ir 183 55 m	Ir 184 3,0 h	Ir 185 1,4 m	Ir 186 16,64 h	Ir 187 10,5 h	Ir 188 41,5 h	Ir 189 11,3 d	Ir 190 1,2 s	Ir 191 1,0 h	Ir 192 27,3 s	Ir 193 10,63 d	Ir 194 171 d	Ir 195 19,15 h	Ir 196 140 h	Ir 197 52 s	Ir 198 8 s	
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν		
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Os 182 22,1 h	Os 183 0,6 h	Os 184 0,02	Os 185 94 d	Os 186 2,0 $\times 10^{19}$ s	Os 187 1,6	Os 188 13,3	Os 189 0,11	Os 190 0,98 m	Os 191 13,10 h	Os 192 6,1 s	Os 193 30,11 h	Os 194 6,0 d	Os 195 6,5 m	Os 196 34,9 m		
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν			
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
Re 181 20 h	Re 182 15 h	Re 183 71 d	Re 184 38,04	Re 185 37,40	Re 186 2,193 a	Re 187 5-10 ¹⁰ s	Re 188 62,60	Re 189 18,66 h	Re 190 1,0 h	Re 191 24,3 h	Re 192 14 h	Re 193 1,1 h	Re 194 42 d	Re 195 2,2	Re 196 9 s	
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν		
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	
W 180 0,13	W 181 121,2 d	W 182 26,3	W 183 14,3	W 184 30,67	W 185 1,67 m	W 186 76,1 d	W 187 23,72 h	W 188 69 d	W 189 11 m	W 190 30,0 m						
β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν	β^- ν						
γ	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ						

„Direct“ experimental techniques III: Coulomb dissociation



**Induce (γ, n) , (γ, α) , and (γ, p) reactions with virtual photons („inverse kinematics“)
+ measure footprints of reaction**

(Super)FRS / (Neu)LAND setup at GSI / FAIR



T. Aumann, Eur. Phys. Journal A 26 (2005) 441

Summary: Measurements with photons

Activation experiments with bremsstrahlung

- Planck-like photon spectrum
- Integrated cross sections are determined
- Daughter nucleus must show observable decay
- Limited to „stable“ nuclei

Experiments with monoenergetic photons (Tagger or laser Compton backscattering)

- Energy dependent cross section $\sigma(E)$ is observed
- Difficult experiments (photon flux !)
- Limited to „stable“ nuclei

Summary: Measurements with photons

Coulomb dissociation with radioactive beams

- Energy dependent cross section is observed
- Very difficult and complex experiments

Ru 94 51.8 m ϵ γ 367; 891... m	Ru 95 1.65 h ϵ ; β^+ 1.2... γ 336; 1097; 627... g	Ru 96 5.54 σ 0.3	Ru 97 2.9 d ϵ γ 216; 324... g	Ru 98 1.87 $\sigma < 8$
Tc 93 43.5 m 2.7 h β^+ 0.8... γ 363; 1520; 1477...; g	(α, γ) 53 m 4.9	Tc 95 60 d ϵ γ 871; 71 8	Tc 96 ϵ ; β^+ ... γ 204; 582...	Tc 97
(γ, p) (p, γ) Mo 92 14.77 σ 2E-7 + 0.06	Mo 93 6.9 h γ 1477; 685; 263...; ϵ γ (950...) g	Mo 94 3.5 · 10^3 a ϵ m	Mo 95 9.23 σ 0.02	Mo 96 15.90 σ 13.4 $\sigma_{n, \alpha}$ 0.000030
				Mo 96 16.68 σ 0.5

Why not go
the other way around ?

Indirect experimental methods: Radiative capture

Measurements of inverse capture reactions
like (p,γ) and (α,γ) can:

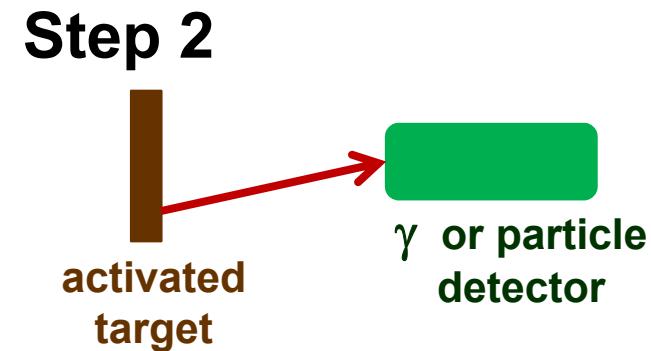
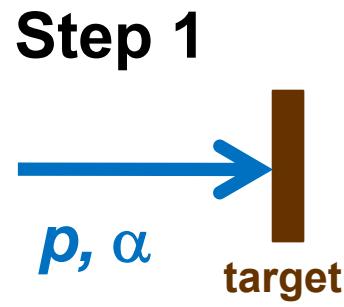
- yield additional information (detailed balance)
- determine the p -nucleus or α -nucleus potential
- allow to study radioactive nuclei

Ru 94 51.8 m	Ru 95 1.65 h	Ru 96 5.54	Ru 97 2.9 d	Ru 98 1.87
ϵ γ 367; 891... m	ϵ ; β^+ 1.2... γ 336; 1097; 627... g	σ 0.23	ϵ γ 216; 324... g	$\sigma < 8$
Tc 93 43.5 m	Tc 94 2.7 h	Tc 95 60 d	Tc 96 52 m	Tc 97 92.2 d
γ 392 ϵ 2645... g	ϵ ; β^+ 0.8... γ 1363; 1520; 1477...; g	ϵ ; β^+ 0.8 γ 871; 703; 850...	ϵ ; β^+ ... 582; 835... γ (39)	ϵ γ 778; 850; 813... γ (97) ϵ no γ
Mo 92 14.77	Mo 93 6.9 h	Mo 94 3.5 · 10^3 a	Mo 95 9.23	Mo 96 15.90
σ 2E-7 + 0.06	γ 1477; 685; 263...; ϵ γ (950...) g	ϵ m	σ 13.4 $\sigma_{n, \alpha}$ 0.000030	σ 0.5

Indirect experimental methods I: Activation experiments after radiative capture

Activation experiments

(e.g., G. G. Kiss *et al.*, PRC 76 (2007) 055807)



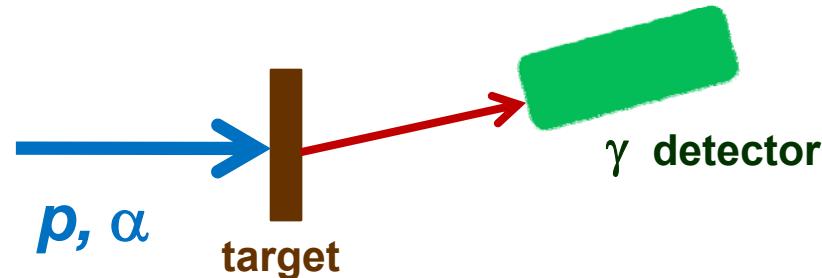
Very sensitive but not always possible.

Indirect experimental methods II: In-beam measurements after radiative capture

In-beam γ spectroscopy

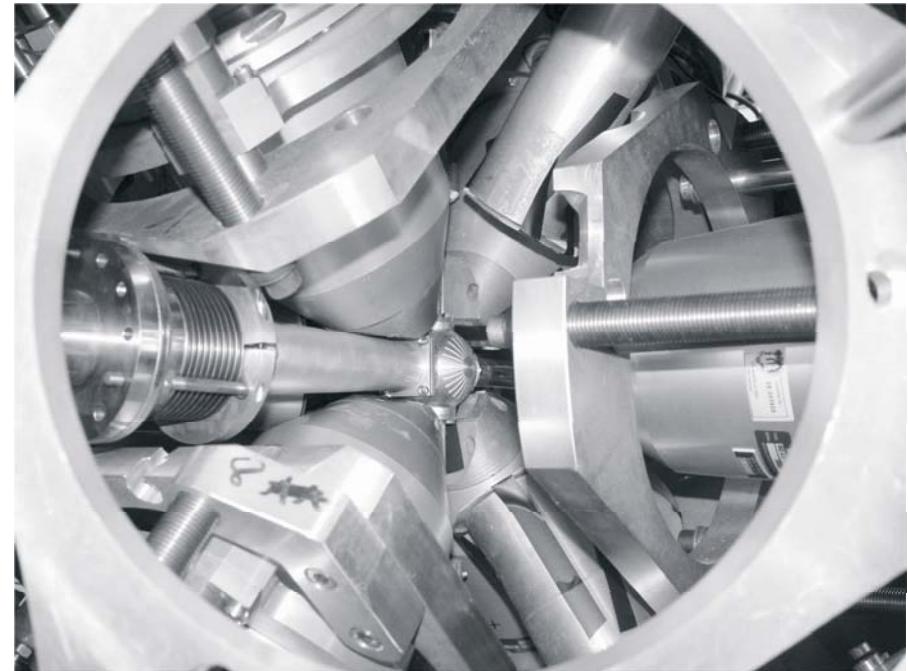
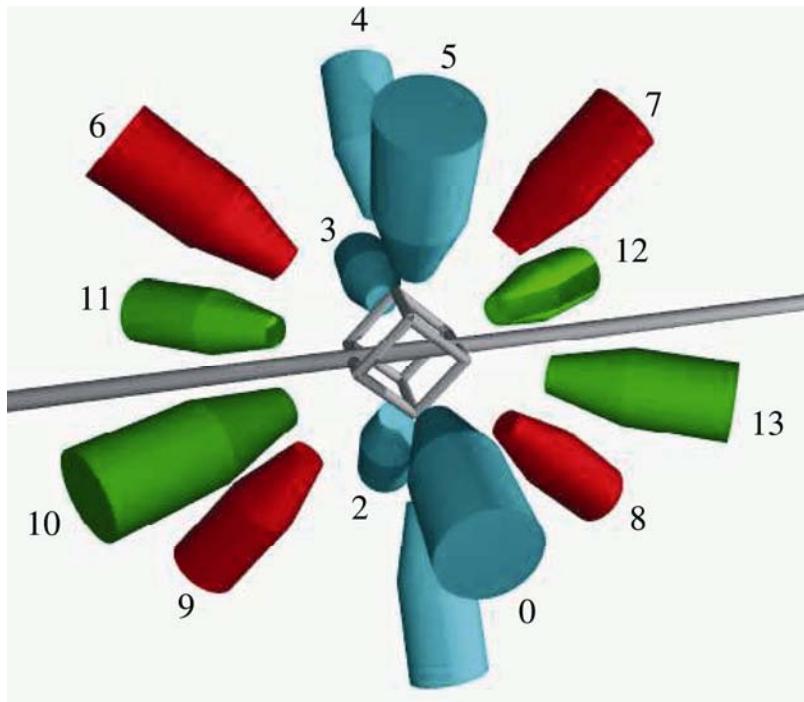
(e.g. with 4π NaI: A. Spyrou et al., PRC 76 (2007) 015802)

(e.g. with HPGe: S. Ganalopoulos et al., PRC 67 (2003) 015801)



Less sensitive but very versatile.

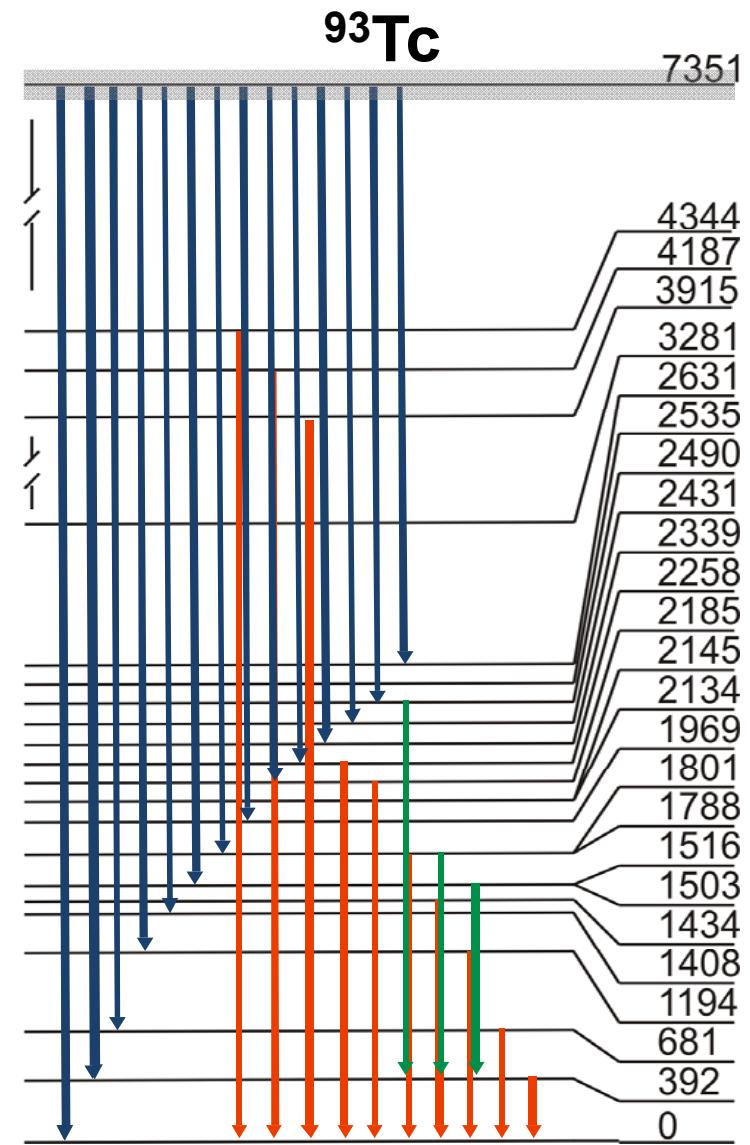
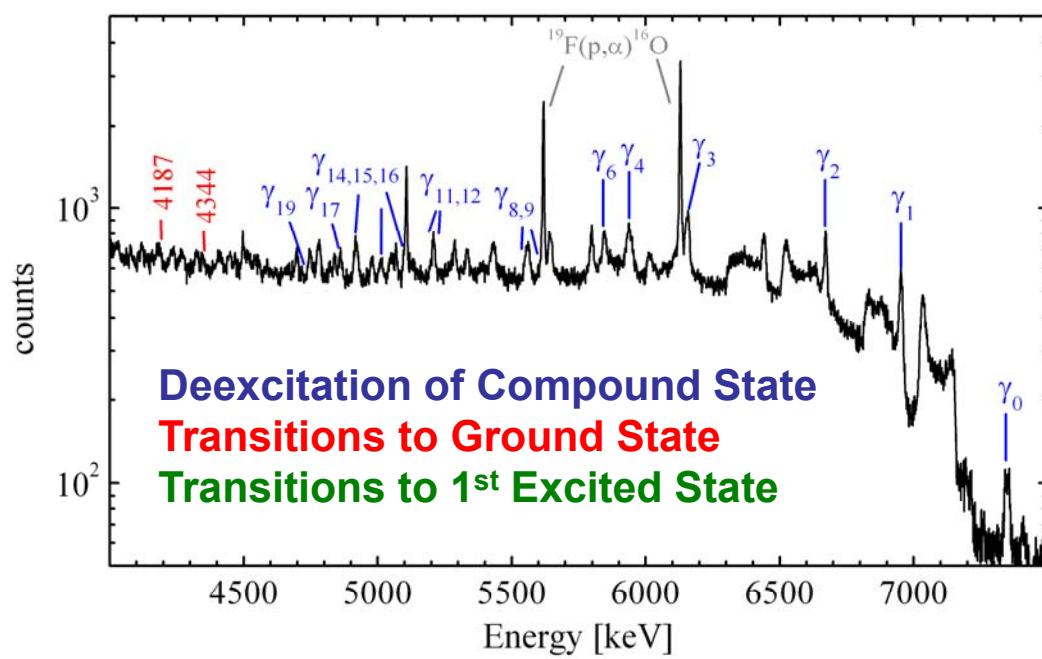
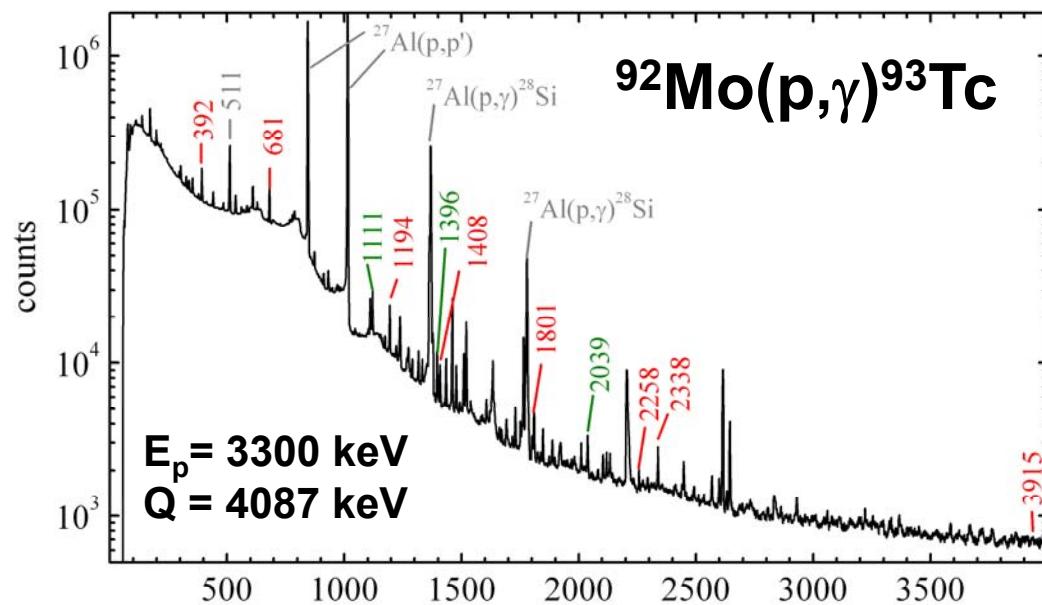
The HORUS γ -detector array @ IKP Köln



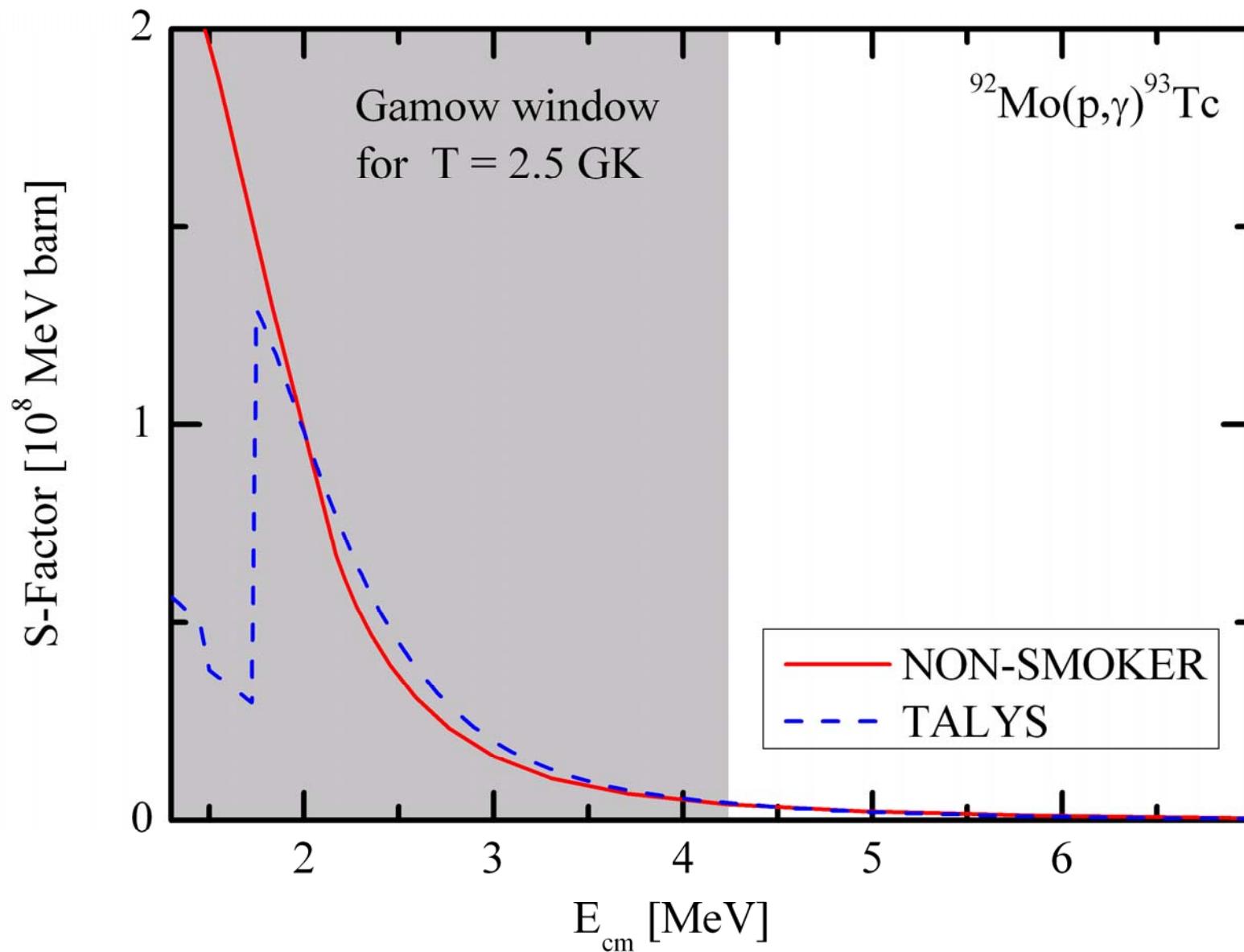
14 HPGe detectors in close geometry

- ⇒ Photopeak efficiency at 1332 keV: ~ 2%
- ⇒ No requirements on reaction products

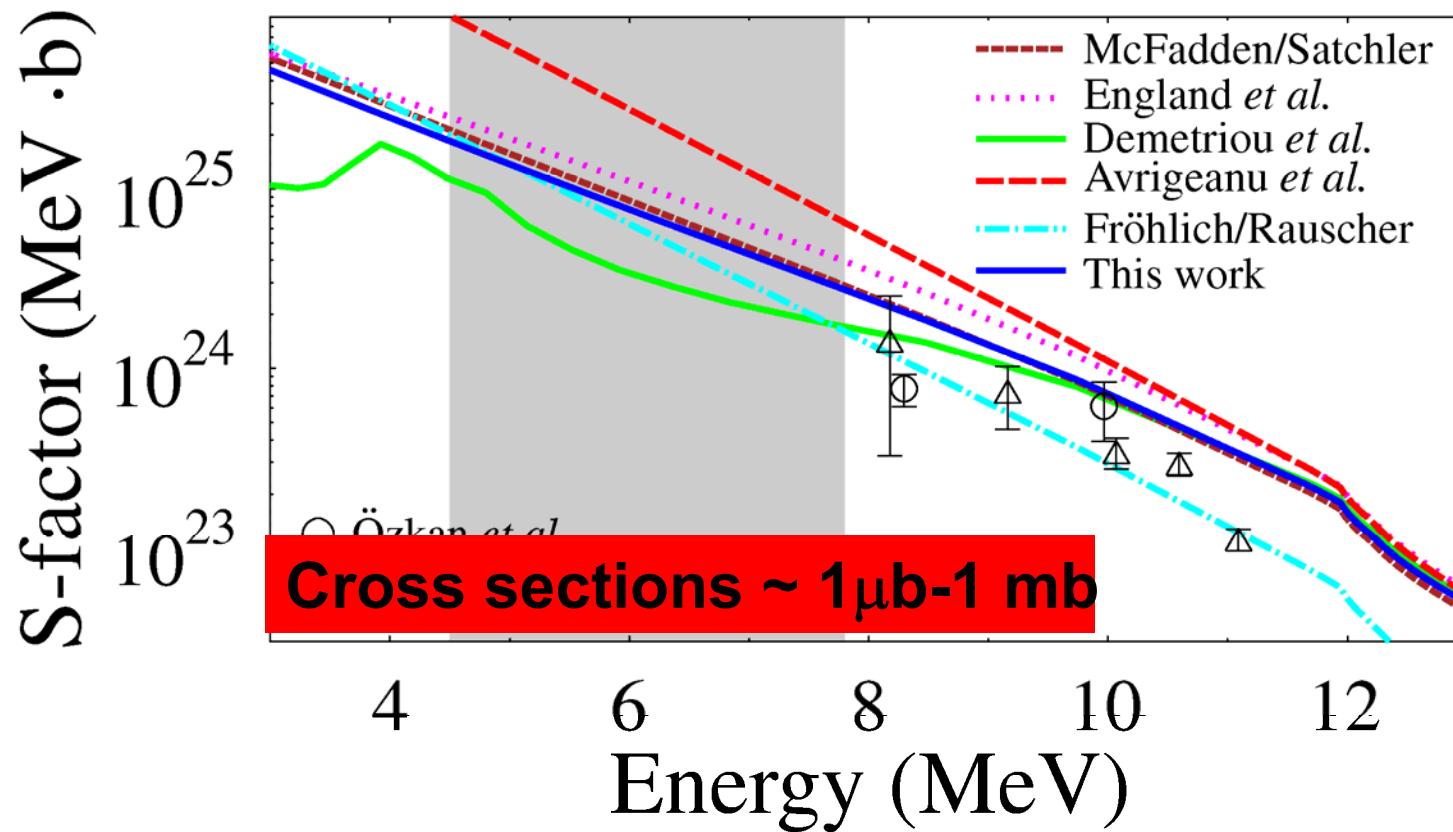
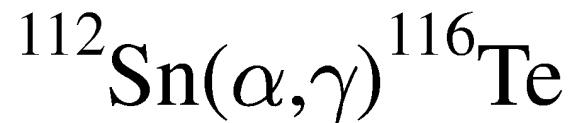
Proton capture on ^{92}Mo at HORUS



Predicted $^{92}\text{Mo}(\text{p},\gamma)$ S-Factor



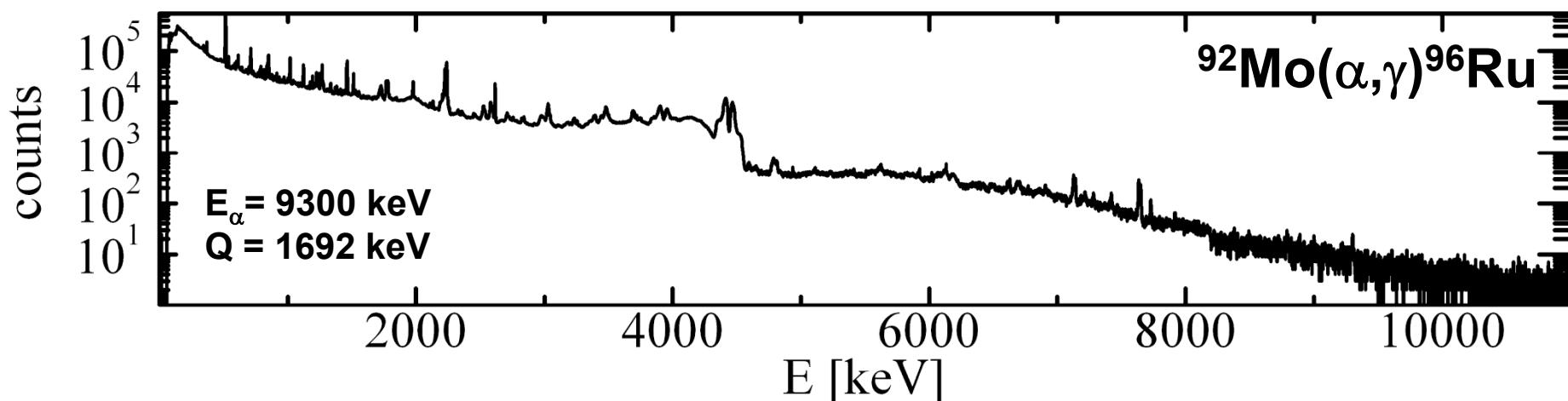
α - capture cross section



N. Özkan *et al.*, PRC 75 (2007) 025801

Overview: P.Demetriou, C. Gramma, S. Goriely, NPA 707 (2002) 253

In-beam α – capture experiment at HORUS



Many background reactions:

Target chamber

- $^{27}\text{Al}(\alpha, n)^{30}\text{P}$
- $^{27}\text{Al}(\alpha, p)^{30}\text{Si}$
- $^{27}\text{Al}(\alpha, \alpha')^{27}\text{Al}$

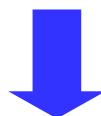
Target contaminants

- $^{13}\text{C}(\alpha, n)^{16}\text{O}$
- $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$
- $^{18}\text{O}(\alpha, n)^{21}\text{Ne}$

Competing reactions

- $^{92}\text{Mo}(\alpha, p)^{95}\text{Tc}$

Decay of radioactive reaction products

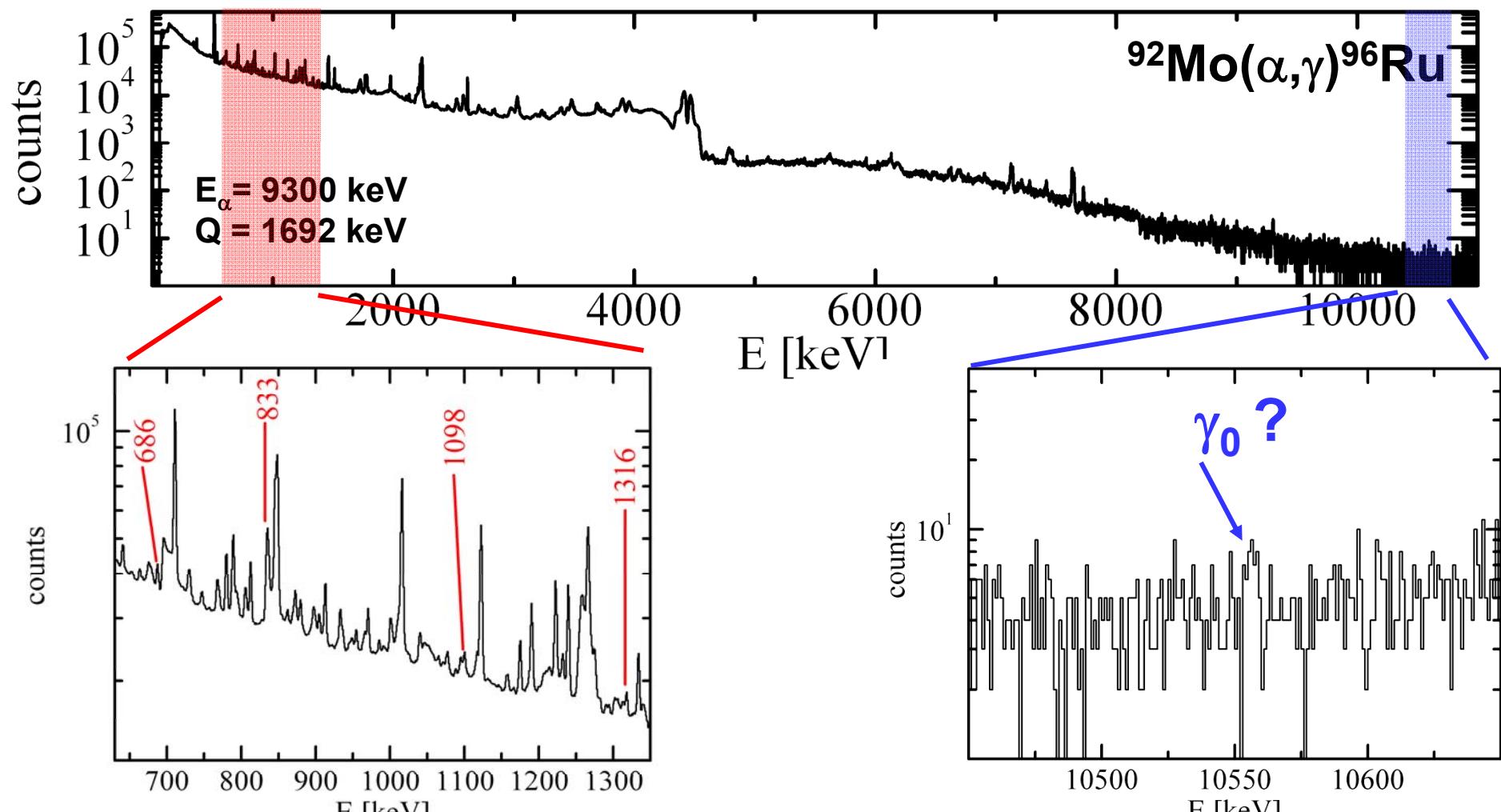


Tantalum coating of chamber



High vacuum or „Cooling Finger“

In-beam α – capture experiment at HORUS



Clear identification of strong low-energetic transitions in ^{96}Ru

First indication of γ_0

PRELIMINARY (experiment in February 2009)

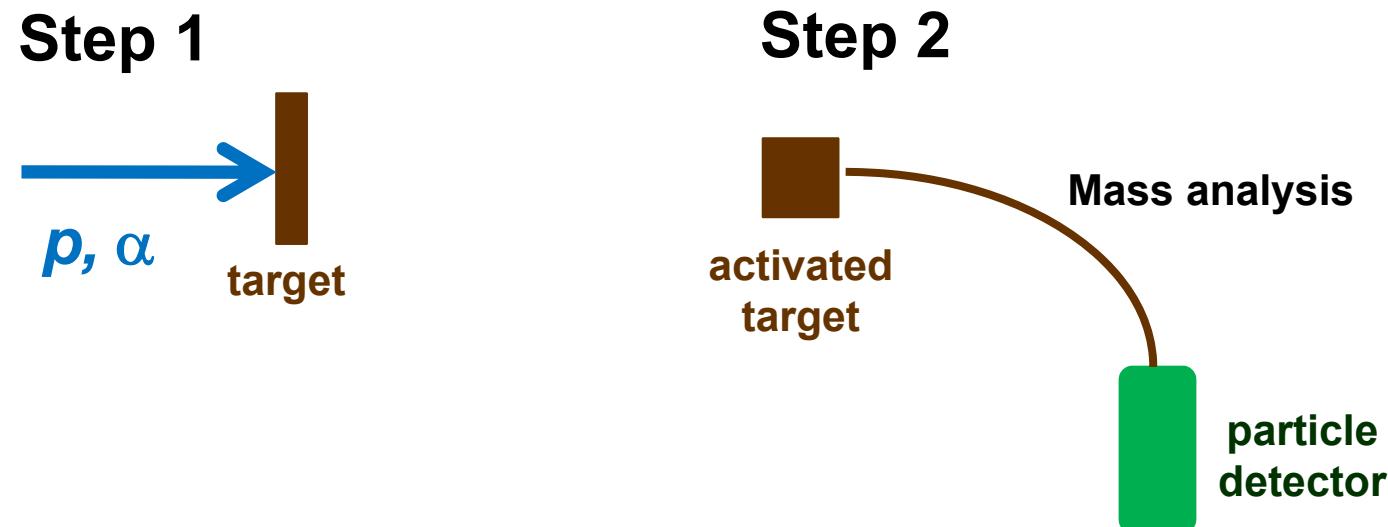
α - capture cross sections

Due to Coulomb barrier (α, γ) experiments become more and more difficult for heavier nuclei.

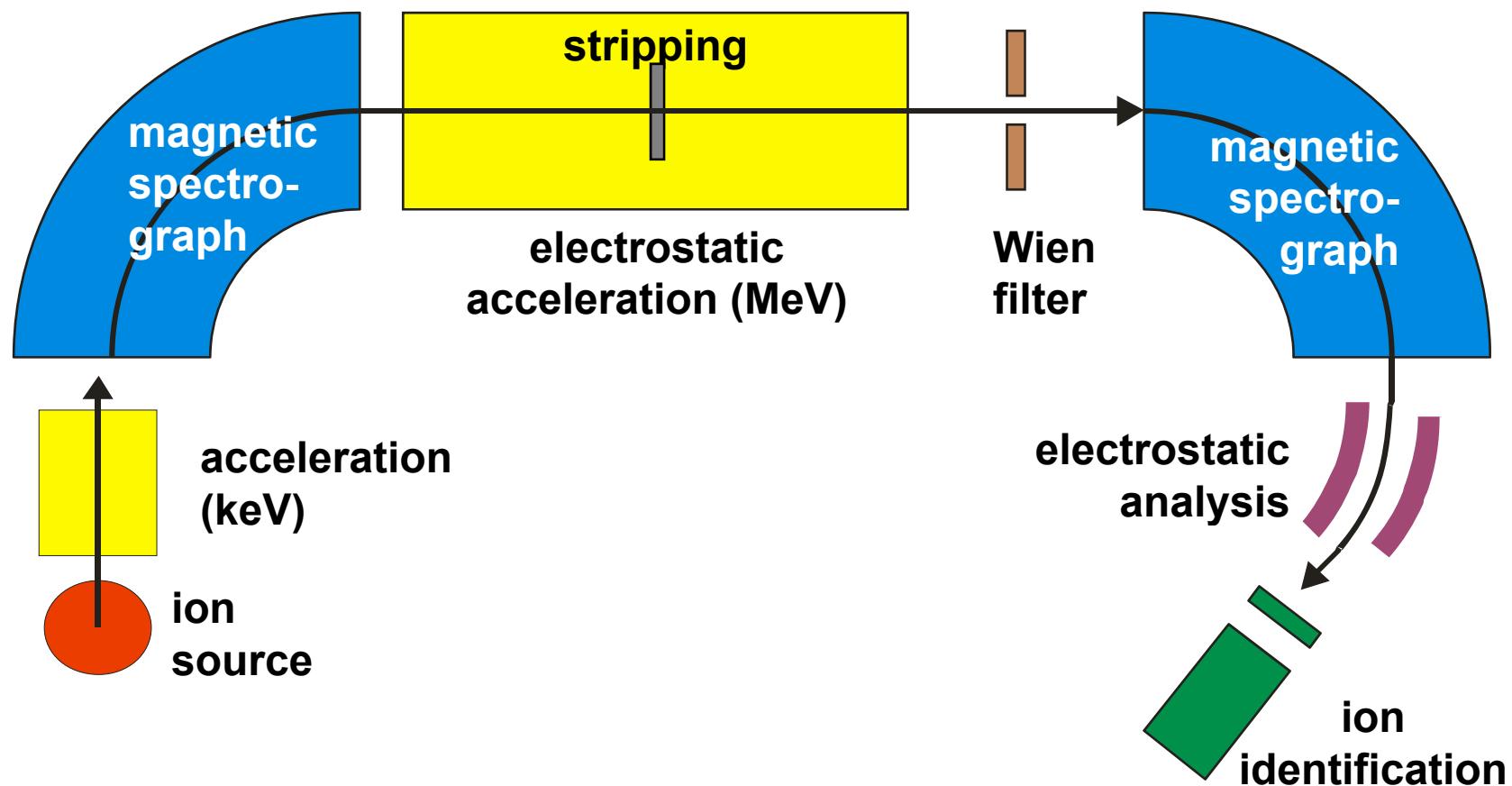
^{145}Tb	^{146}Tb	^{147}Tb	^{148}Tb	^{149}Tb	^{150}Tb					
30 s β^+ γ 258; 988; 537... m; g	23 s β^+ γ 1579; 1079; 1417...	8 s β^+ γ 7.2... γ 1971; 1579...	1.83 m ϵ β^+ γ 1152; 694; 140...	1.65 h β^+ γ 784; 632; 489; 882... 1079...	2.2 m β^+ 2.2... γ 784; 784; 489; 882... 1079...	60 m β^+ 3.8; 4.6... γ 784; 784; 489; 882... 1079...	4.2 m β^+ ϵ α 3.99... β^+ 1.8... γ 796; 796; 165... 165...	4.1 h β^+ ϵ α 3.97... β^+ 1.8... γ 352; 352; 165... 165...	5.8 m β^+ ϵ ; β^+ 3.1; γ 638; 650; 827; 438... 496...	3.67 h β^+ ϵ ; β^+ 3.1; γ 3.7... α 3.49; γ 638; 496...
^{144}Gd 4.5 m β^+ 3.3... γ 333; 2433; 630; 347...	^{145}Gd 85 s β^+ γ 721... 330	^{146}Gd 23.9 m β^+ γ 2.3... 1758; 1881; 1042...	^{147}Gd 48.3 d β^+ γ 155; 116; 115...	^{148}Gd 38.1 h ϵ ; β^+ γ 229; 396; 929...	^{149}Gd 74.6 a α 3.6... γ 400	^{150}Gd 9.28 d ϵ ; α 3.016 γ 150; 299; 347...				
^{143}Eu 2.6 m β^+ 4.1... γ 1107; 1537; 1913; 108; 1805...; g	^{144}Eu 10.2 s β^+ γ 5.2... 1660; 818...	^{145}Eu 5.93 d β^+ γ 1.7... 894; 1659; 654...	^{146}Eu 4.51 d β^+ γ 1.5... 74...; 633; 63...	^{147}Eu 24.6 d ϵ ; β^+ α 2.91 γ 197; 121; 678...	^{148}Eu 55.6 d ϵ ; β^+ α 2.63 γ 550; 630; 611...					
^{142}Sm 72.4 m ϵ β^+ 1.0 γ (679)	^{143}Sm 65 s β^+ γ 271 (669...)	^{144}Sm 3.07 σ 1.6	^{145}Sm 340 d ϵ ; γ 61; (492...) σ 280	^{146}Sm $1.03 \cdot 10^8$ a α 2.455	^{147}Sm 14.99 α 2.235; σ 56 σ_n , α 0.0006					
^{141}Pm 20.9 m β^+ 2.7... γ 1223; 886; 194; 1346... g	^{142}Pm 40.5 s β^+ γ 3.8... 1576...	^{143}Pm 265 d ϵ no β^+ γ 742	^{144}Pm 1.0 a ϵ ; no β^+ γ 618; 697; 477...	^{145}Pm 17.7 a ϵ ; α 2.24 γ 72; (67) e^-	^{146}Pm 5.53 a ϵ ; β^- 0.8... γ 454; 747; 736... σ 8400					

(α spectroscopy: E. Somorjai et al., Astron. Astrophys. 333 (1998) 1112)

Indirect experimental methods III: Mass spectrometry after radiative capture



Accelerator Mass Spectrometry (AMS)



High sensitivity: isotopic ratios down to 10^{-15} .

High efficiency: amounts of 10^5 nuclei.

Separation of isobars possible.

Accelerator Mass Spectrometry (AMS)

Typical application:
Detection of smallest
amounts of ^{14}C

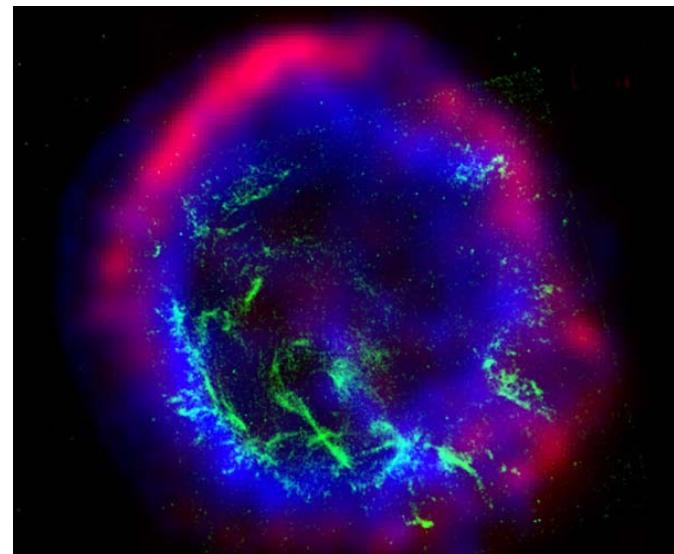


Further application:
Detection of other
cosmogenic nuclides
(e.g. ^{10}Be , ^{26}Al , ^{36}Cl)



Accelerator Mass Spectrometry (AMS)

But as well:
**Detection of other nuclides
produced in the laboratory
or by cosmic events**



Famous examples:

$^{26}\text{Mg}(p,n)^{26}\text{Al}$: M. Paul et al., PLB 94 (1980) 303

$^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$: Nassar et al., PRL 96 (2006) 041102

^{60}Fe content in ferromanganese crusts: K. Knie et al., PRL 93 (2004) 17

Accelerator Mass Spectrometry (AMS)

- Huge demand for AMS in geosciences, archaeology, ...
- Existing facilities do not like to test „new“ isotopes
- Only a handful „normal“ accelerator laboratories like Notre Dame or MLL Munich are using AMS for non-standard applications

(see *D. Robertson et al., NIM B 266 (2008) 3481*)

Accelerator Mass Spectrometry (AMS)

In 2007 the German Funding Agency DFG decided to install a new „high performance“ 6 MV AMS facility in Germany



Application from the University of Cologne:

Geography

(U. Radtke)

Geology

(M. Melles, M. Staubwasser)

Mineralogy Hannover (now GFZ Potsdam)

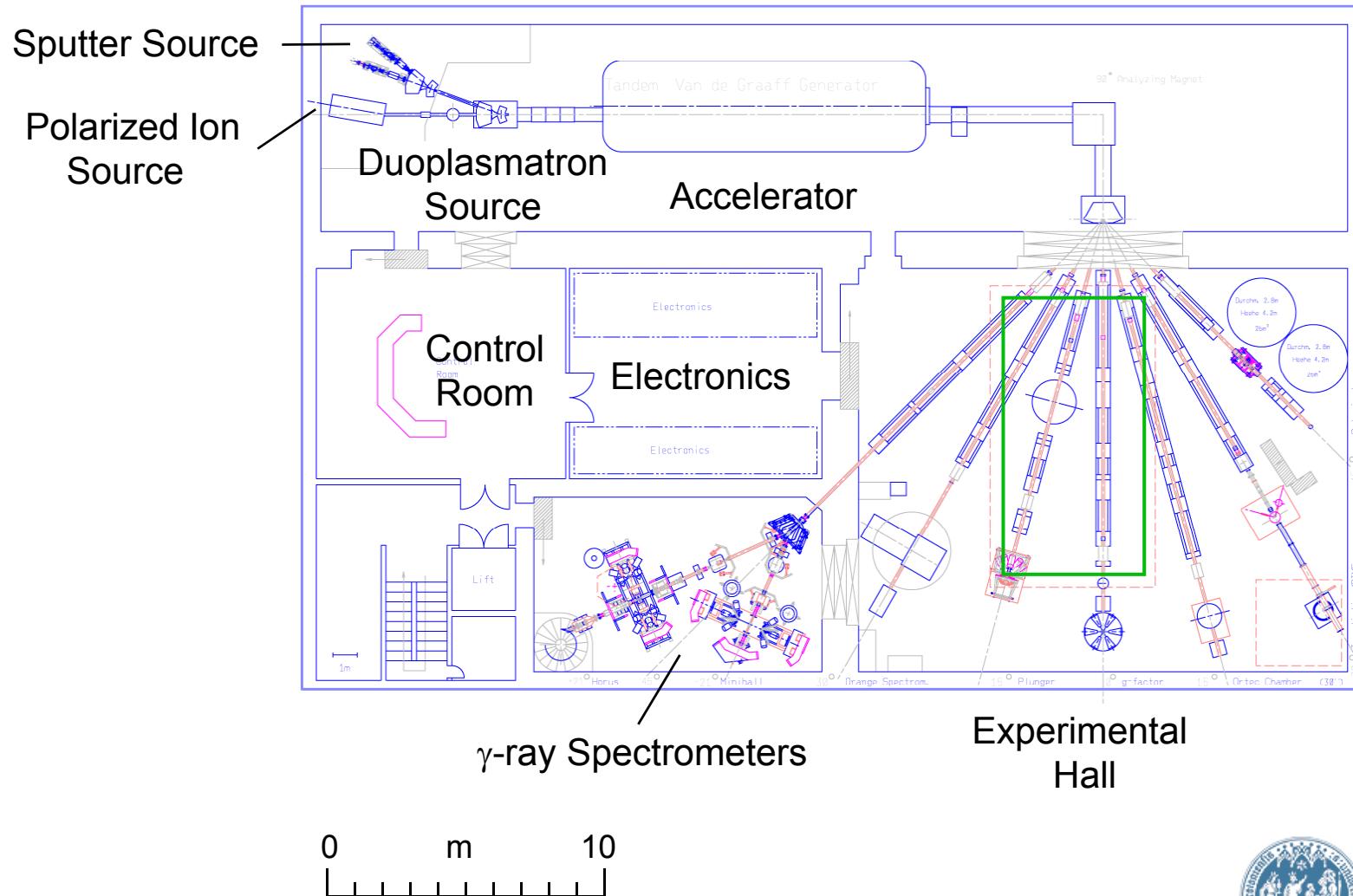
(F. von Blanckenburg)

Nuclear Physics

(A. Dewald, J. Jolie, A. Zilges)

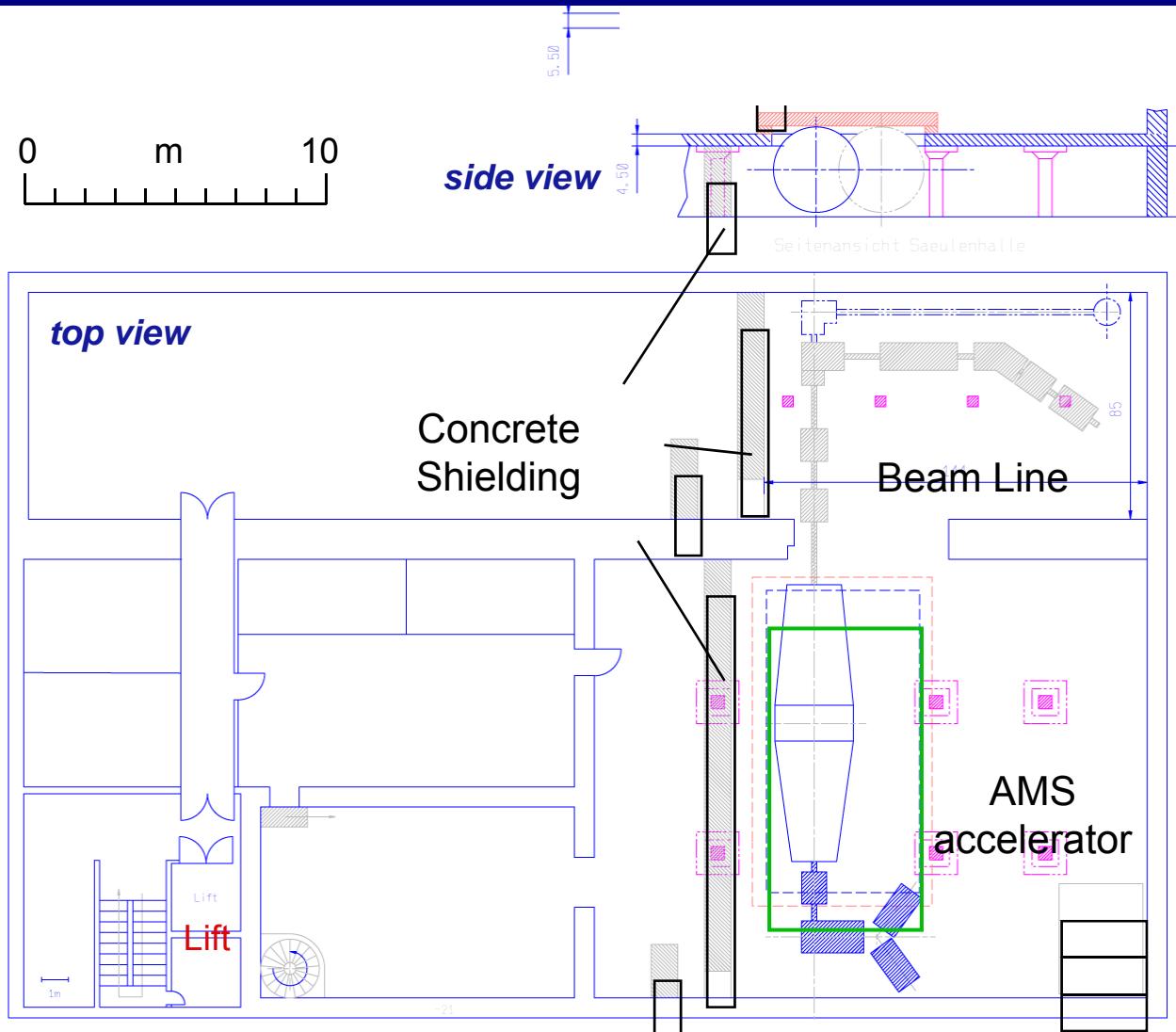
About 20% of total beamtime reserved
for developments and nuclear physics !

The existing 10 MV Tandem Accelerator (1st basement) Institute for Nuclear Physics, Universität zu Köln



Universität
zu Köln

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



Funded by **DFG** and



University
of Cologne

The new 6 MV Tandemtron Accelerator Institute for Nuclear Physics, University of Cologne

Total investment: about 9 M€

Annual running costs: about 0.3 M€

Additional personnel: 2 Professors, 2 Scientists, 3 Technicians, 4 Operators



AMSCologne

A. Dewald, J. Jolie, and A. Zilges, Nuclear Physics News 18 (2008) 26

Funded by **DFG** and



University
of Cologne

Facilities at the Universität zu Köln

- The 10 MV Tandem and the 6 MV AMS Cologne run completely independently
- Sample preparation including Nuclear Chemistry on site
- No complicated PAC procedures
- Delivery of AMS tandemron: early 2010
- Commissioning: mid 2010

COME AND SEE (AND USE) !



Experimental techniques to investigate the p process of nucleosynthesis

M. Büssing, M. Elvers, J. Endres, J. Hasper

Institut für Kernphysik, Universität zu Köln

L. Kern, S. Müller, D. Savran,
A. Sauerwein, V. Simon, K. Sonnabend

Institut für Kernphysik, TU Darmstadt

*Supported by **DFG** (ZI 510/5-1) and by BMBF*

More information and references: www.zilges.de