

Gamma-induced reactions in explosive nucleosynthesis

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

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The p-process: Nuclear reaction network

Pb 188 25,5 s	Pb 189 51 s	Pb 190 1,2 m	Pb 191 2,2 m 5,4 m	Pb 192 3,5 m	Pb 193 5,6 m 4,9 m	Pb 194 12,0 m	Pb 195 15,0 m - 16 s	Pb 196 36,4 m	Pb 197 43 s - 16 s	Pb 198 2,40 h	Pb 199 12,2 h - 13 h	Pb 200 21,5 h	Pb 201 81 s	Pb 202 84 h	Pb 203 163 s 526-164 s	Pb 204 82 s 31,3 h	Pb 204 67,2 m 1,4						
α β^+ γ $\nu\bar{\nu}$	γ β^+ γ $\nu\bar{\nu}$																						
Tl 187 18,4 s	Tl 188 45 s	Tl 189 1,2 m	Tl 190 1,4 m 2,3 m ?	Tl 191 3,7 m	Tl 192 5,4 m	Tl 193 10,0 m	Tl 194 9,6 m	Tl 195 33 s	Tl 196 3,6 s 1,18 h	Tl 197 1,4 h	Tl 198 1,8 h	Tl 199 2,84 h	Tl 199 1,87 h	Tl 200 5,2 h	Tl 201 26,1 h	Tl 202 73,1 h	Tl 203 12,23 d	Tl 203 29,524					
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																						
Hg 186 1,4 m	Hg 187 24 m	Hg 188 2,2 m	Hg 189 3,2 m	Hg 190 4,7 m	Hg 190 7,7 m	Hg 191 20,0 m	Hg 191 50,0 m - 50 m	Hg 193 4,9 h	Hg 194 11,1 h 520 a	Hg 194 40 h	Hg 195 0,15	Hg 196 0,15	Hg 197 1,1 h	Hg 198 5,97	Hg 199 42,8 s	Hg 200 16,07	Hg 201 23,10	Hg 201 13,18	Hg 202 29,86				
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																						
Au 18 4,2 m	Au 187 4,2 m	Au 187 8,4 m	Au 187 8,4 m	Au 189 4,6 m	Au 190 28,3 m	Au 190 12,8 m	Au 191 1 s	Au 191 3,18 h	Au 192 5,0 h	Au 193 3,9 s	Au 194 17,65 h	Au 194 38,0 h	Au 195 32,3 s	Au 195 109,7 d	Au 196 6,7 h	Au 197 7,73 s	Au 198 102	Au 199 2,30 d	Au 199 3,139 d	Au 200 13,7	Au 200 48,4 m		
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				
Pt 184 17,3 m	Pt 185 33 m	Pt 186 1,2 h	Pt 186 2,0 h	Pt 187 2,3	Pt 188 11 h	Pt 189 0,01	Pt 190 6,5	Pt 190 1,0 h	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d - 30 s	Pt 194 0,79	Pt 195 4,02 d	Pt 195 33,8	Pt 196 4,02 d	Pt 196 25,3	Pt 197 94,4 m	Pt 197 18,3 h	Pt 198 7,2	Pt 199 13,8 a	Pt 200 50,8 m		
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				
Ir 183 55 m	Ir 184 3,0 h	Ir 185 3,0 h	Ir 186 16,64 h	Ir 187 10,5 h	Ir 188 41,5 h	Ir 188 13,3 d	Ir 189 3,5 h	Ir 189 1,18 h	Ir 190 4,84 s	Ir 190 3,73 s	Ir 191 201 s	Ir 191 14,76 d	Ir 192 10,63 d	Ir 192 62,7	Ir 193 171 d	Ir 193 19,15 h	Ir 194 2,8 h	Ir 194 2,5 h	Ir 195 140 h	Ir 196 52 s	Ir 197 8,9 m	Ir 198 5,8 m	
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				
Os 182 22,1 h	Os 183 0,9 h	Os 183 13,0 h	Os 185 0,02	Os 185 94 d	Os 186 0,58	Os 186 2,0 - 10 ¹⁰ s	Os 187 1,6	Os 188 13,3	Os 189 8 h	Os 189 18,1	Os 190 8,9 m	Os 190 26,4	Os 191 13,10 h	Os 191 15,4 d	Os 192 6,1 s	Os 192 41,0	Os 193 10,11 h	Os 194 6,0 a	Os 195 6,5 m	Os 196 34,9 m			
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				
Re 181 20 h	Re 182 18 h	Re 183 71 d	Re 184 109 d	Re 185 37,40	Re 186 2 - 10 ² a	Re 186 35,25 h	Re 187 5 - 10 ¹⁰ d	Re 187 62,60	Re 188 18,8 m	Re 188 16,98 h	Re 189 24,3 h	Re 189 3,0 h	Re 190 3,1 m	Re 190 62,7	Re 191 171 d	Re 191 19,15 h	Re 192 2,8 h	Re 192 16 s	Re 192 4,1	Re 192 16 s	Re 192 16 s	118	120
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				
W 180 0,13	W 181 121,2 d	W 182 26,3	W 183 14,4	W 184 30,67	W 185 1,67 m	W 186 76,1 d	W 186 28,6	W 187 23,72 h	W 187 1,1 m	W 188 69 d	W 188 11 m	W 189 30,0 m											
γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$	γ $\nu\bar{\nu}$																				

(γ, n)

(γ, p)

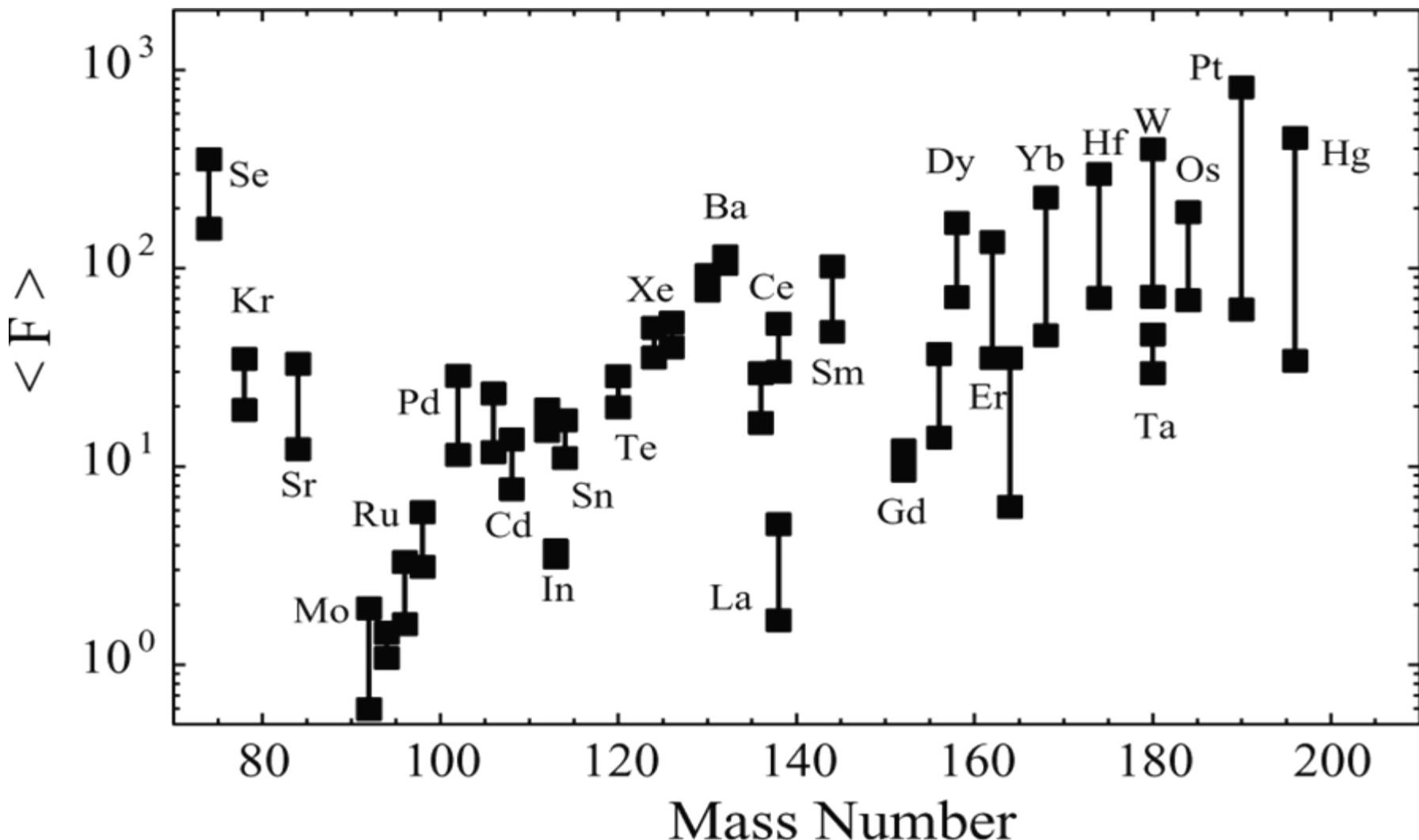
(γ, α)

β^+

122

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

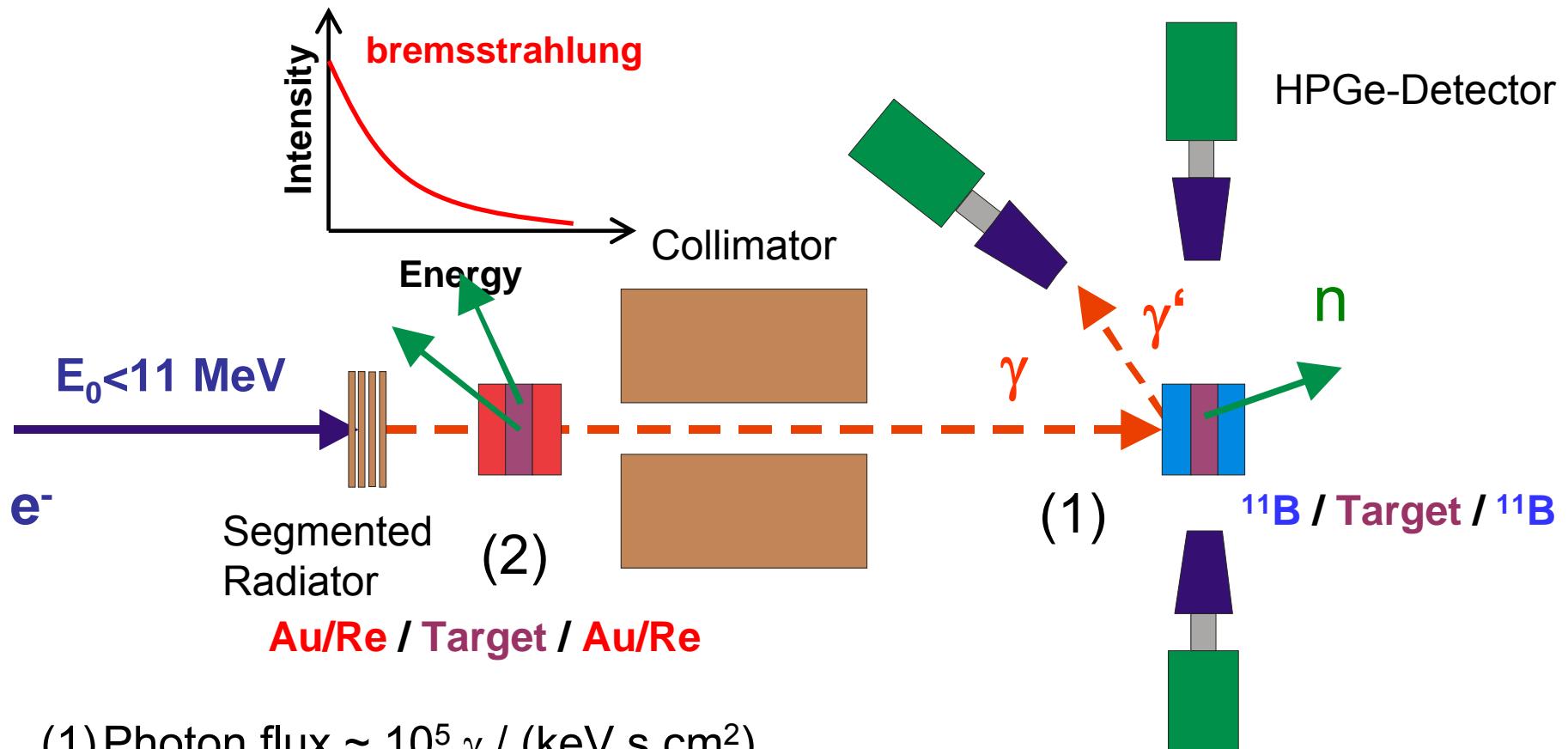
Nuclear Physics input for the p-process

- 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**
 - SUPERFRS/NEULAND setup at GSI/FAIR
 - talk by Konstanze Boretzky on Thursday

The photoactivation setup at S-DALINAC

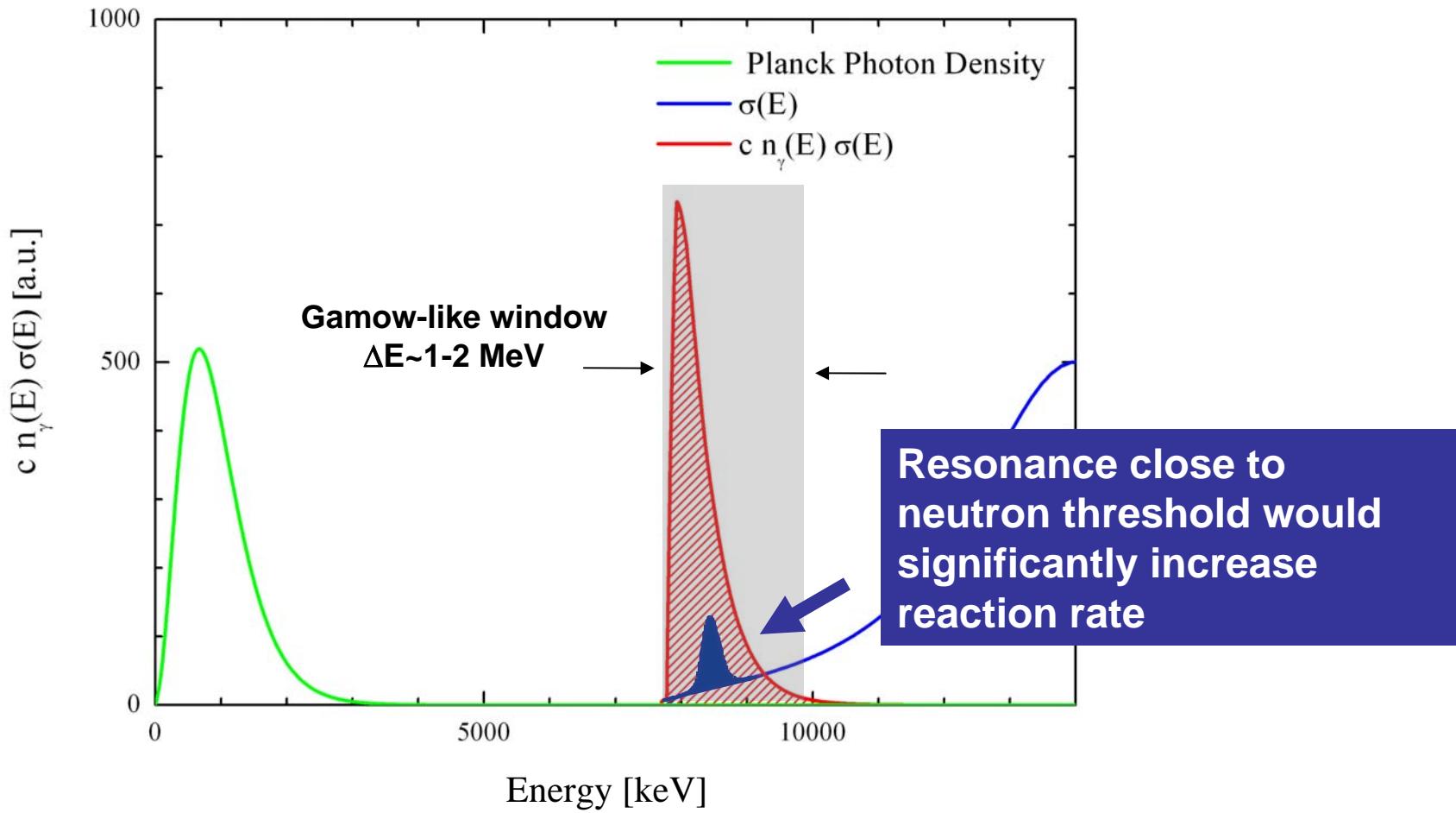


(1) Photon flux $\sim 10^5 \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{11}\text{B}(\gamma, \gamma')$

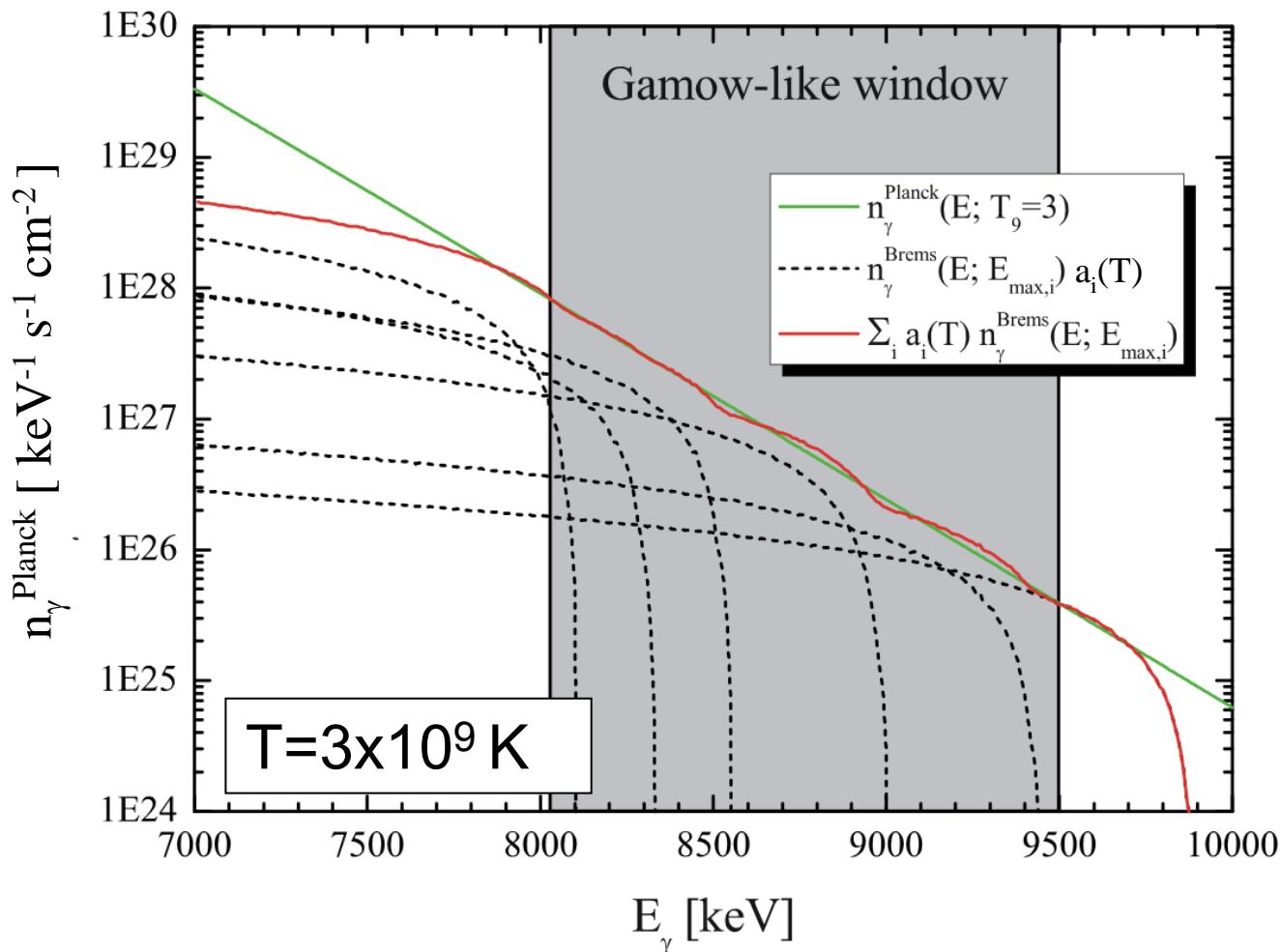
(2) Photon flux $\sim 10^7 \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{197}\text{Au}(\gamma, n)$ and $^{187}\text{Re}(\gamma, n)$

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

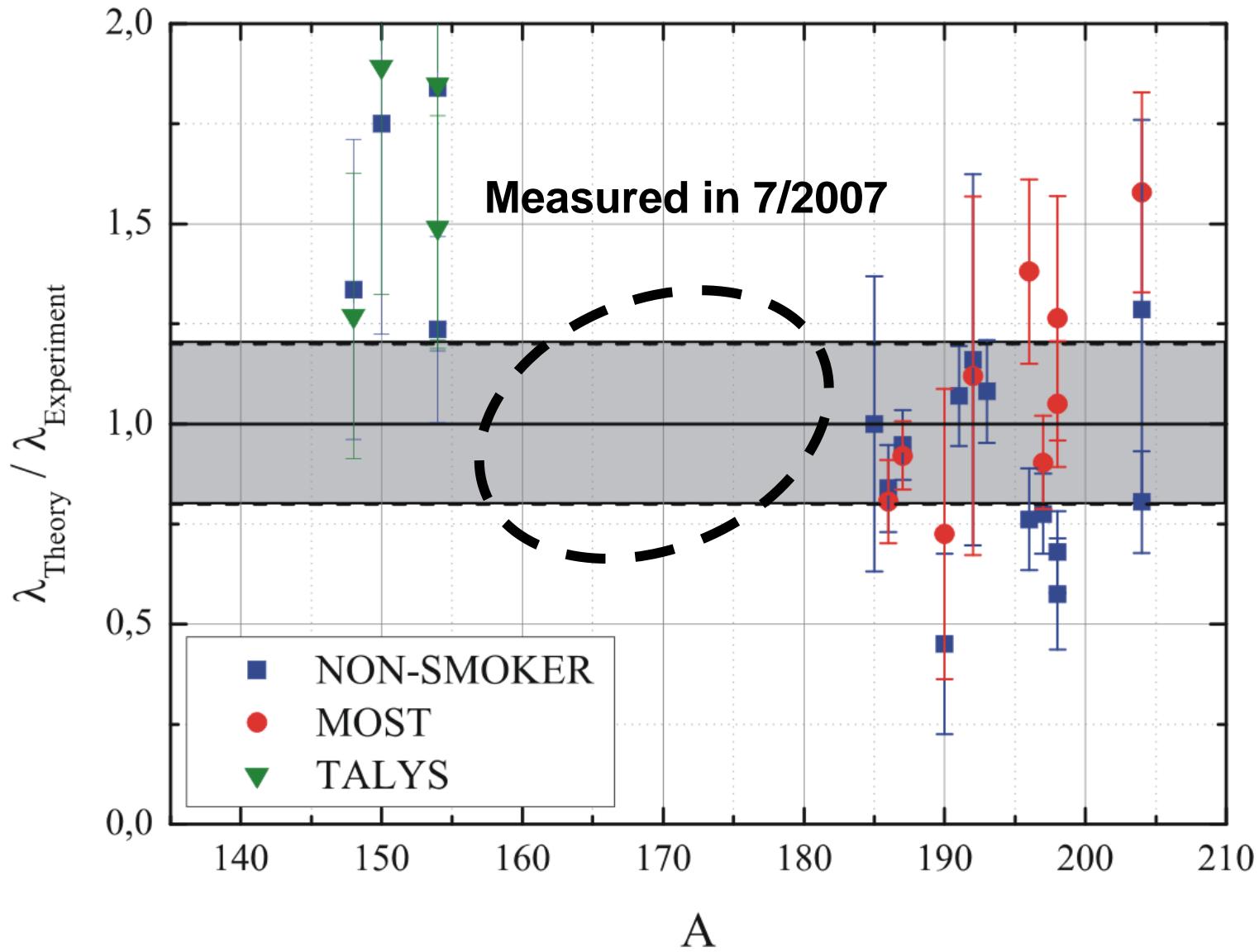
Groundstate reaction rates @ 2.5×10^9 K

Isotope	$\lambda_{\text{exp,gs}}$	Reference	$\lambda_{\text{NONS,gs}}$	$\lambda_{\text{MOST,gs}}$
^{186}W	310(40)	K. Sonnabend et al., ApJ 583 (2003) 506	260	250
^{185}Re	19(7)	S. Müller et al., Phys. Rev. C 73 (2006) 025804	19	44
^{187}Re	76(7)		72	70
^{190}Pt	0.4(2)	K. Vogt et al., Phys. Rev. C 63 (2001) 055802	0.18	0.29
^{192}Pt	0.5(2)		0.58	0.56
^{198}Pt	87(21)		50	110
^{197}Au	6.2(8)	K. Vogt et al., Nucl. Phys. A 707 (2002) 241	4.81	5.6
^{196}Hg	0.42(7)	K. Sonnabend et al., Phys. Rev. C 70 (2004) 035802	0.32	0.58
^{198}Hg	2.0(3)		1.36	2.1
^{204}Hg	57(21)		73.3	170
^{204}Pb	1.9(3)		1.53	3.0
^{191}Ir	4.3(5)	J. Hasper, submitted	4.6	-
^{193}Ir	13.5(16)		14.6	-

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

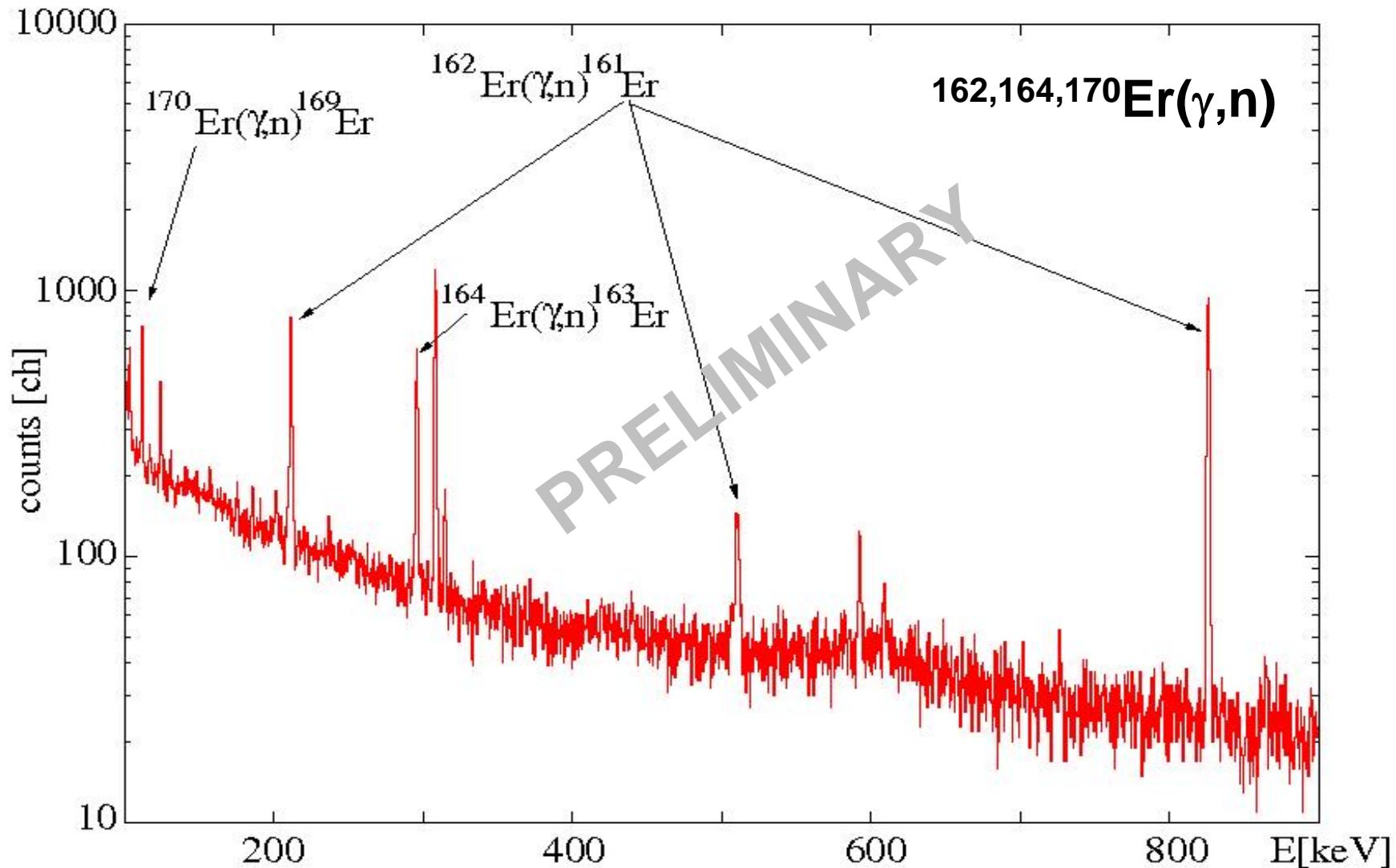
T. Rauscher and F.-K. Thielemann, ADNDT 75 (2000) 1

Groundstate reaction rates @ 2.5×10^9 K



M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1
T. Rauscher and F.-K. Thielemann, ADNDT 75 (2000) 1
A. J. Koning et al., AIP 769 (2004) 1 154

Photodissociation of Er isotopes



J. Hasper and S. Müller, priv. comm.

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

Untagged photons from bremsstrahlung
measure always INTEGRATED reaction rates:

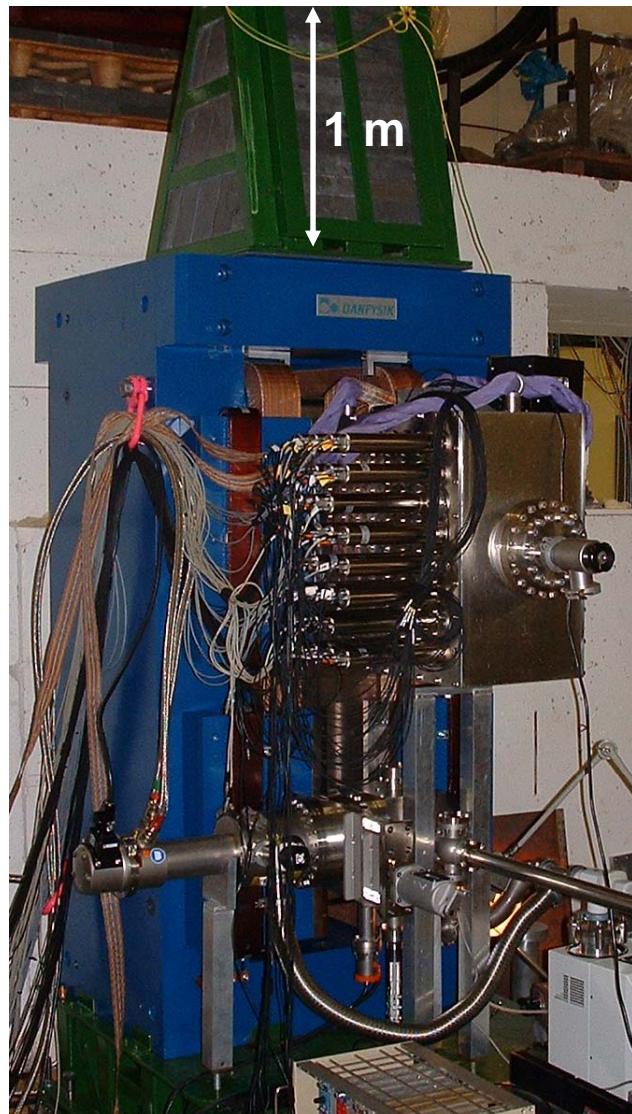
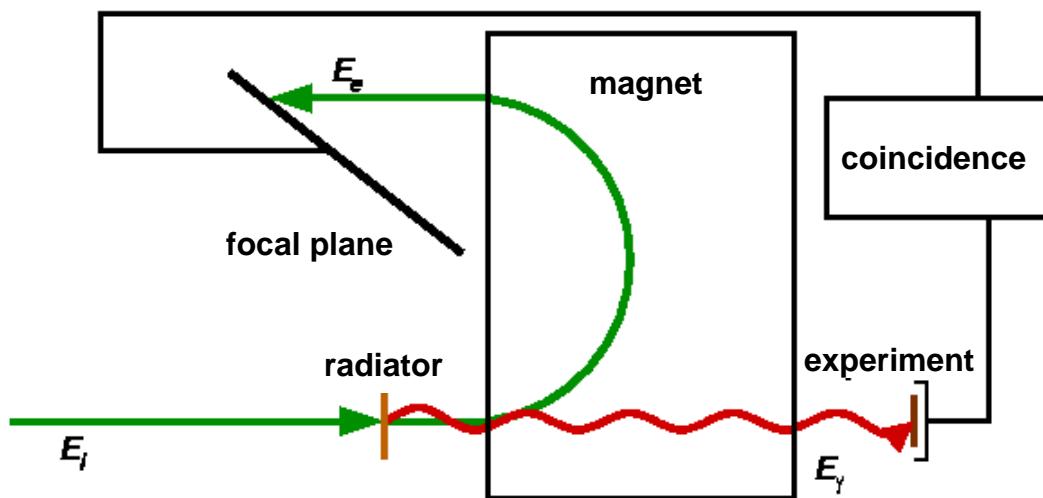
$$\lambda(T) = c \int n_\gamma(E) \sigma(E) dE$$

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

Photon tagger NEPTUN @ S-DALINAC



Energy range: $6 \text{ MeV} \leq E_\gamma \leq 20 \text{ MeV}$

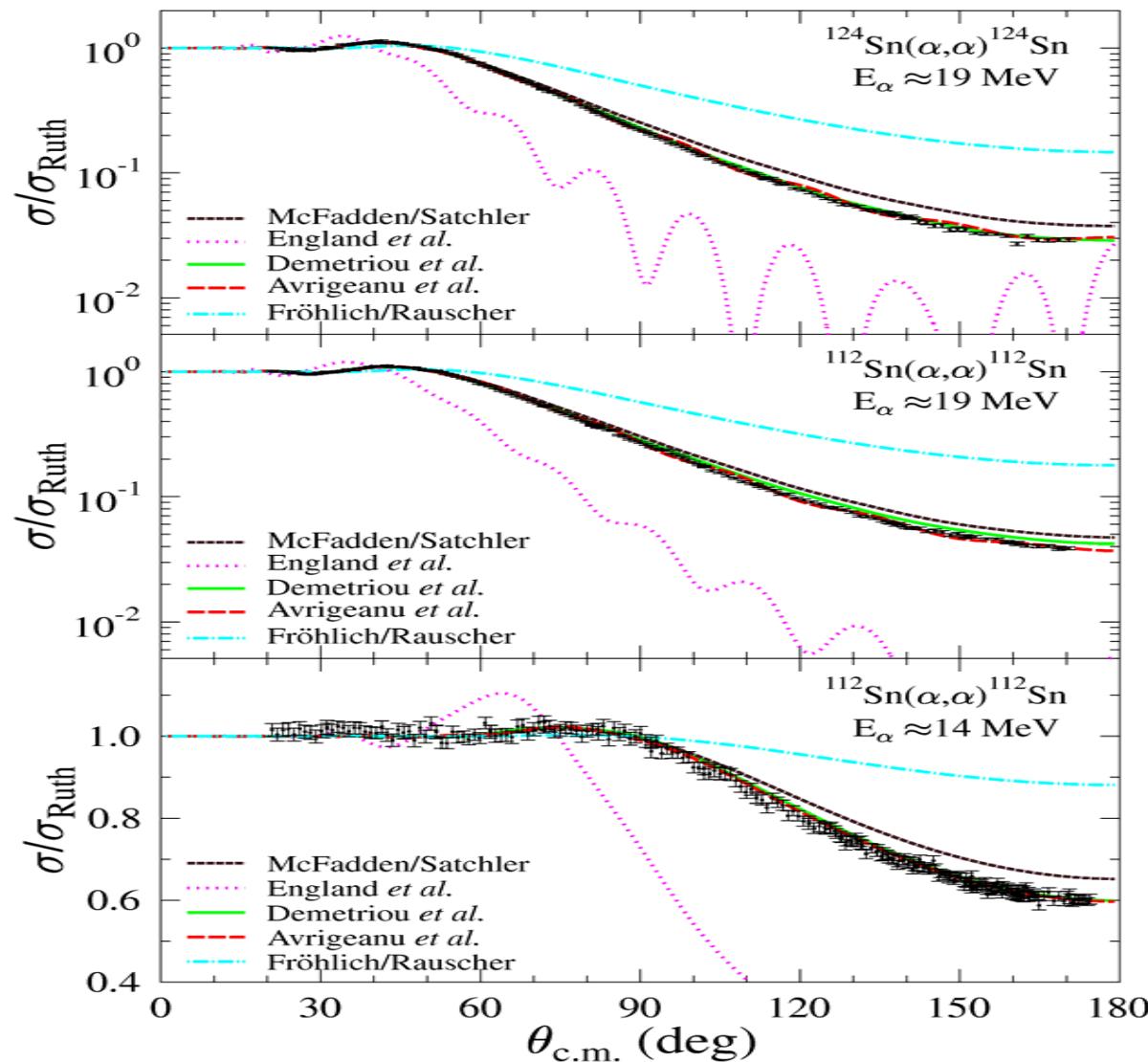
Energy resolution: $\Delta E = 25 \text{ keV} @ 10 \text{ MeV}$

Photon intensity: $\approx 10^4 \text{ keV}^{-1}\text{s}^{-1}$

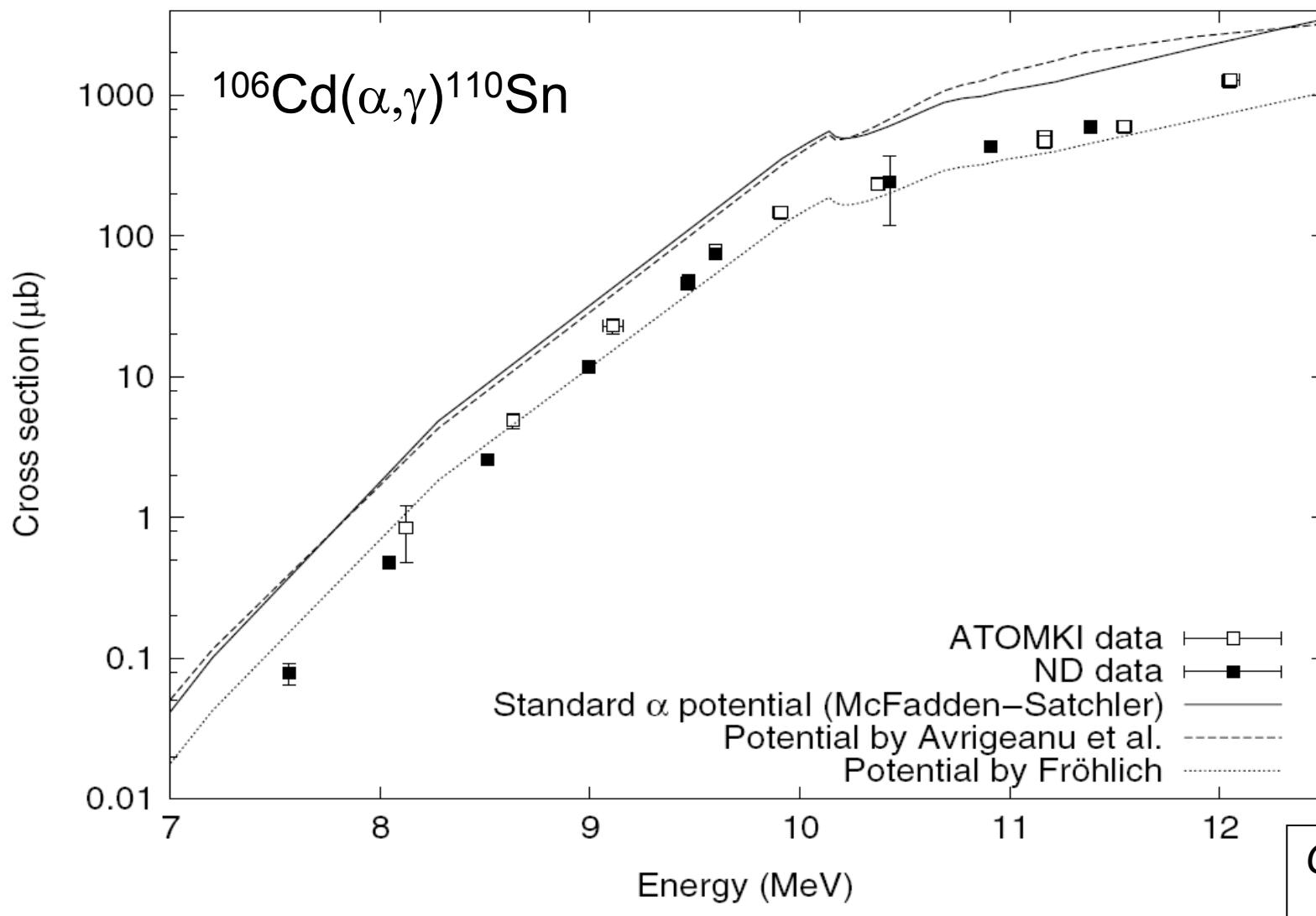
→ Measure (γ, γ') , (γ, n) , (γ, p) ,
and (γ, α) cross sections

„Indirect“ measurements: α -nucleus potentials

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



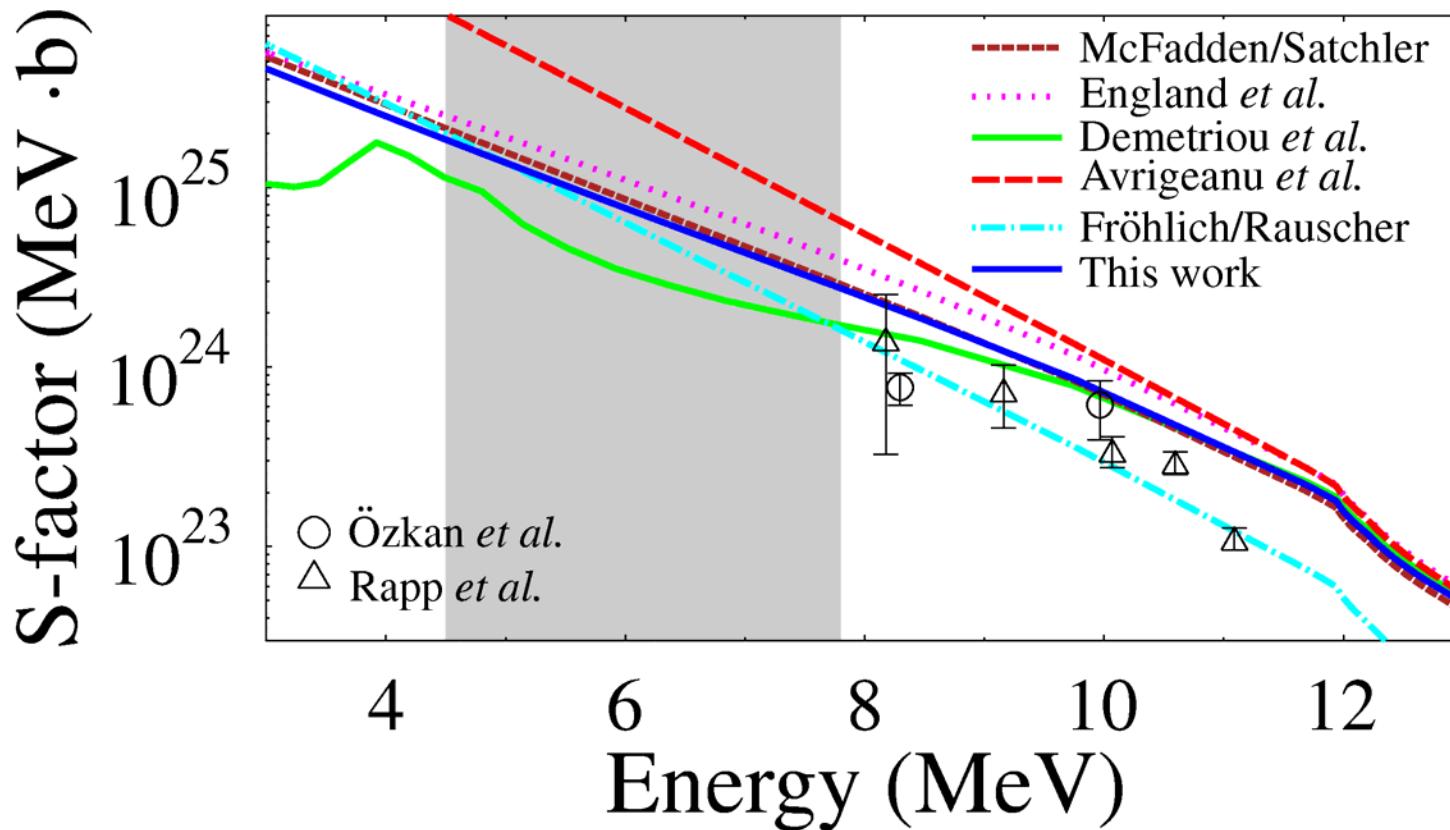
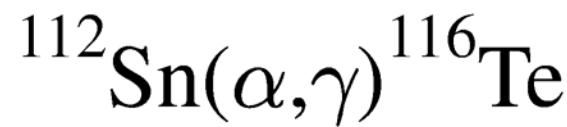
α - capture cross sections



Courtesy of
Zs. Fülöp

ATOMKI – NOTRE DAME - Collaboration

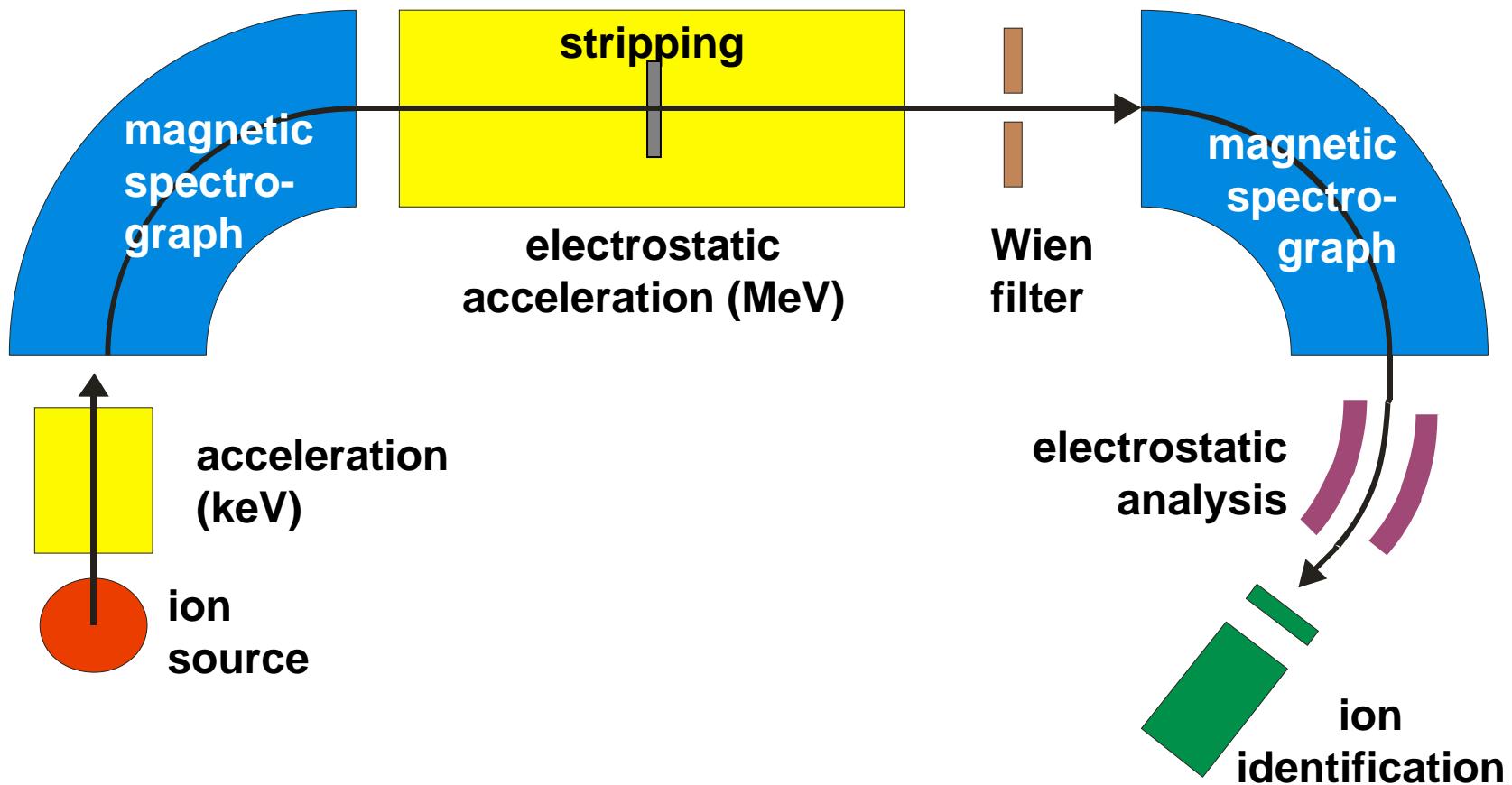
α - capture cross section



N. Özkan et al., PRC 75 (2007) 025801

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

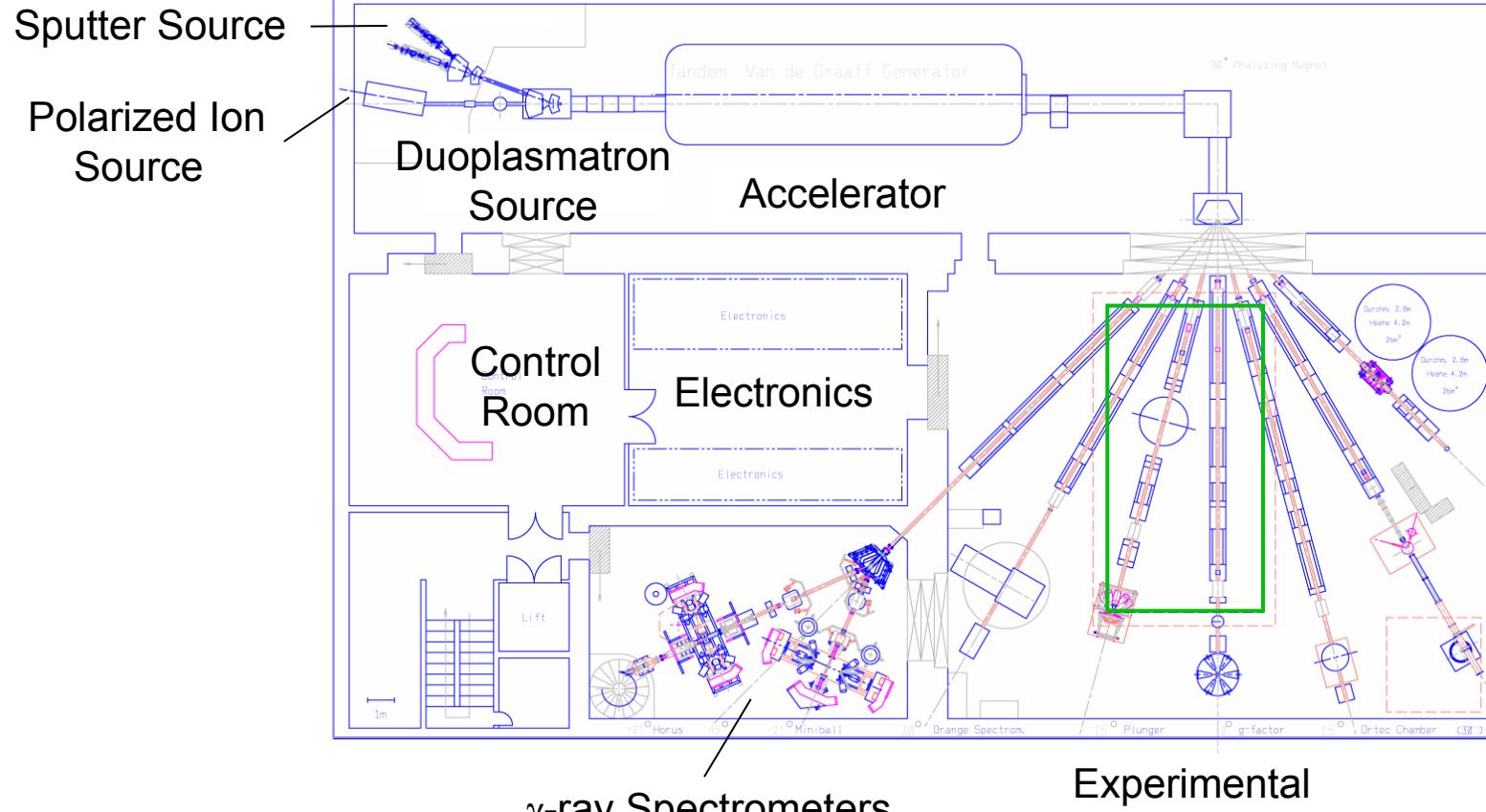
Accelerator Mass Spectrometry



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

High efficiency: amounts of 10^5 nuclei

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



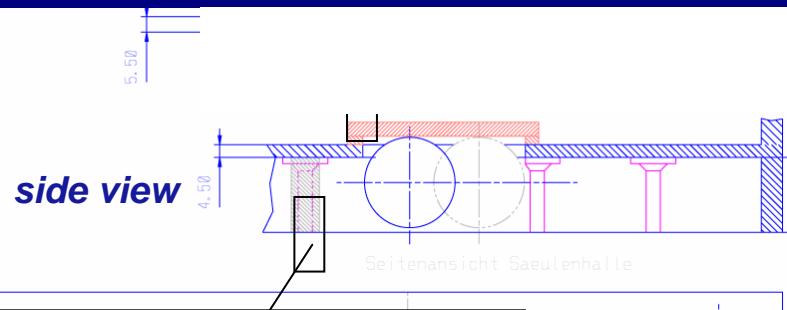
0 m 10



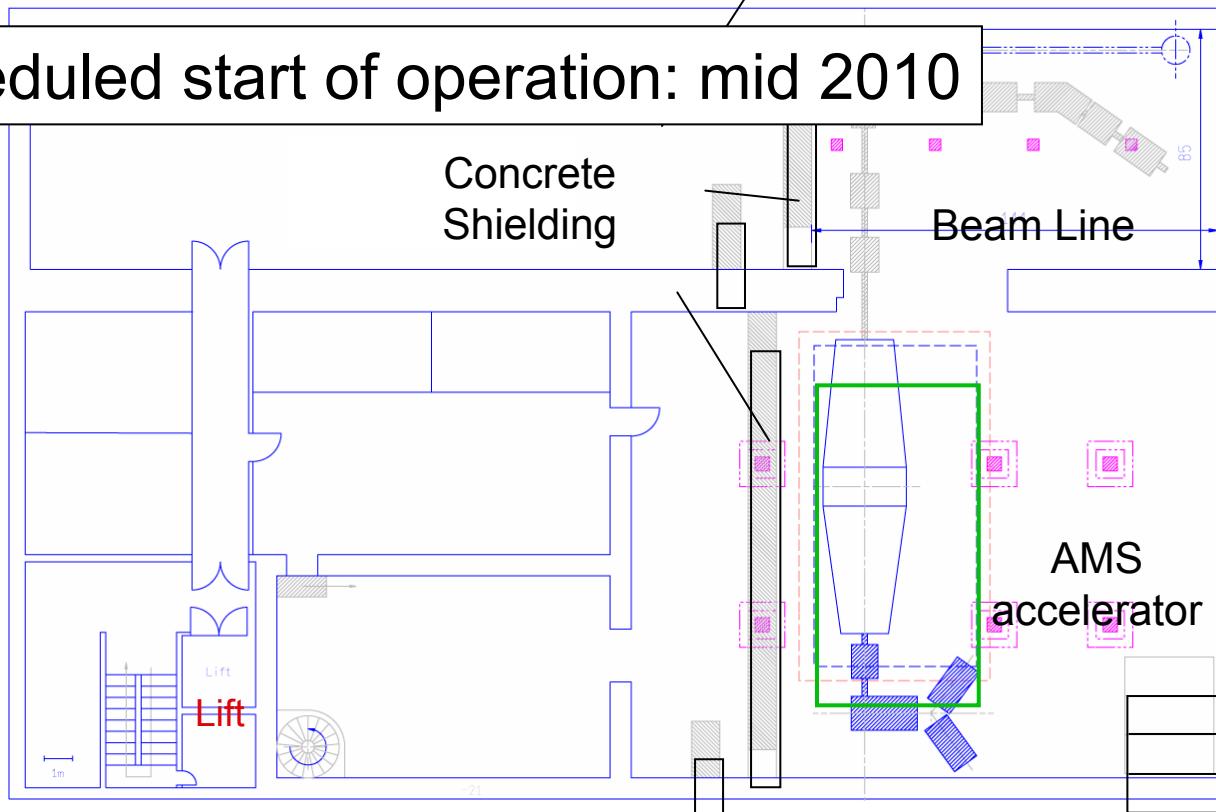
Universität
zu Köln

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

0 m 10



Scheduled start of operation: mid 2010



Funded by **DFG** and



University
of Cologne

Gamma-induced reactions in explosive nucleosynthesis

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More information and references: www.zilges.de