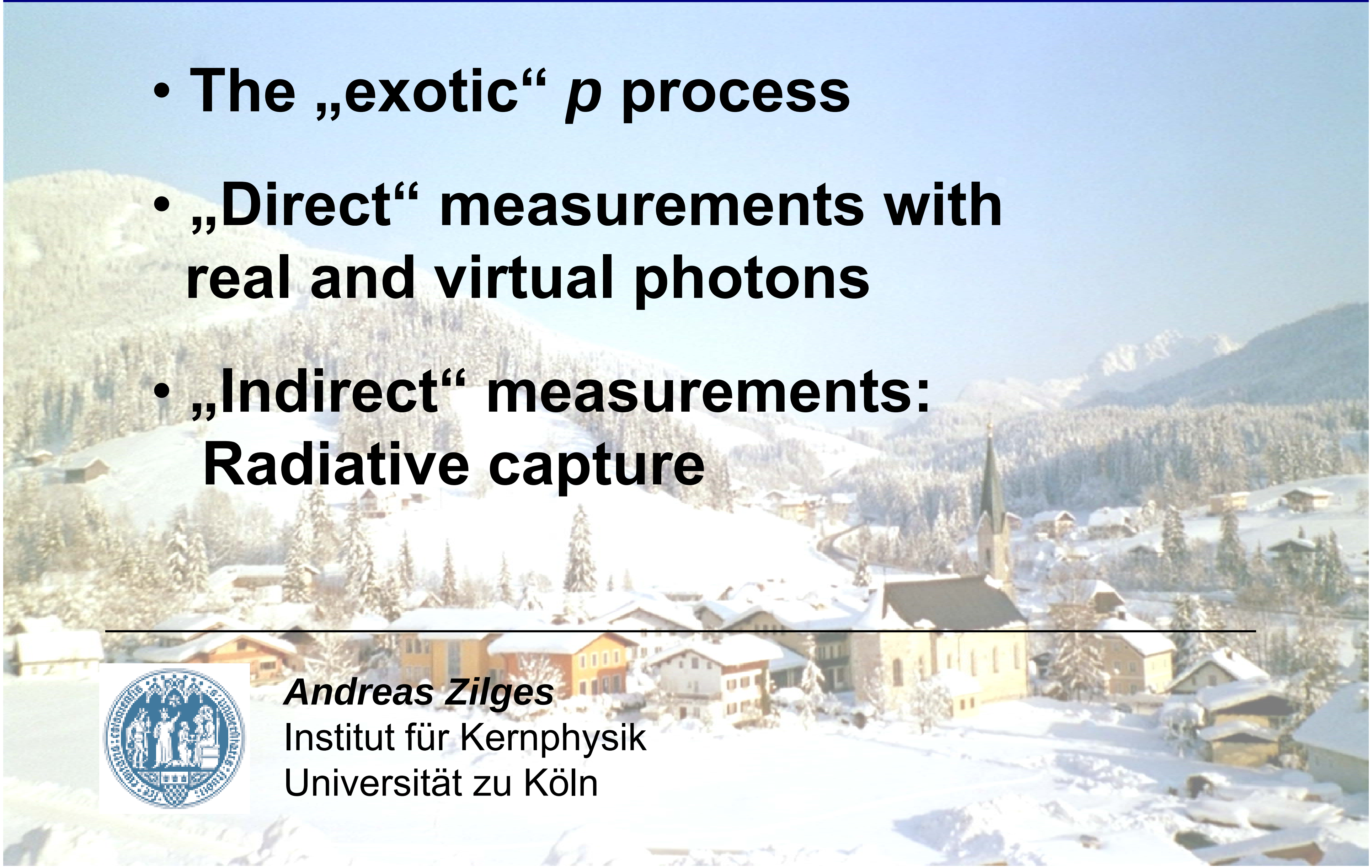
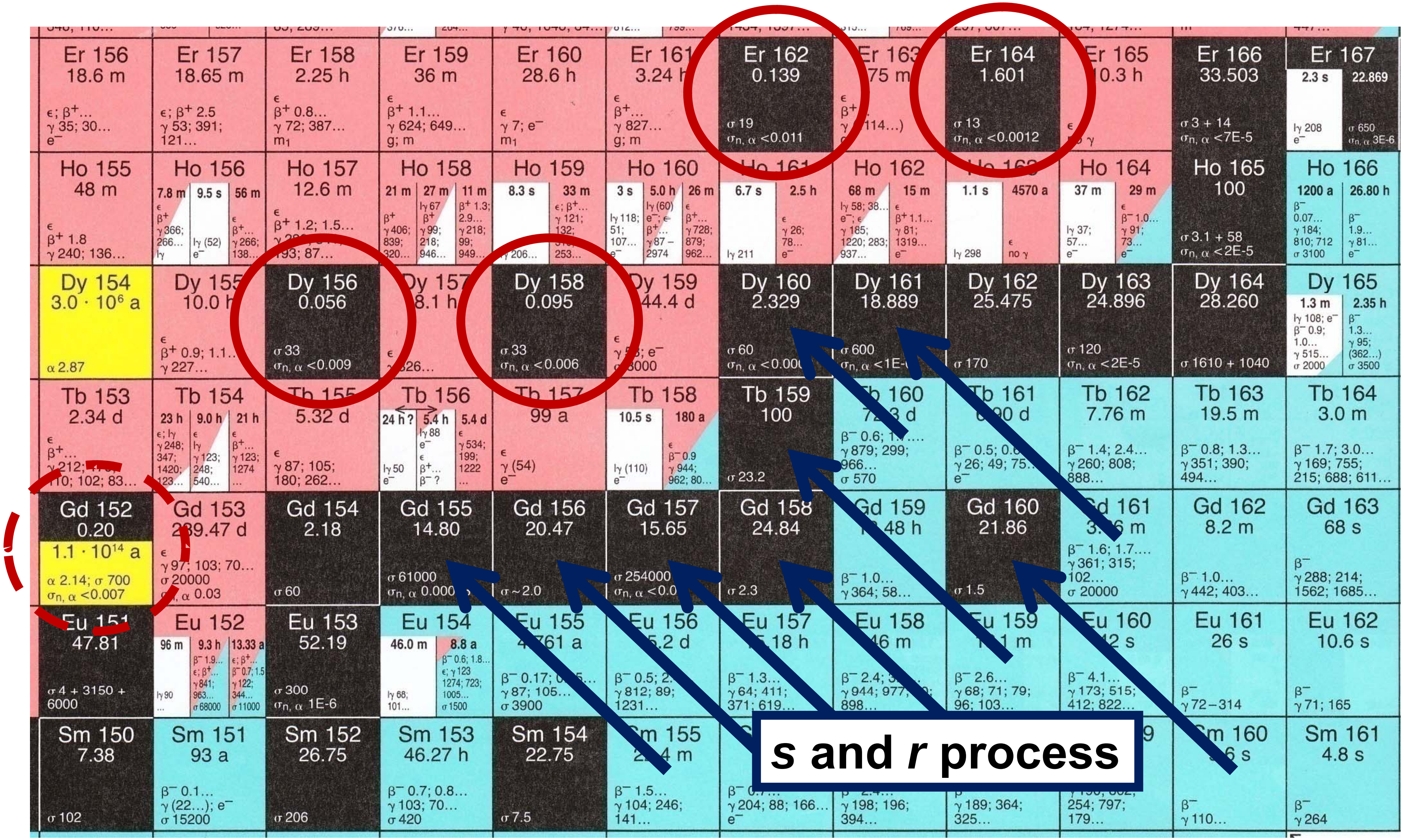
Experimental techniques to investigate the *p* process of nucleosynthesis



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

Andreas Zilges
Institut für Kernphysik
Universität zu Köln

p nuclei

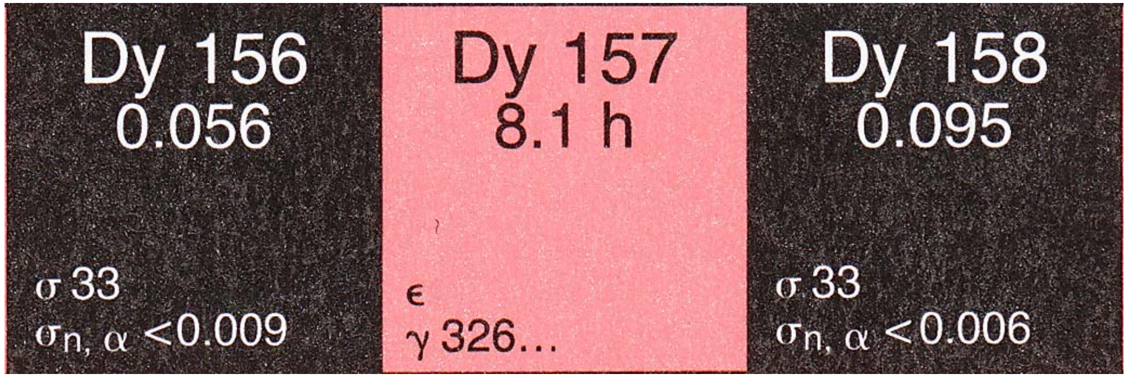


s and *r* process

p nuclei

- 35 proton rich stable nuclei with A > 70
- typical isotopic abundance < 1%
- typical abundance $5x10^{-4}$ ($Si=10^6$)

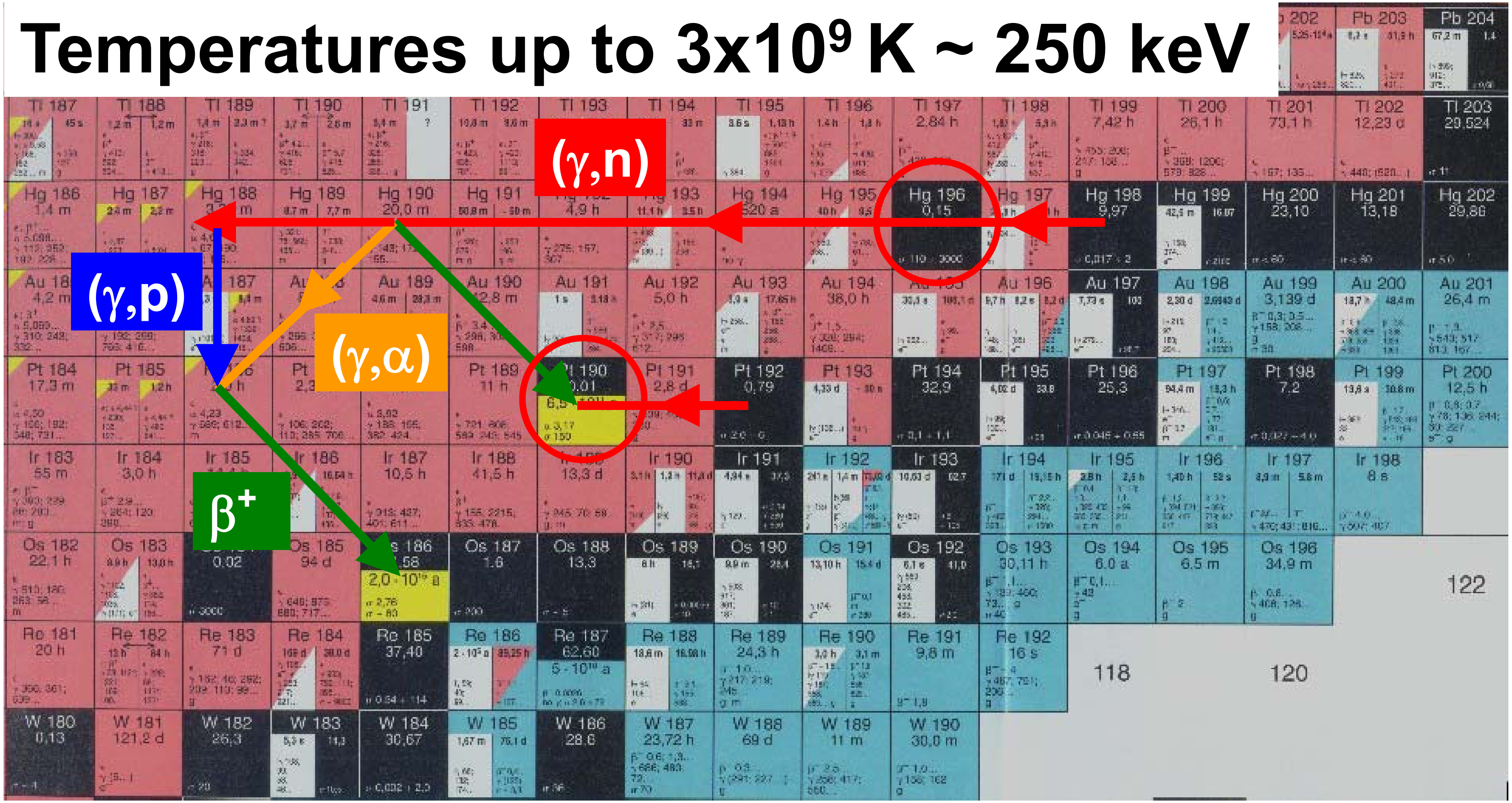
Ru 96
5.54
σ 0.23



Dy 156	Dy 157	Dy 158
0.056	8.1 h	0.095
σ 33 $\sigma_{n,\alpha}$ <0.009	ε γ 326…	σ 33 $\sigma_{n,\alpha}$ <0.006

The *p* process: Nuclear reaction network

Temperatures up to 3×10^9 K ~ 250 keV



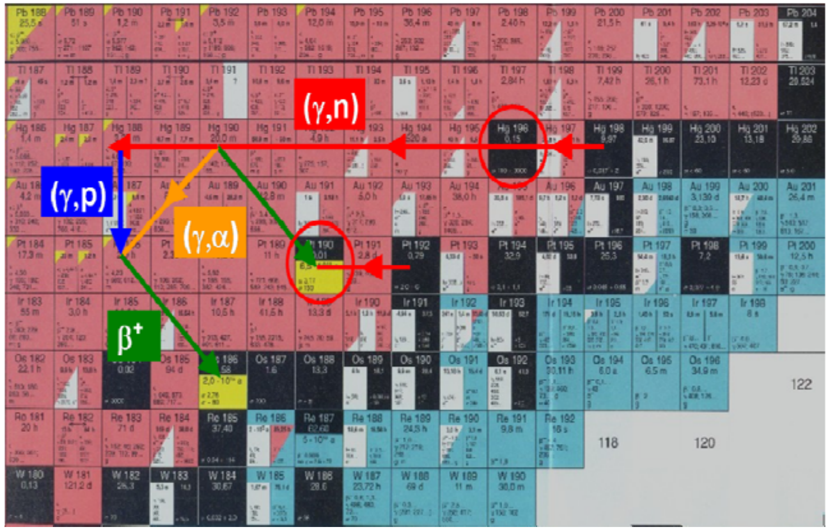
For lighter nuclei there may be competing reactions: (n,γ), (p,γ), (α,γ), νp-process

The *p* process: Nuclear reaction network

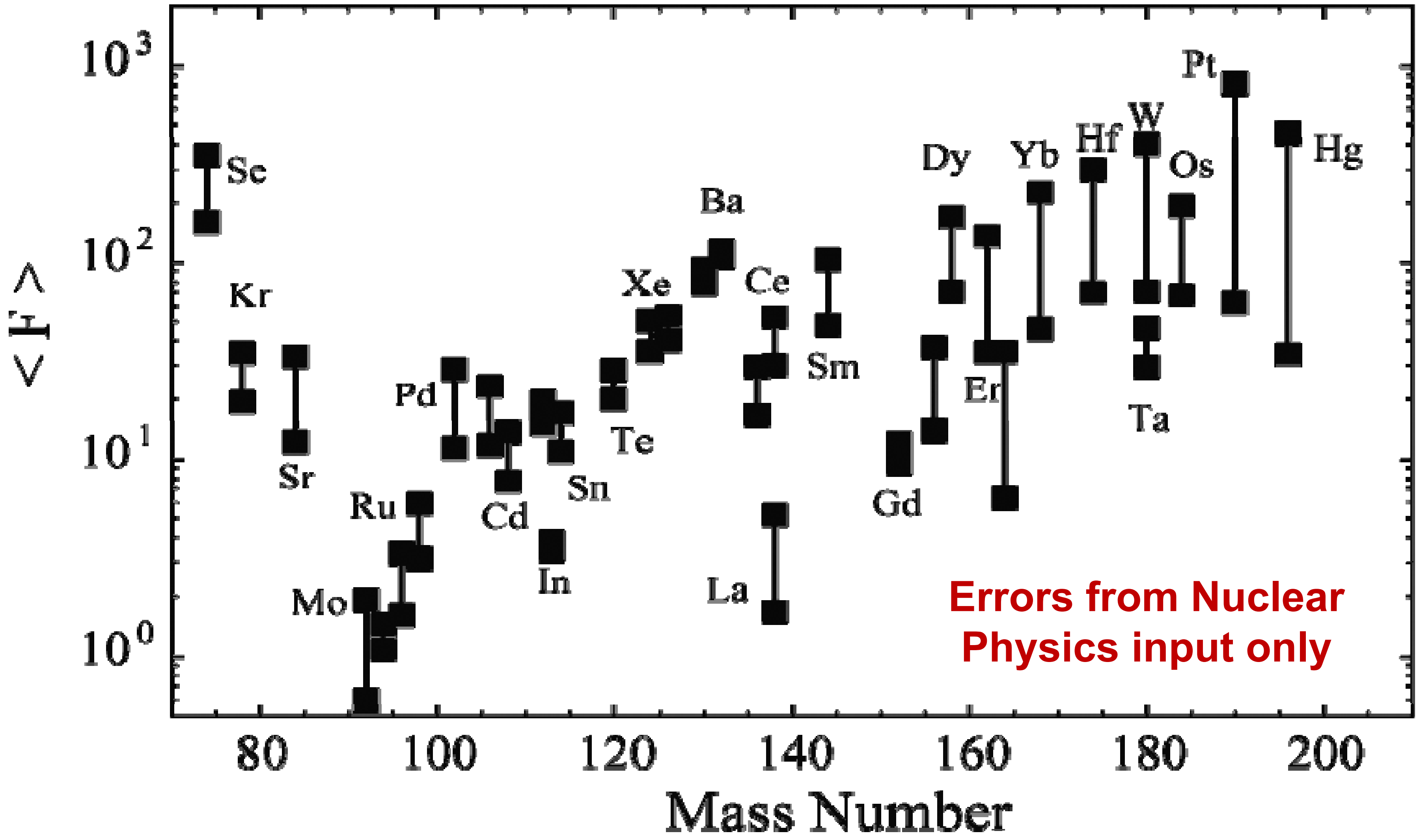
This network involves about 20.000 reaction rates

Statistical model calculations

Experiments are necessary to check and to constrain the model assumptions



Abundance of *p* nuclei: Prediction vs. observation



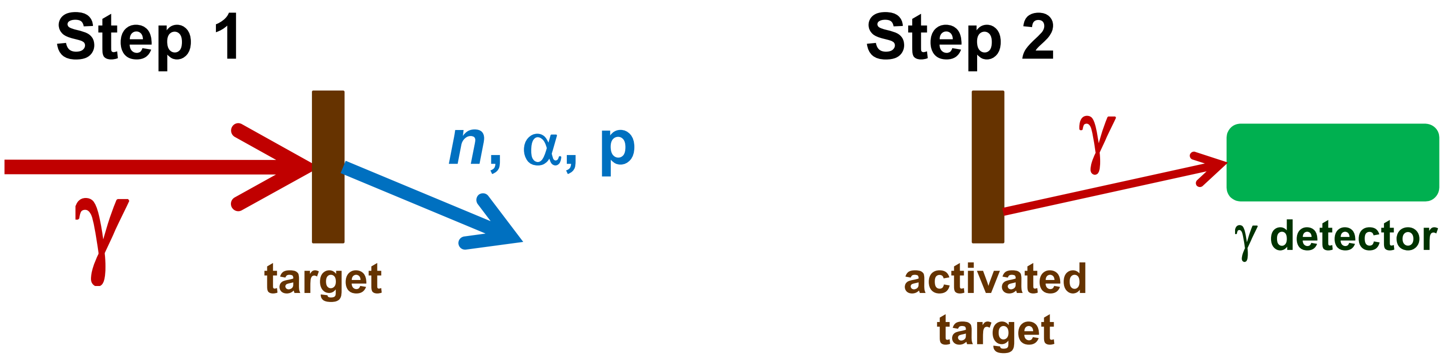
Errors from Nuclear Physics input only

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

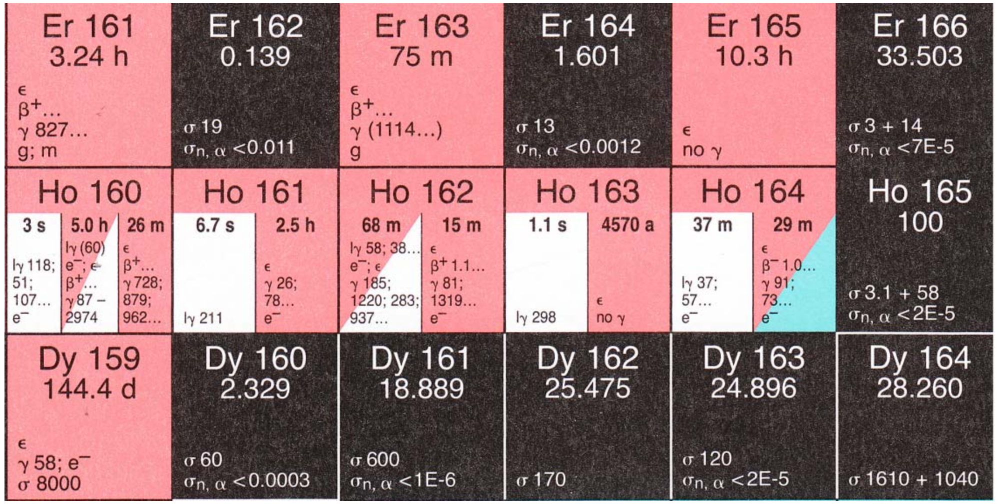
Nuclear Physics input for the *p* process

- 🟢 **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

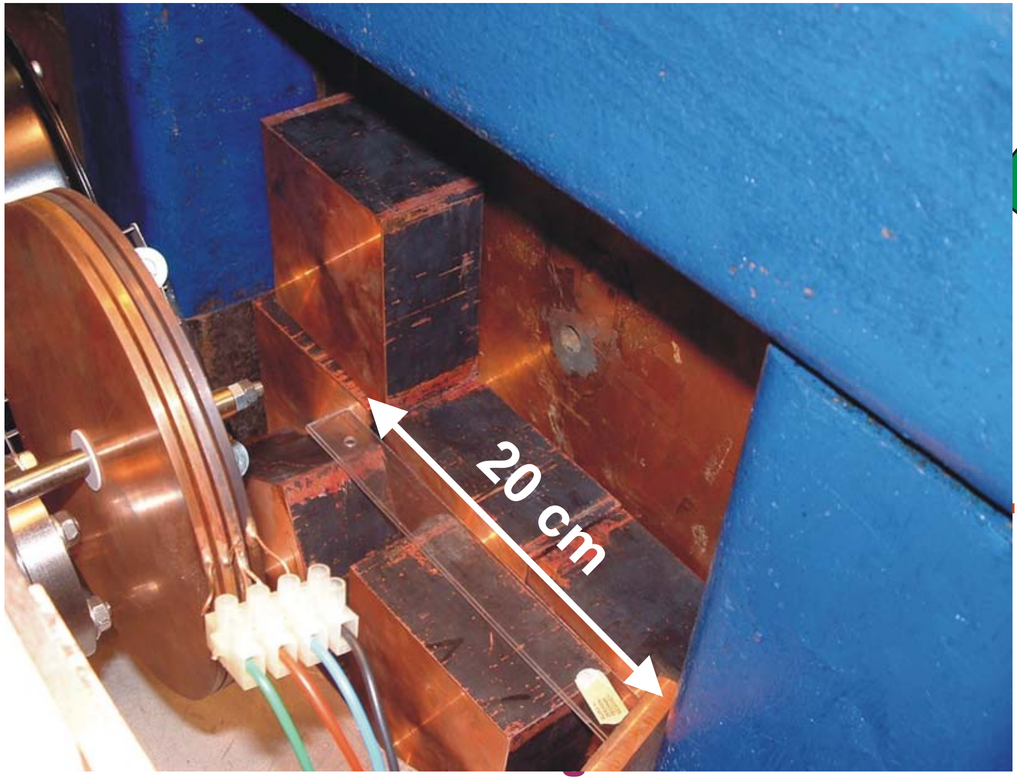


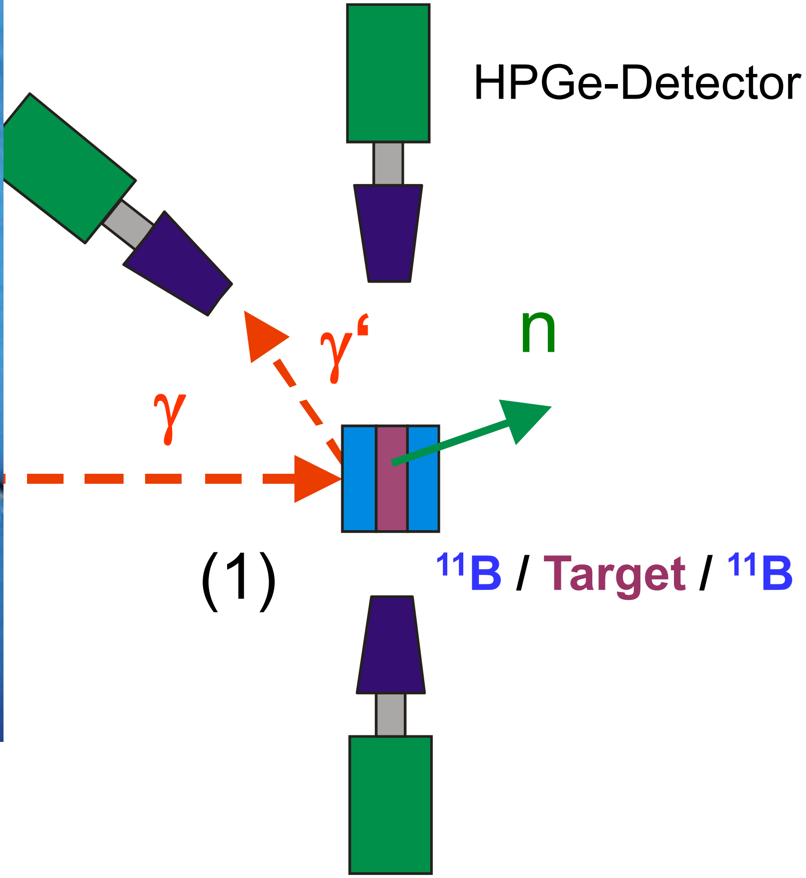
Induce (γ,*n*), (γ,α), and (γ,*p*) reactions with real photons + measure activation



Er 161 3.24 h ϵ β^+… γ 827… g; m	Er 162 0.139 σ 19 $\sigma_{n,\alpha}$ <0.011	Er 163 75 m ϵ β^+… γ (1114…) g	Er 164 1.601 σ 13 $\sigma_{n,\alpha}$ <0.0012	Er 165 10.3 h ϵ no γ	Er 166 33.503 σ 3 + 14 $\sigma_{n,\alpha}$ <7E-5
Ho 160 3 s: Iγ 118; 51; 107… e^- 5.0 h: Iγ (60) e^-; ϵ β^+… γ 87 – 2974 26 m: ϵ β^+… γ 728; 879; 962…	Ho 161 6.7 s: Iγ 211 2.5 h: ϵ γ 26; 78… e^-	Ho 162 68 m: Iγ 58; 38… e^-; ϵ γ 185; 1220; 283; 937… 15 m: ϵ β^+ 1.1… γ 81; 1319… e^-	Ho 163 1.1 s: Iγ 298 4570 a: ϵ no γ	Ho 164 37 m: Iγ 37; 57… e^- 29 m: ϵ β^- 1.0… γ 91; 73… e^-	Ho 165 100 σ 3.1 + 58 $\sigma_{n,\alpha}$ <2E-5
Dy 159 144.4 d ϵ γ 58; e^- σ 8000	Dy 160 2.329 σ 60 $\sigma_{n,\alpha}$ <0.0003	Dy 161 18.889 σ 600 $\sigma_{n,\alpha}$ <1E-6	Dy 162 25.475 σ 170	Dy 163 24.896 σ 120 $\sigma_{n,\alpha}$ <2E-5	Dy 164 28.260 σ 1610 + 1040

Photoactivation with bremsstrahlung



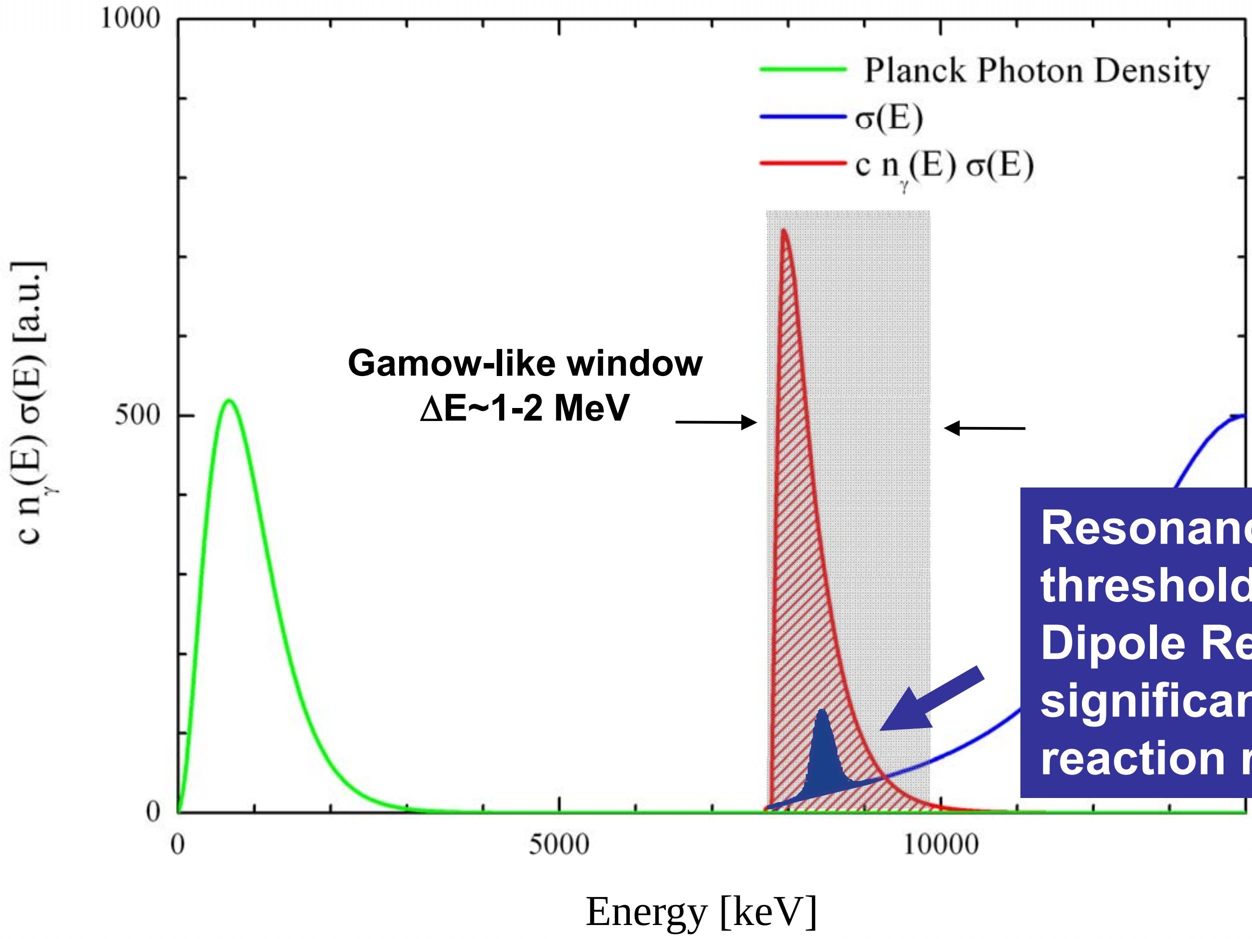


(1) Photon flux ~ 10^5 γ / (keV s cm^2)
Calibration of the photon flux via **^{11}B(γ,γ‘)**

(2) Photon flux ~ 10^7 γ / (keV s cm^2)
Calibration of the photon flux via **^{197}Au(γ,n)** and **^{187}Re(γ,n)**

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

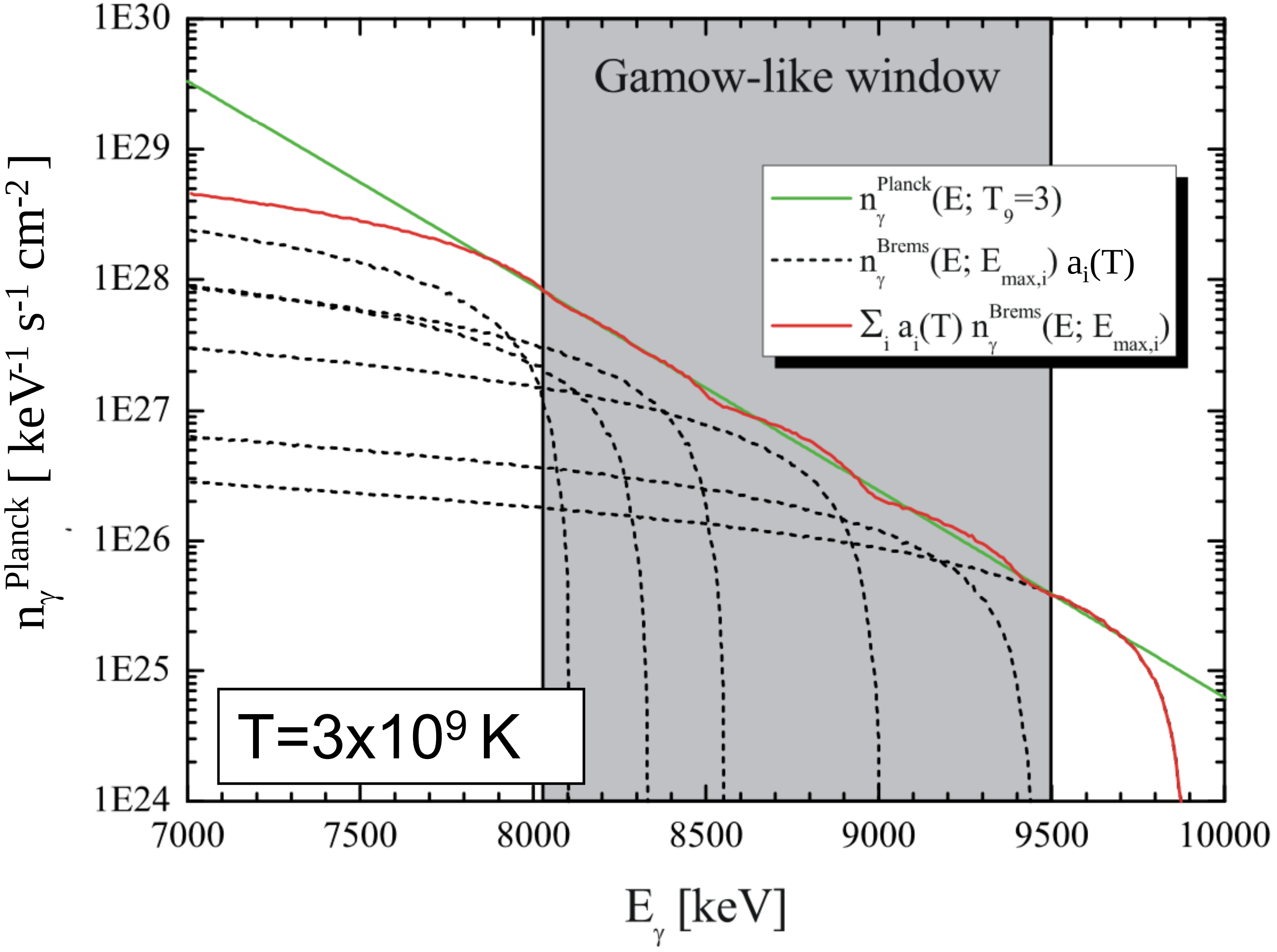
Reaction rate: $\lambda(T) = c \int n_\gamma(E)\,\sigma(E)\,dE$



Gamow-like window
ΔE~1-2 MeV

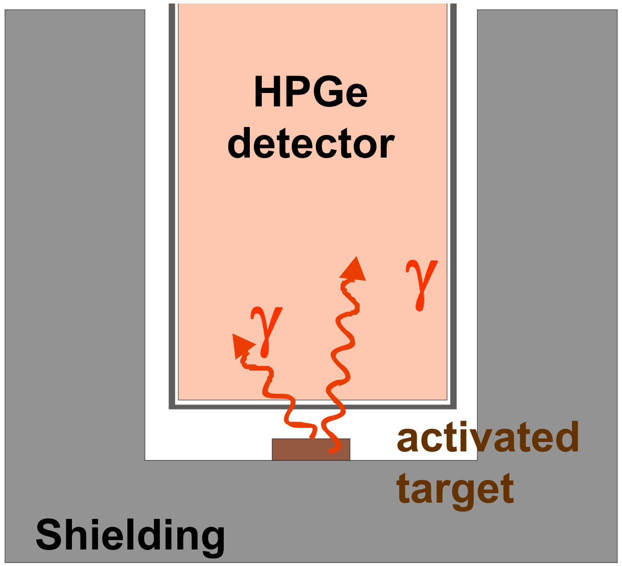
Resonance close to neutron threshold (e.g. Pygmy Dipole Resonance) would significantly increase reaction rate

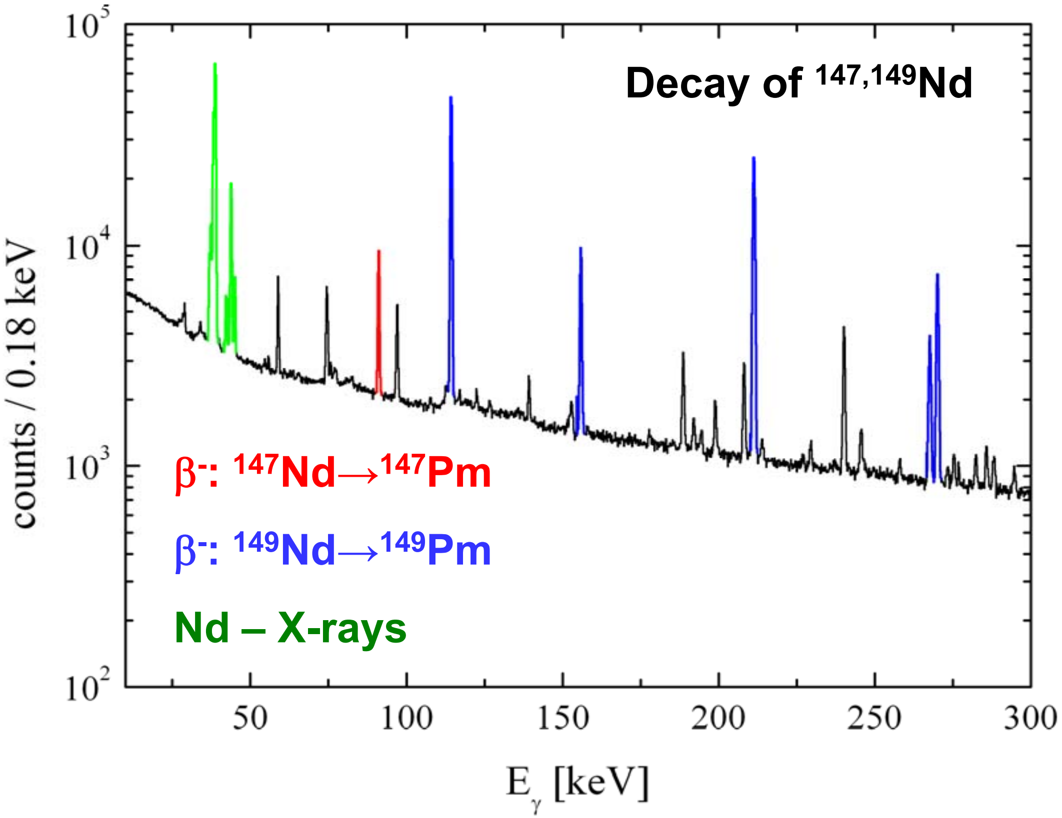
Production of a quasi-thermal spectrum



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

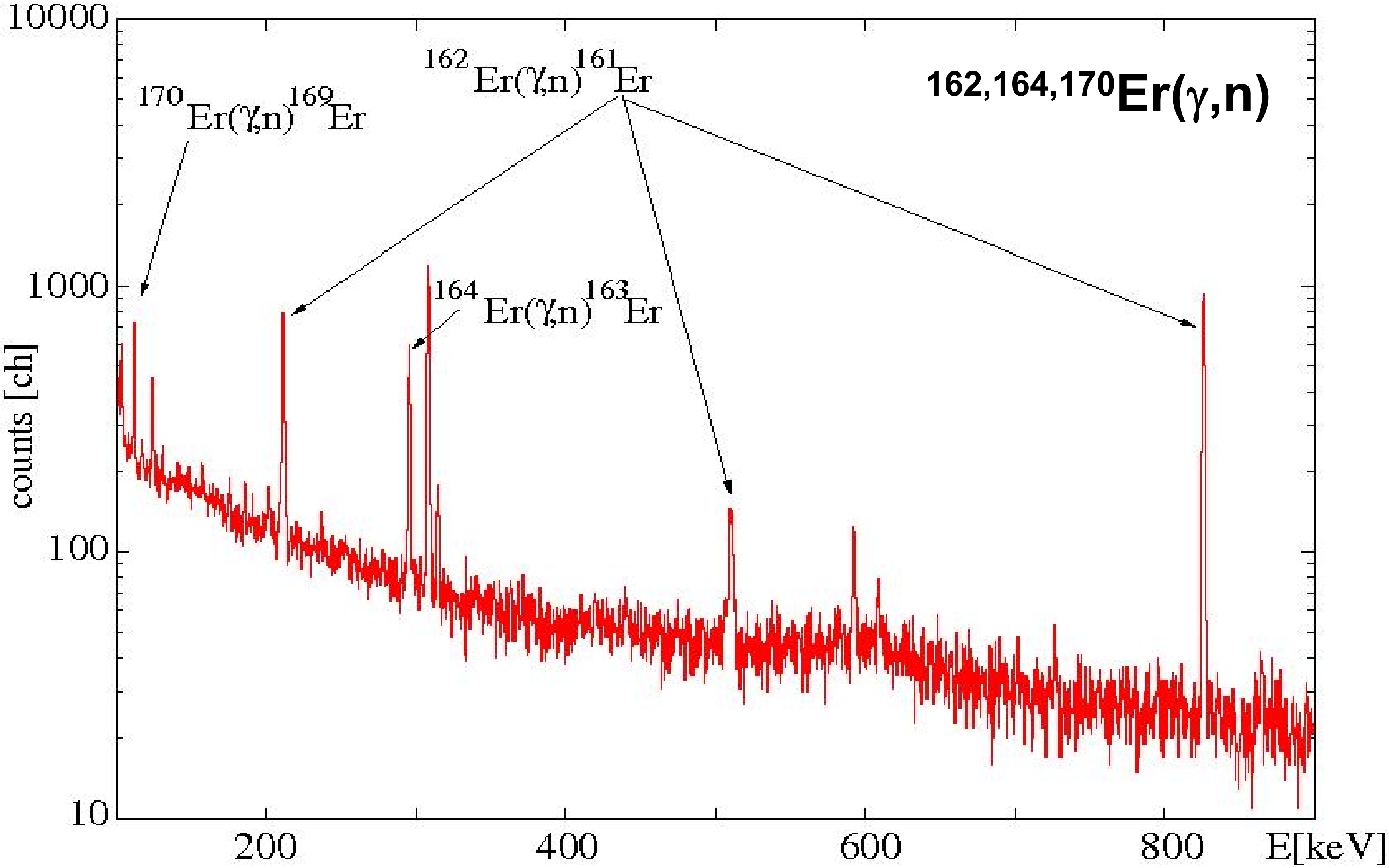
Activation measurement





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 @ 2.5x10⁹ K

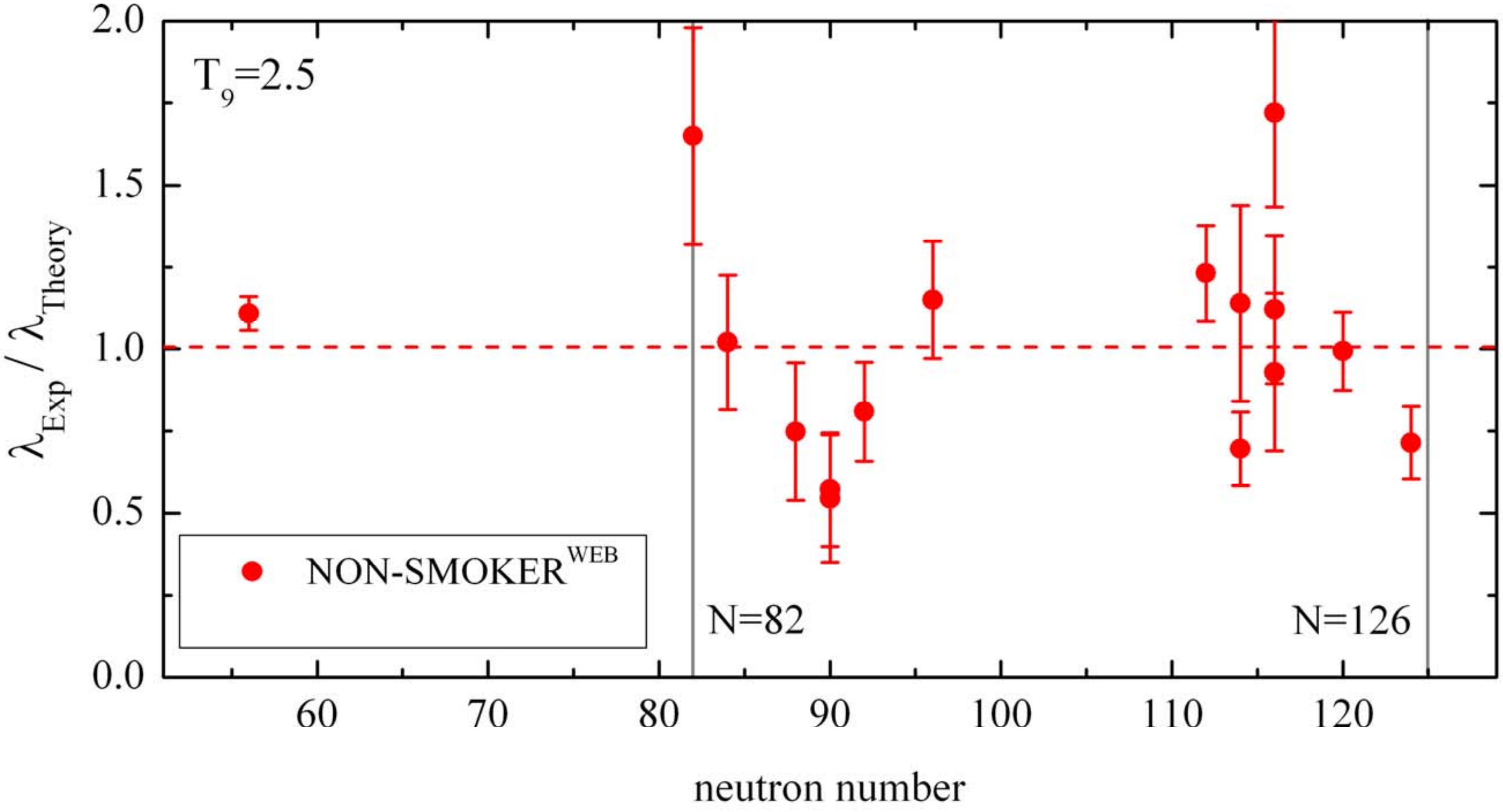
Isotope	$\lambda_{exp,gs}$	Reference	$\lambda_{NONS,gs}$	$\lambda_{TALYS,gs}$
^{148}Nd	65(18)	J. Hasper et al., PRC 77 (2008) 015803	86	82
^{150}Nd	41(12)		72	77
^{154}Sm	7.5(1.4)		9.2	11
^{187}Re	91(11)	S. Müller et al., PRC 73 (2006) 025804	74	99
^{190}Pt	0.6(2)	K. Vogt et al., PRC 63 (2001) 055802	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 @ 2.5x10^{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 σ(E)

Untagged photons from bremsstrahlung measure always INTEGRATED reaction rates:

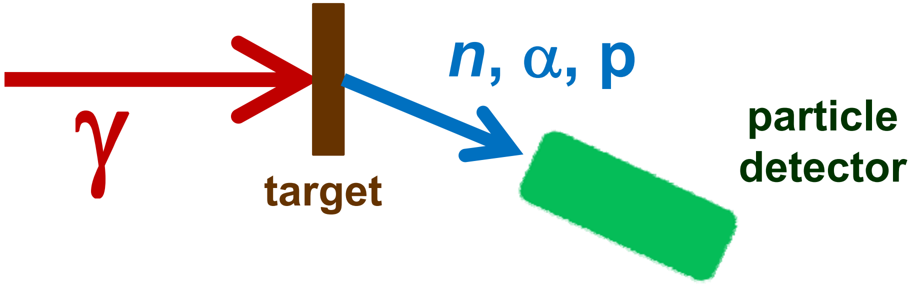
$$\lambda(T) = c \int n_\gamma(E)\,\boxed{\sigma(E)}\,dE$$

Additional information can be deduced from the shape of the cross section σ(Eγ)

→ **use photons with „known“ energy**

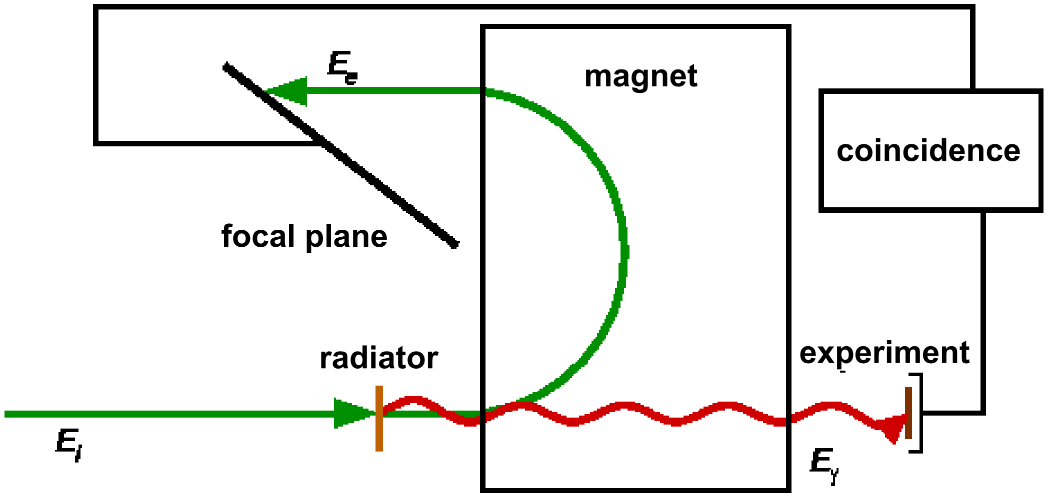
- **Tagged bremsstrahlung photons**
- **Laser Compton Backscattering**

„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*

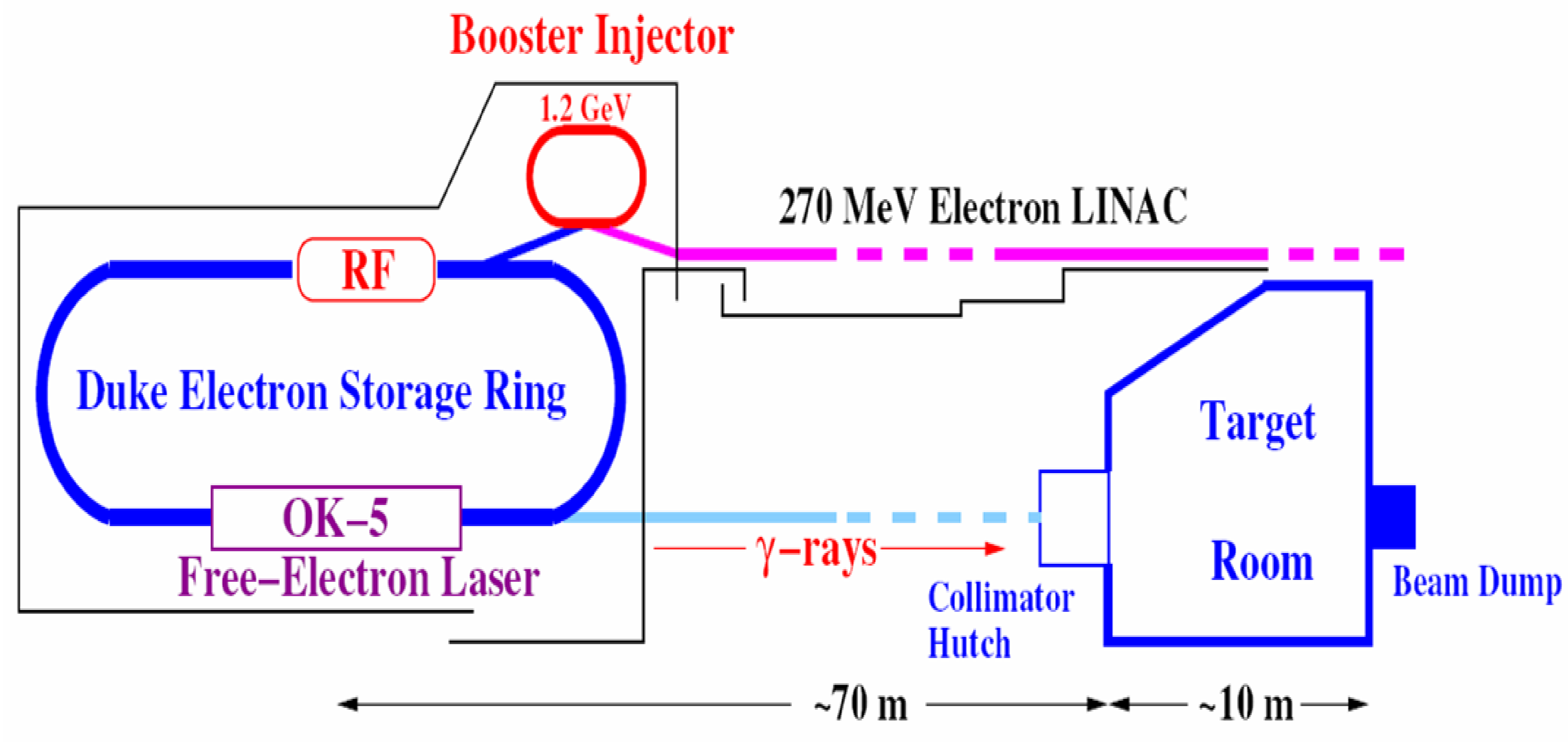
Photon tagger NEPTUN @ S-DALINAC



- 6 MeV ≤ E_γ ≤ 20 MeV
- ΔE = 25 keV @ 10 MeV
- Photon intensity: ≈ 10^4 $\text{keV}^{-1}\text{s}^{-1}$

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

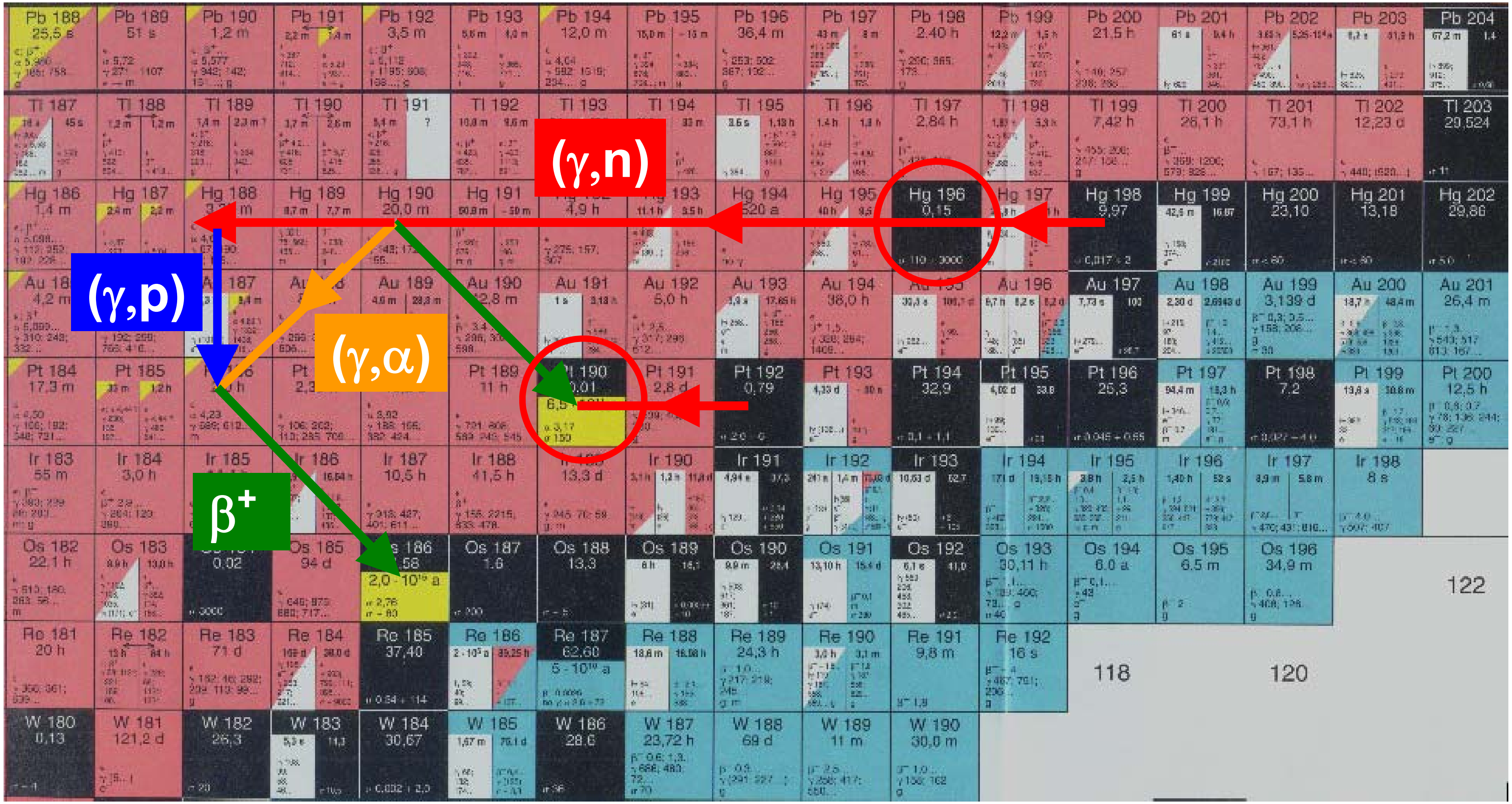
Laser Compton Backscattering at HIγS (Duke)



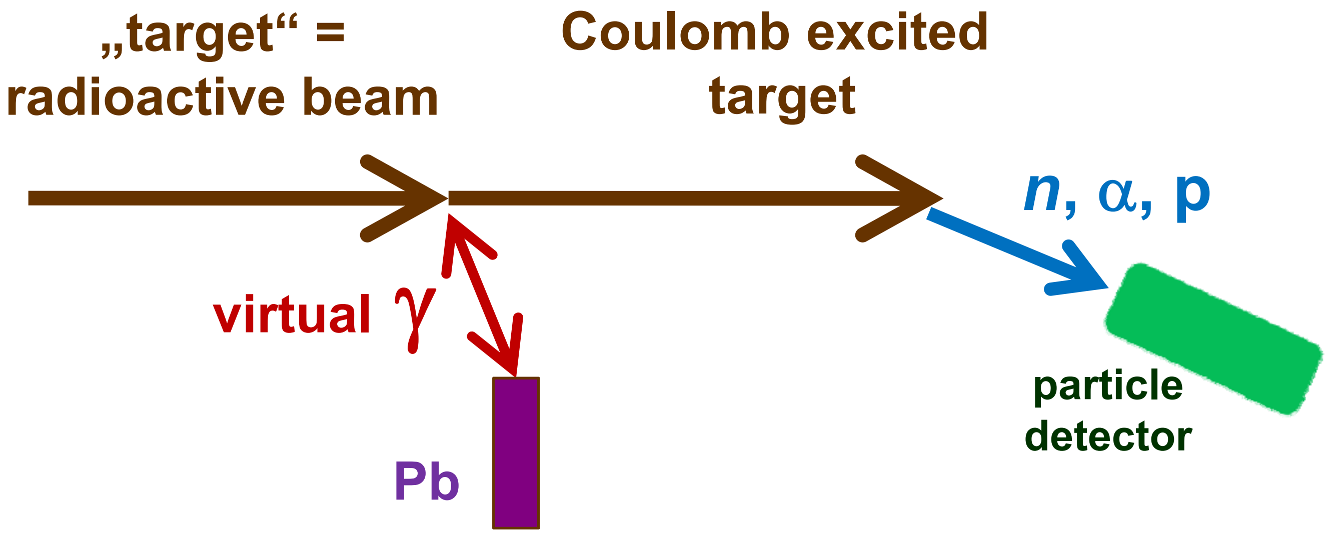
→ **see next talk by Anne Sauerwein**

The limitations of real photon experiments

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

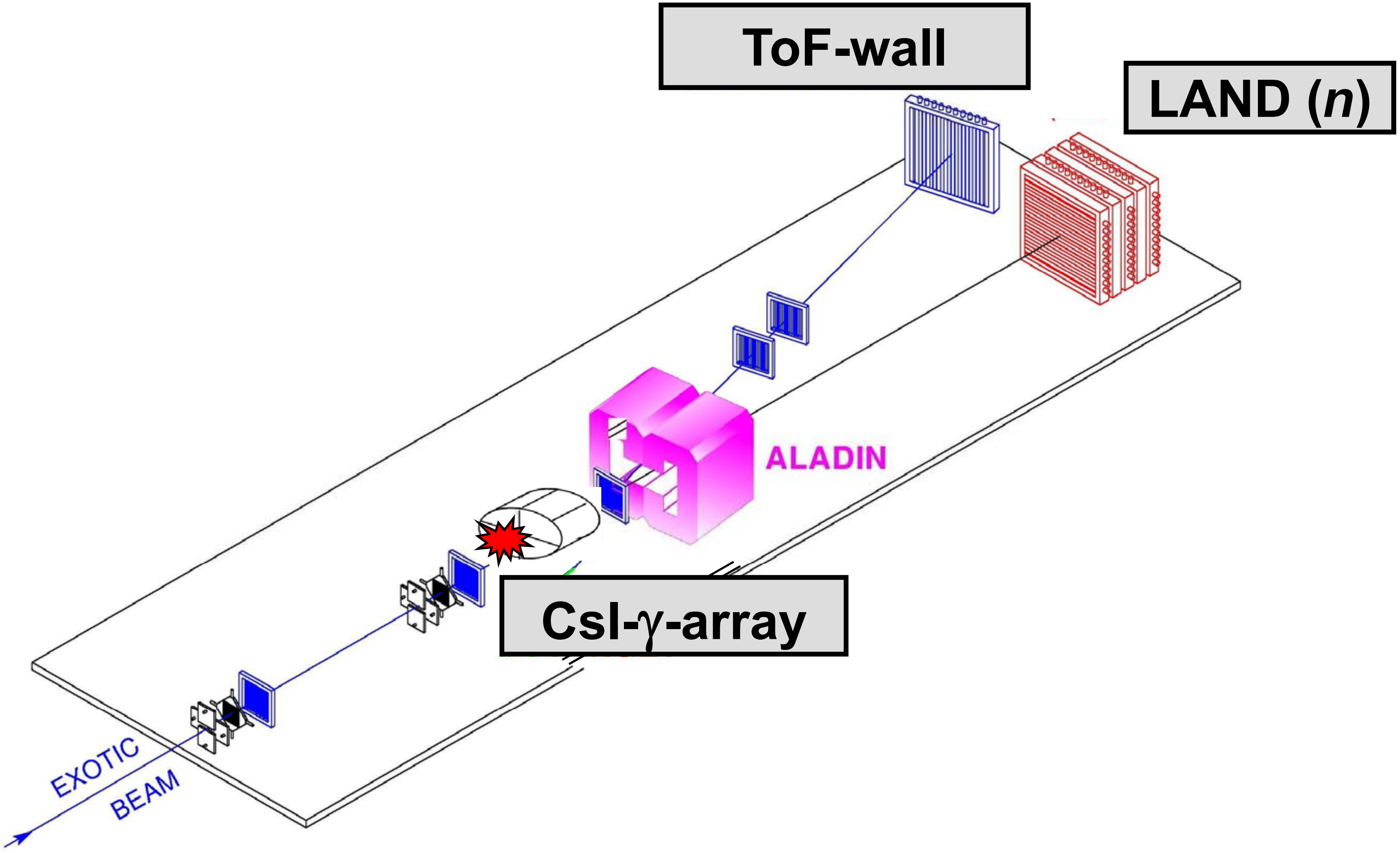


„Direct“ experimental techniques III: Coulomb dissociation



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

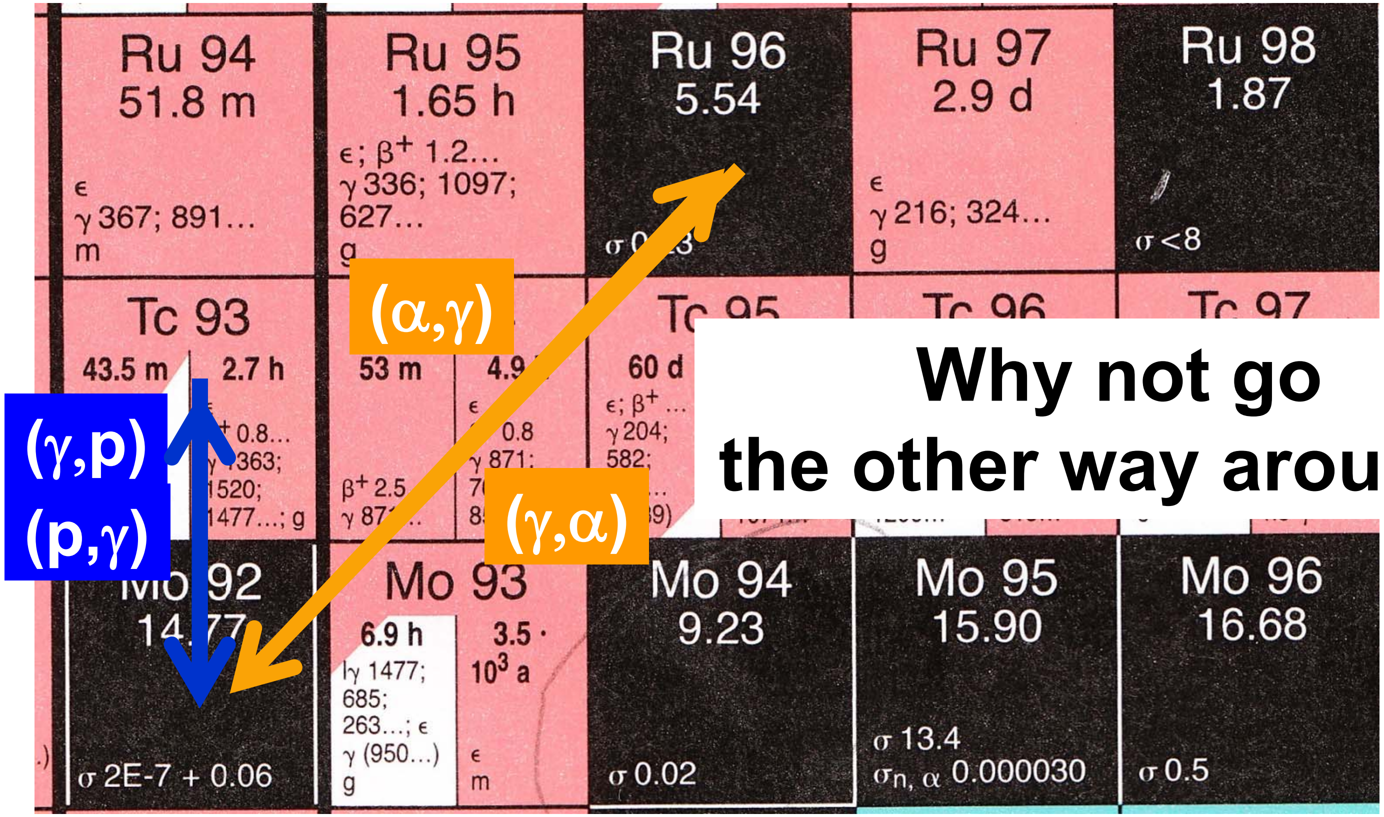
Experiments with monoenergetic photons (Tagger or laser Compton backscattering)

- 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

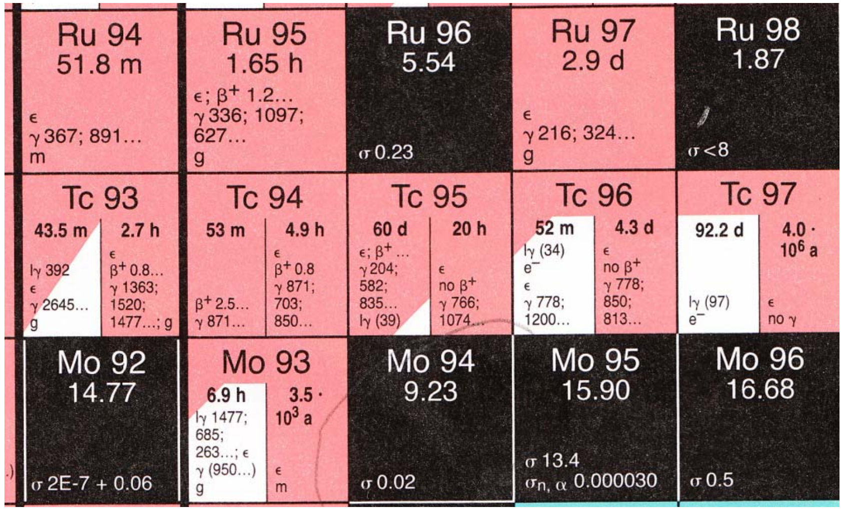


Why not go
the other way around ?

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**

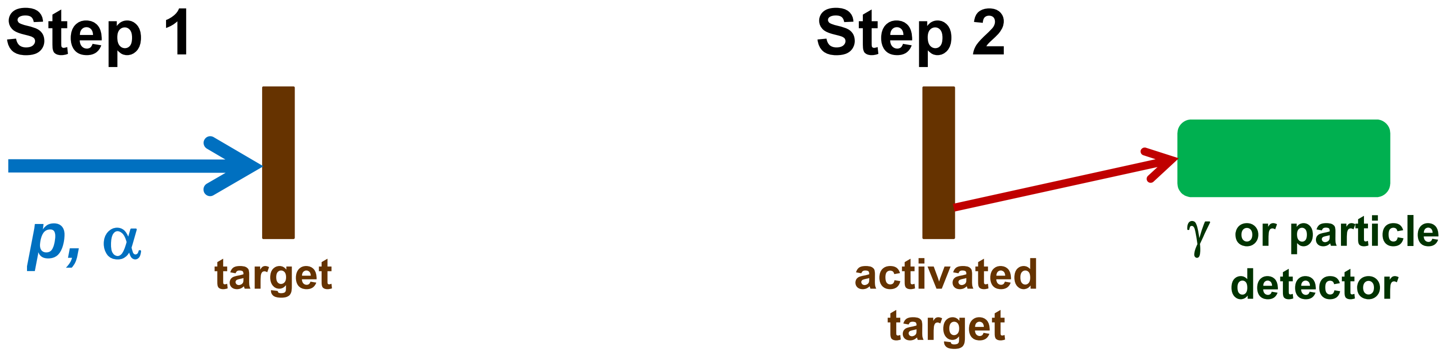


Ru 94 51.8 m ϵ γ 367; 891… m	Ru 95 1.65 h ϵ; β^+ 1.2… γ 336; 1097; 627… g	Ru 96 5.54 σ 0.23	Ru 97 2.9 d ϵ γ 216; 324… g	Ru 98 1.87 σ <8
Tc 93 43.5 m Iγ 392 ϵ γ 2645… g 2.7 h ϵ β^+ 0.8… γ 1363; 1520; 1477…; g	Tc 94 53 m β^+ 2.5… γ 871… 4.9 h ϵ β^+ 0.8 γ 871; 703; 850…	Tc 95 60 d ϵ; β^+… γ 204; 582; 835… Iγ (39) 20 h ϵ no β^+ γ 766; 1074…	Tc 96 52 m Iγ (34) e^- ϵ γ 778; 1200… 4.3 d ϵ no β^+ γ 778; 850; 813…	Tc 97 92.2 d Iγ (97) e^- $4.0 \cdot 10^6$ a ϵ no γ
Mo 92 14.77 σ 2E-7 + 0.06	Mo 93 6.9 h Iγ 1477; 685; 263…; ϵ γ (950…) g $3.5 \cdot 10^3$ a ϵ m	Mo 94 9.23 σ 0.02	Mo 95 15.90 σ 13.4 $\sigma_{n,\alpha}$ 0.000030	Mo 96 16.68 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*)

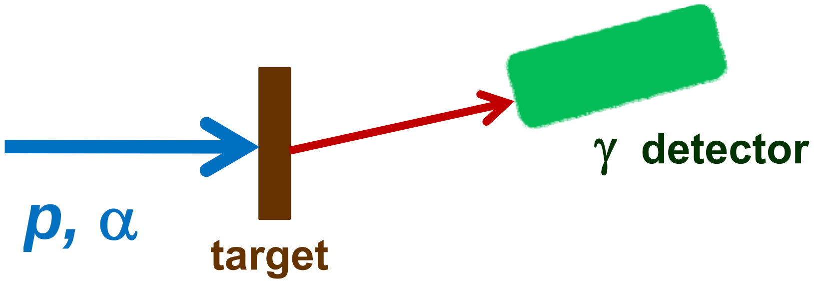


Very sensitive but not always possible.

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

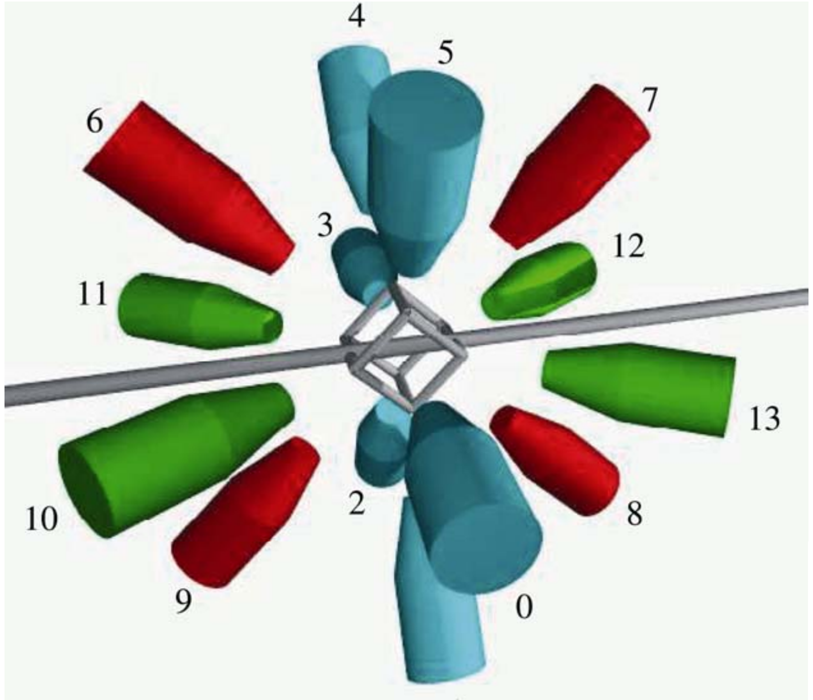
In-beam γ spectroscopy

(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

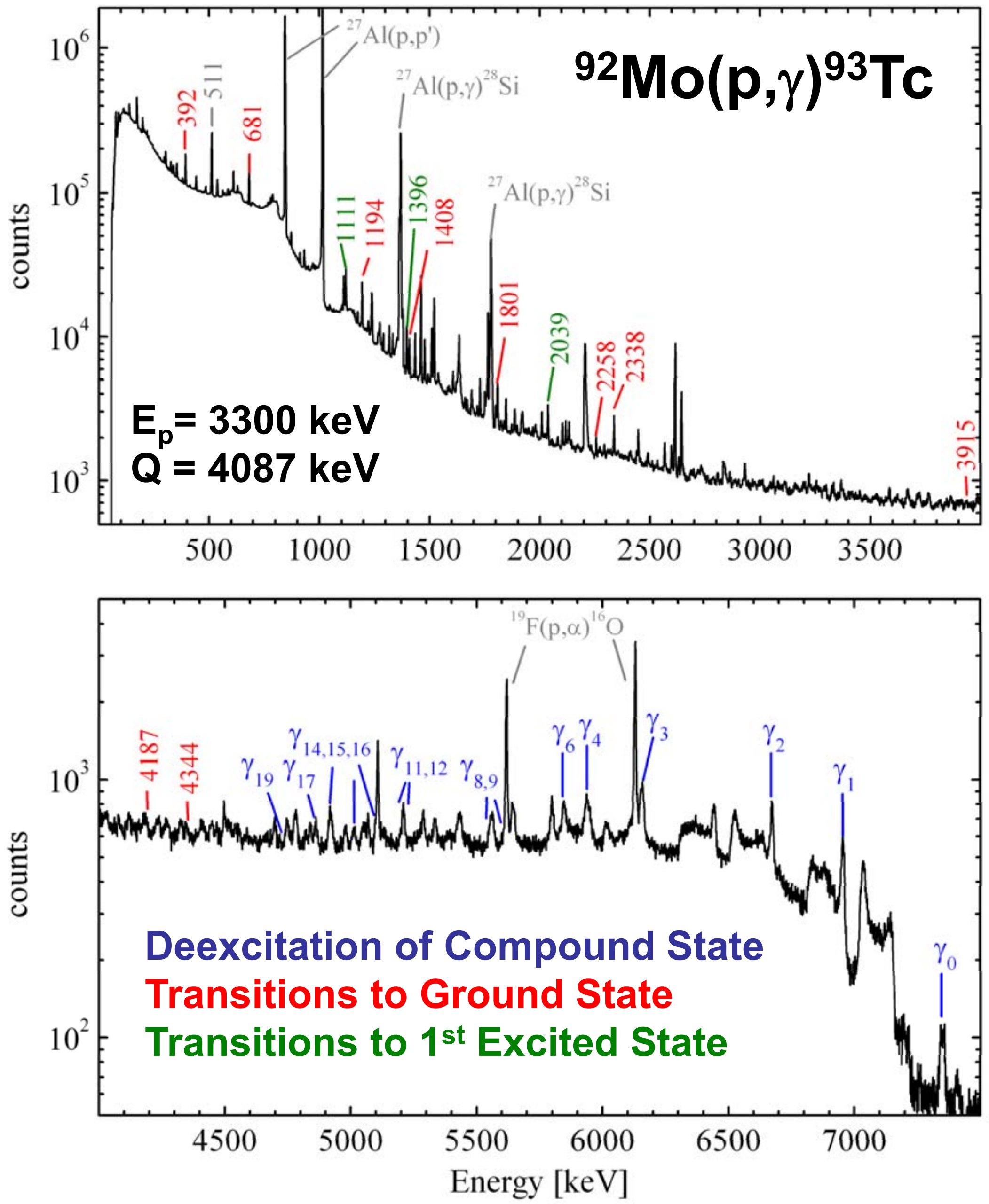


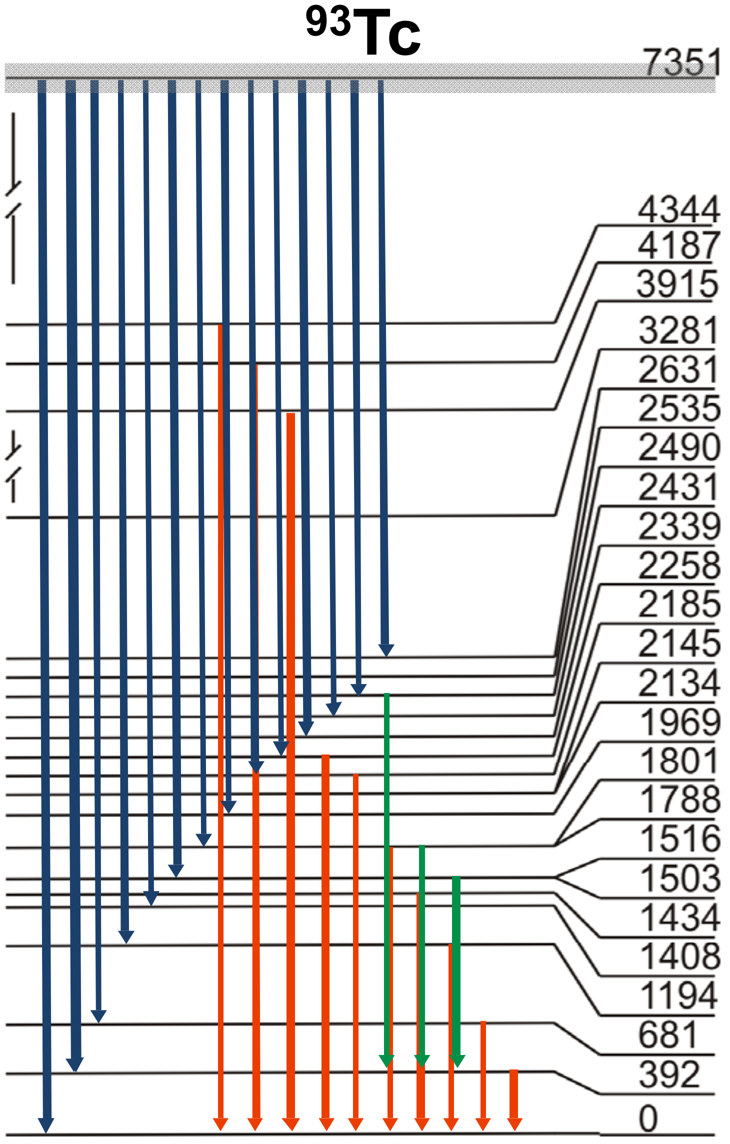
14 HPGe detectors in close geometry

⇨ **Photopeak efficiency at 1332 keV: ~ 2%**

⇨ **No requirements on reaction products**

Proton capture on ^{92}Mo at HORUS



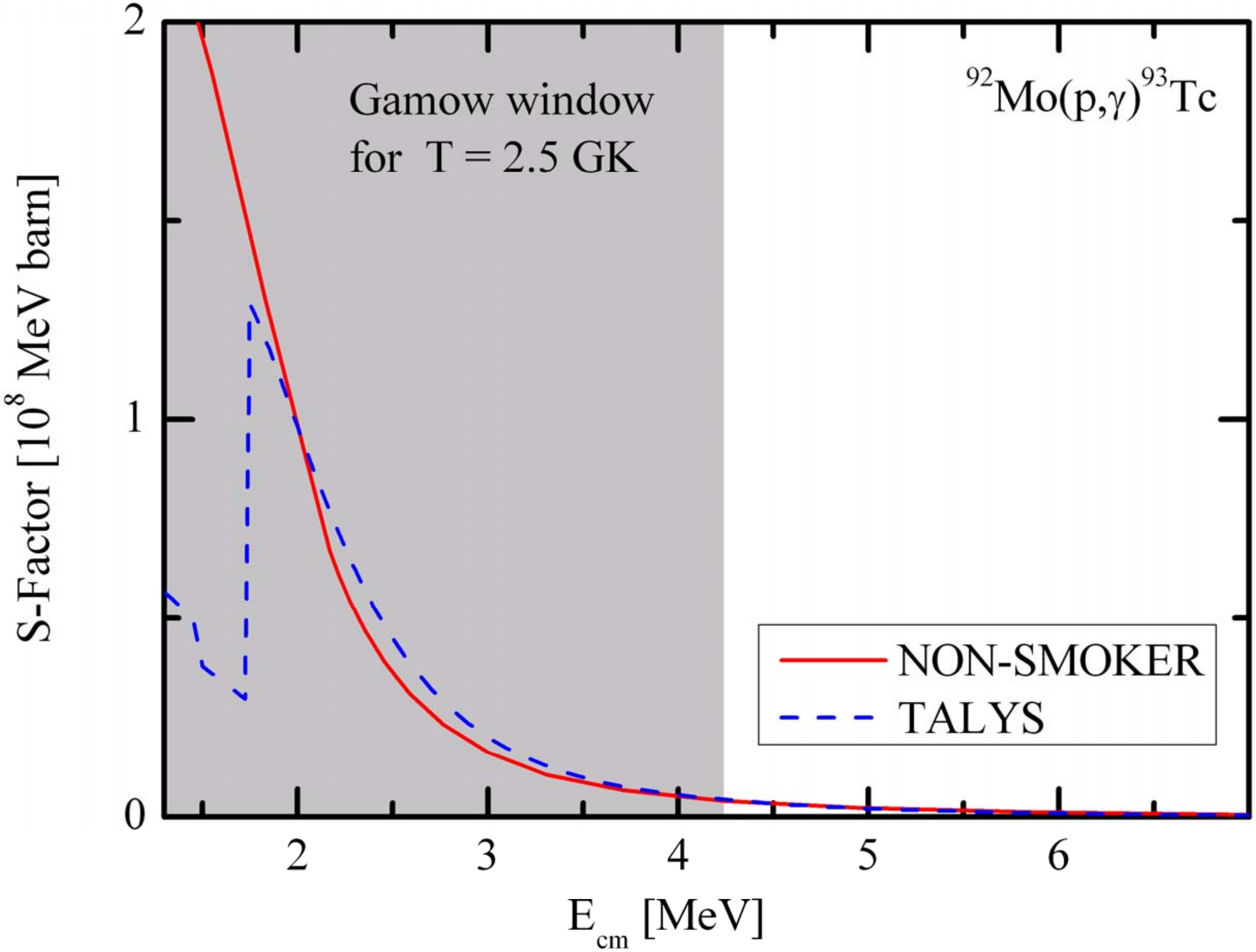


Deexcitation of Compound State

Transitions to Ground State

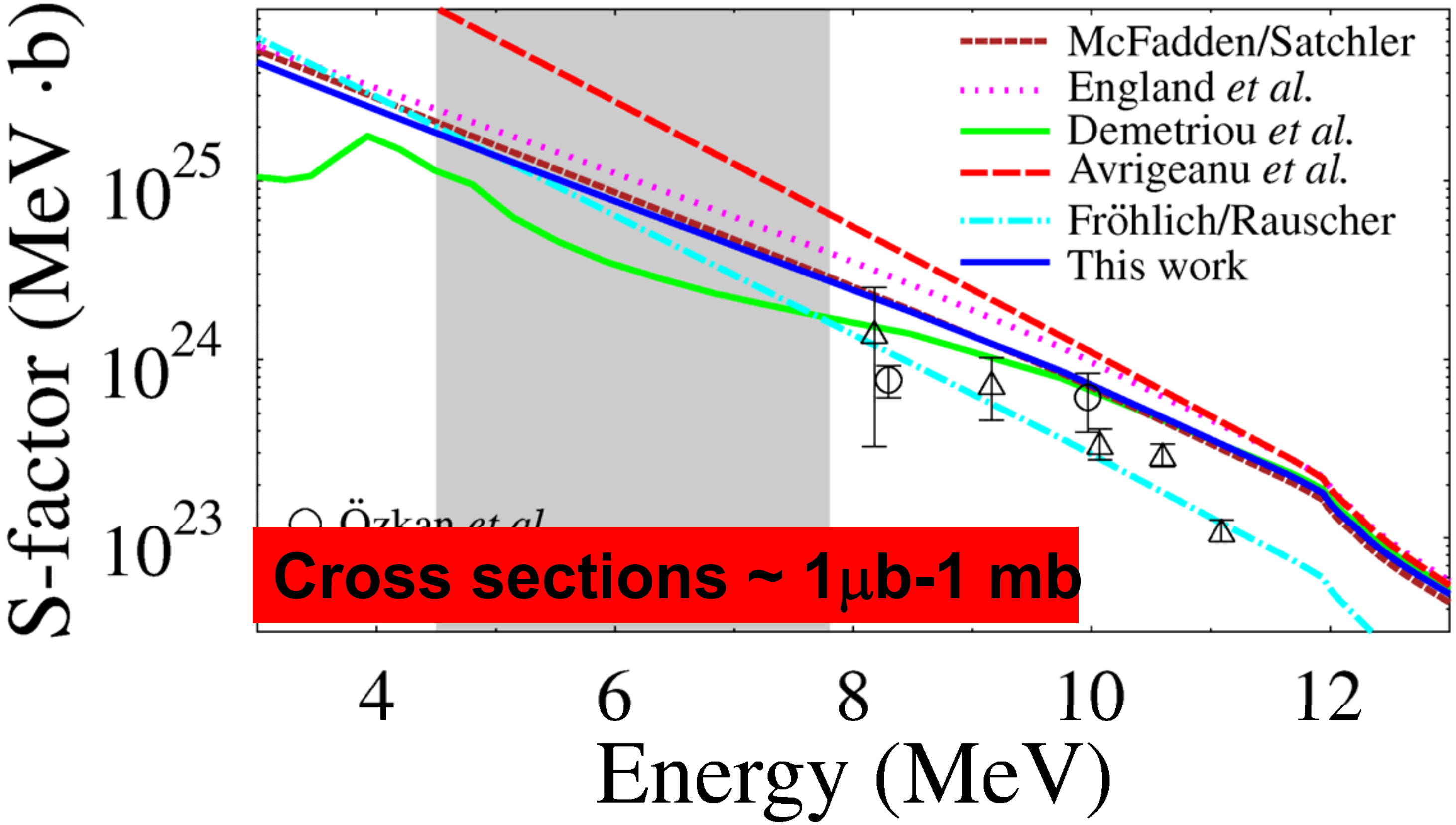
Transitions to 1st Excited State

Predicted ^{92}Mo(p,γ) S-Factor



α - capture cross section

$^{112}Sn(\alpha,\gamma)^{116}Te$

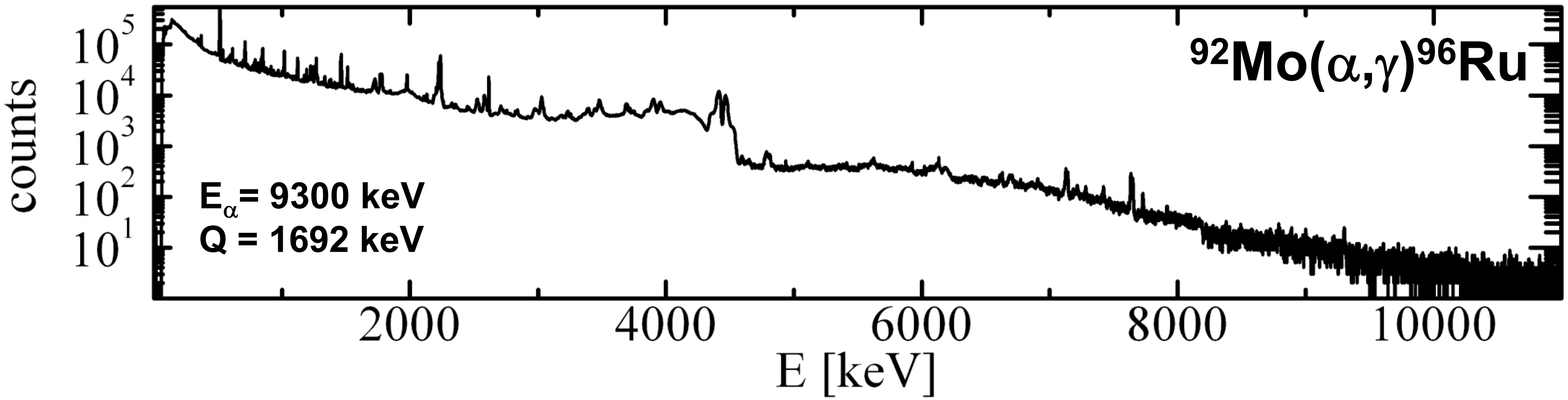


Cross sections ~ 1μb-1 mb

N. Özkan et al., PRC 75 (2007) 025801

*<u>Overview:</u> P.Demetriou, C. Grama, S. Goriely, NPA **707** (2002) 253*

In-beam α – capture experiment at HORUS



Many background reactions:

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

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

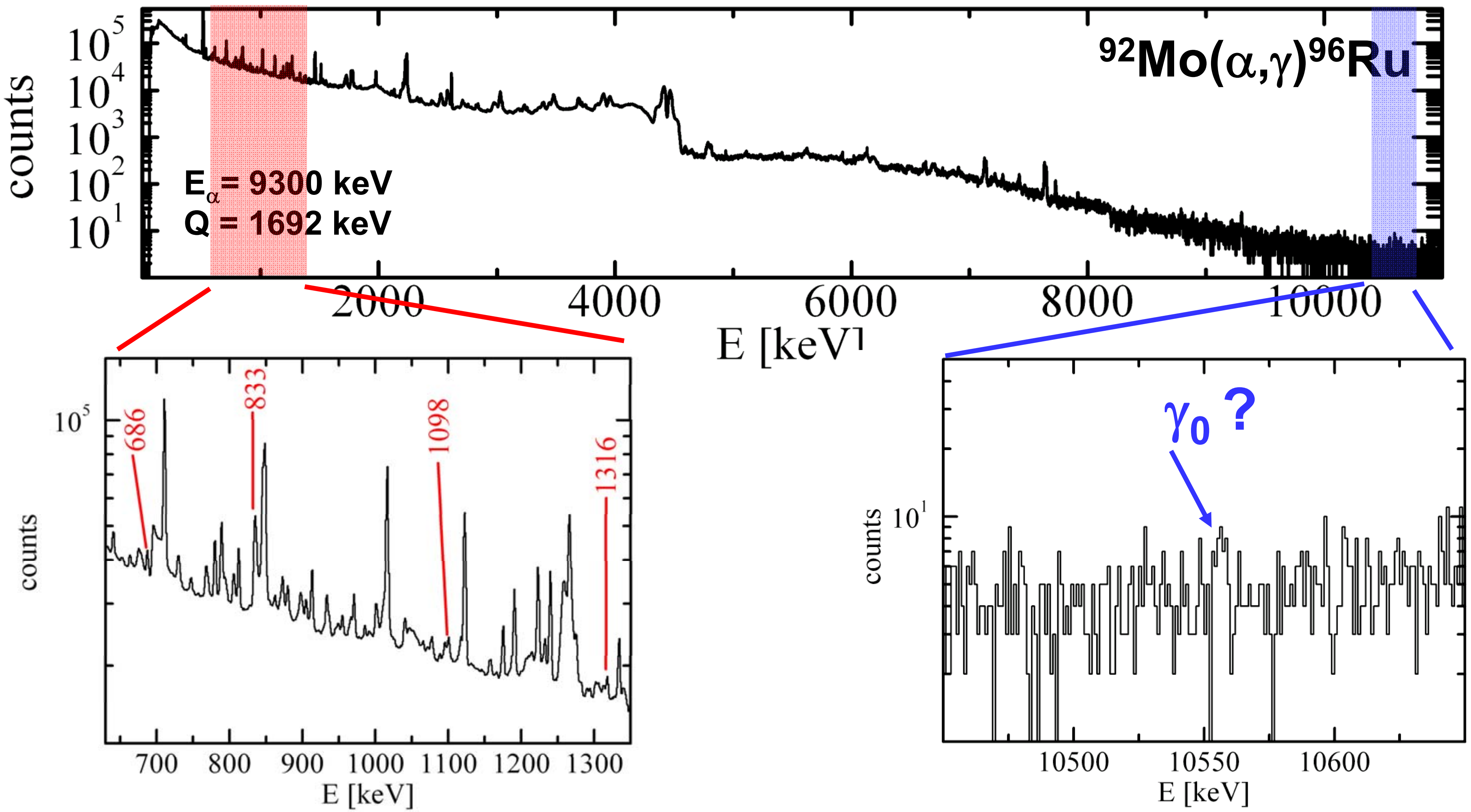
Competing reactions
- $^{92}Mo(\alpha,p)^{95}Tc$

Decay of radioactive reaction products

Tantalum coating of chamber

High vacuum or „Cooling Finger“

In-beam α – capture experiment at HORUS



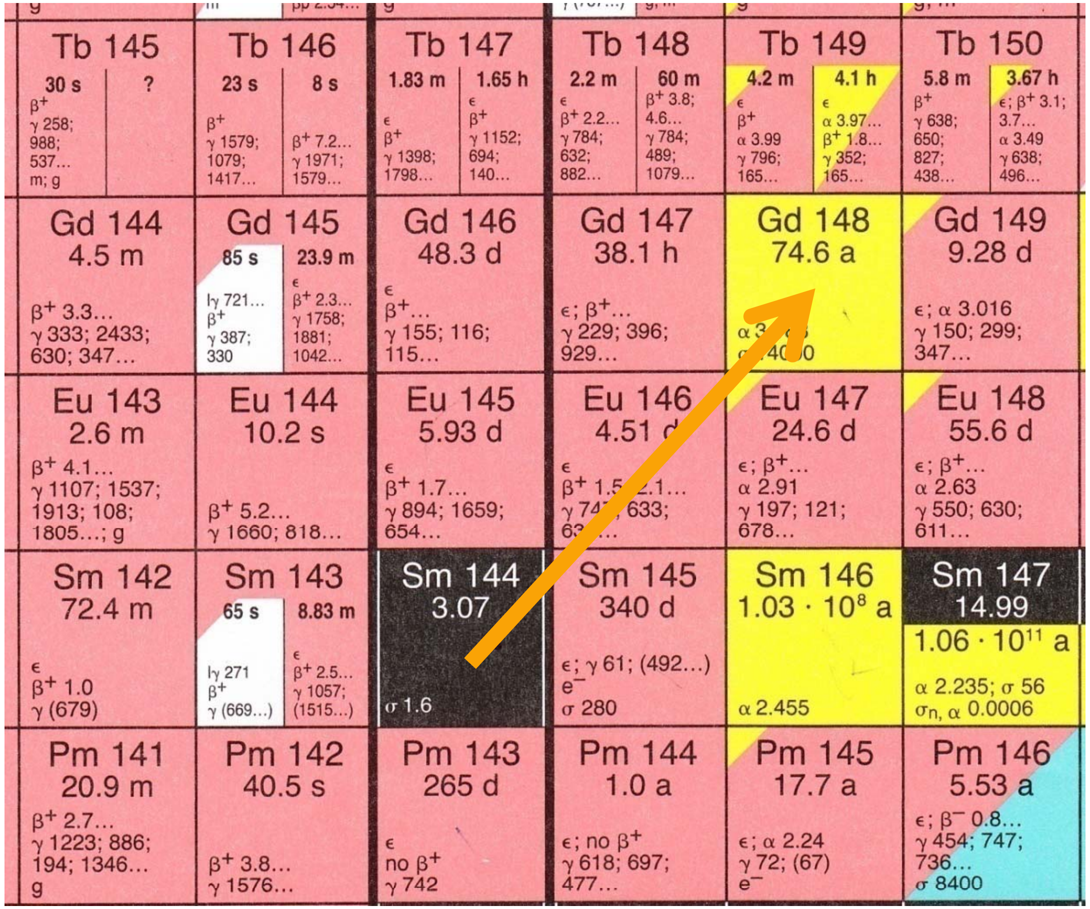
Clear identification of strong low-energetic transitions in ^{96}Ru

First indication of γ_0

PRELIMINARY (experiment in February 2009)

α - capture cross sections

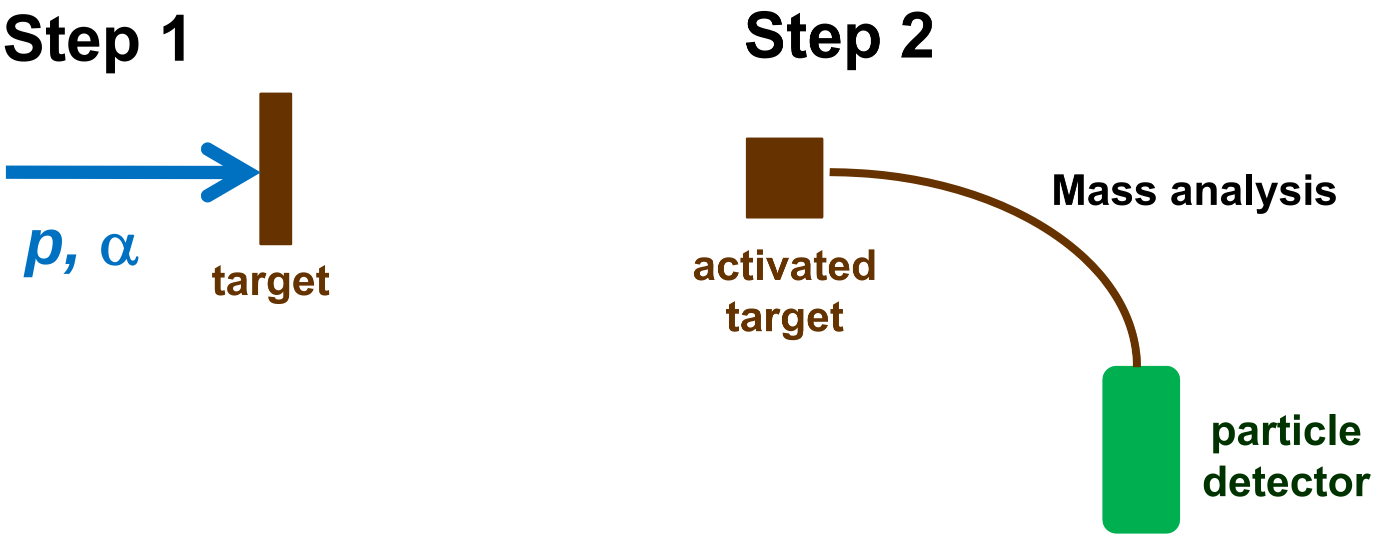
Due to Coulomb barrier (α,γ) experiments become more and more difficult for heavier nuclei.



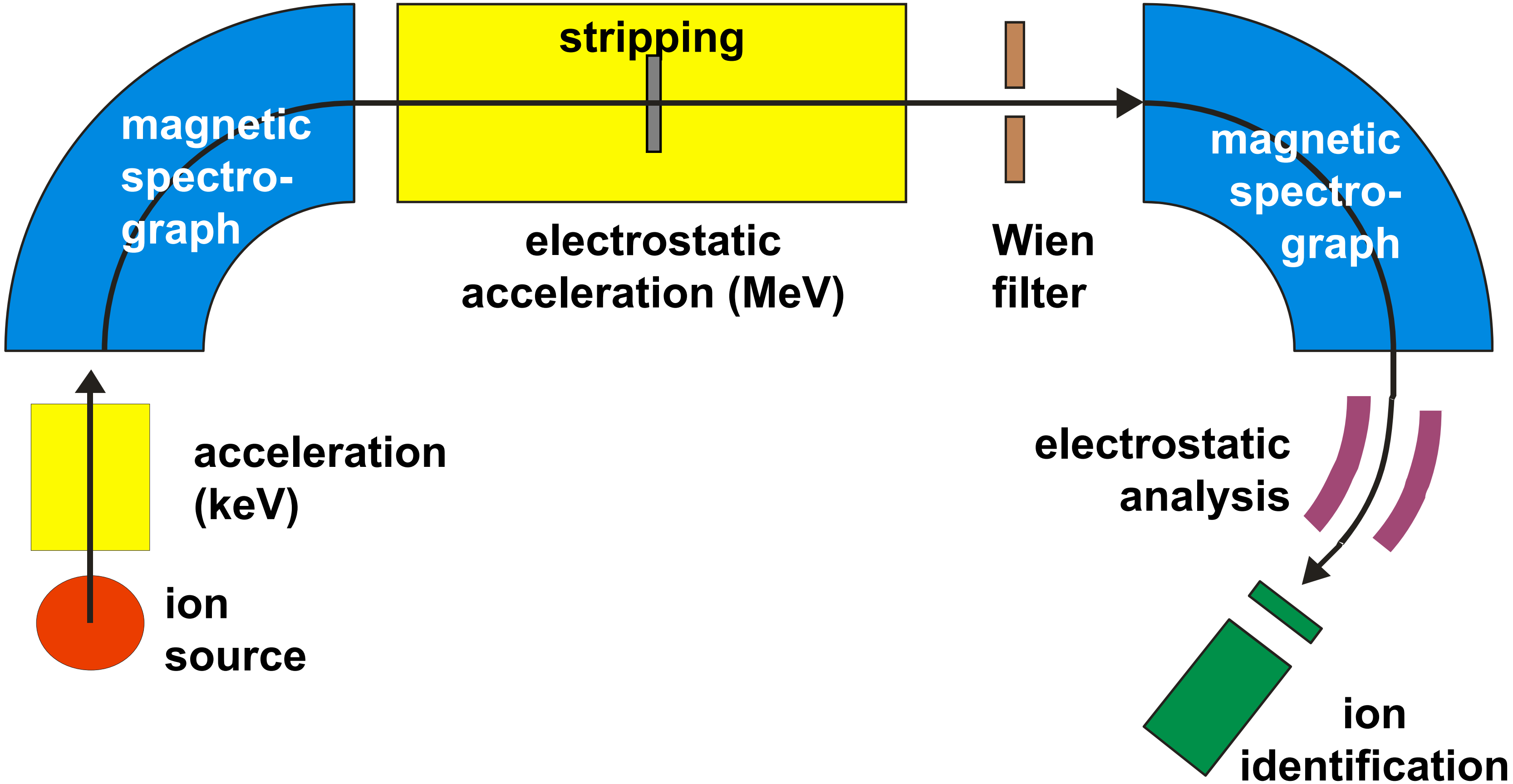
Tb 145 30 s β^+ γ 258; 988; 537… m; g ?	Tb 146 23 s β^+ γ 1579; 1079; 1417… 8 s β^+ 7.2… γ 1971; 1579…	Tb 147 1.83 m ε β^+ γ 1398; 1798… 1.65 h ε β^+ γ 1152; 694; 140…	Tb 148 2.2 m ε β^+ 2.2… γ 784; 632; 882… 60 m β^+ 3.8; 4.6… γ 784; 489; 1079…	Tb 149 4.2 m ε β^+ α 3.99 γ 796; 165… 4.1 h ε α 3.97… β^+ 1.8… γ 352; 165…	Tb 150 5.8 m β^+ γ 638; 650; 827; 438… 3.67 h ε; β^+ 3.1; 3.7… α 3.49 γ 638; 496…
Gd 144 4.5 m β^+ 3.3… γ 333; 2433; 630; 347…	Gd 145 85 s Iγ 721… β^+ γ 387; 330 23.9 m ε β^+ 2.3… γ 1758; 1881; 1042…	Gd 146 48.3 d ε β^+… γ 155; 116; 115…	Gd 147 38.1 h ε; β^+… γ 229; 396; 929…	Gd 148 74.6 a α 3[illegible] [illegible]40[illegible]0	Gd 149 9.28 d ε; α 3.016 γ 150; 299; 347…
Eu 143 2.6 m β^+ 4.1… γ 1107; 1537; 1913; 108; 1805…; g	Eu 144 10.2 s β^+ 5.2… γ 1660; 818…	Eu 145 5.93 d ε β^+ 1.7… γ 894; 1659; 654…	Eu 146 4.51 d ε β^+ 1.5[illegible]2.1… γ 74[illegible] 633; 63[illegible]…	Eu 147 24.6 d ε; β^+… α 2.91 γ 197; 121; 678…	Eu 148 55.6 d ε; β^+… α 2.63 γ 550; 630; 611…
Sm 142 72.4 m ε β^+ 1.0 γ (679)	Sm 143 65 s Iγ 271 β^+ γ (669…) 8.83 m ε β^+ 2.5… γ 1057; (1515…)	Sm 144 3.07 σ 1.6	Sm 145 340 d ε; γ 61; (492…) e^- σ 280	Sm 146 $1.03 \cdot 10^8$ a α 2.455	Sm 147 14.99 $1.06 \cdot 10^{11}$ a α 2.235; σ 56 $\sigma_{n,\alpha}$ 0.0006
Pm 141 20.9 m β^+ 2.7… γ 1223; 886; 194; 1346… g	Pm 142 40.5 s β^+ 3.8… γ 1576…	Pm 143 265 d ε no β^+ γ 742	Pm 144 1.0 a ε; no β^+ γ 618; 697; 477…	Pm 145 17.7 a ε; α 2.24 γ 72; (67) e^-	Pm 146 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.

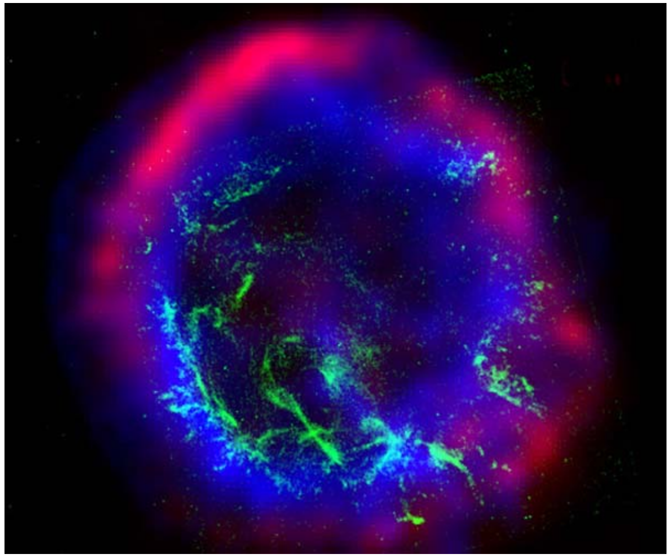
Accelerator Mass Spectrometry (AMS)

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

^{40}Ca(α,γ)^{44}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)

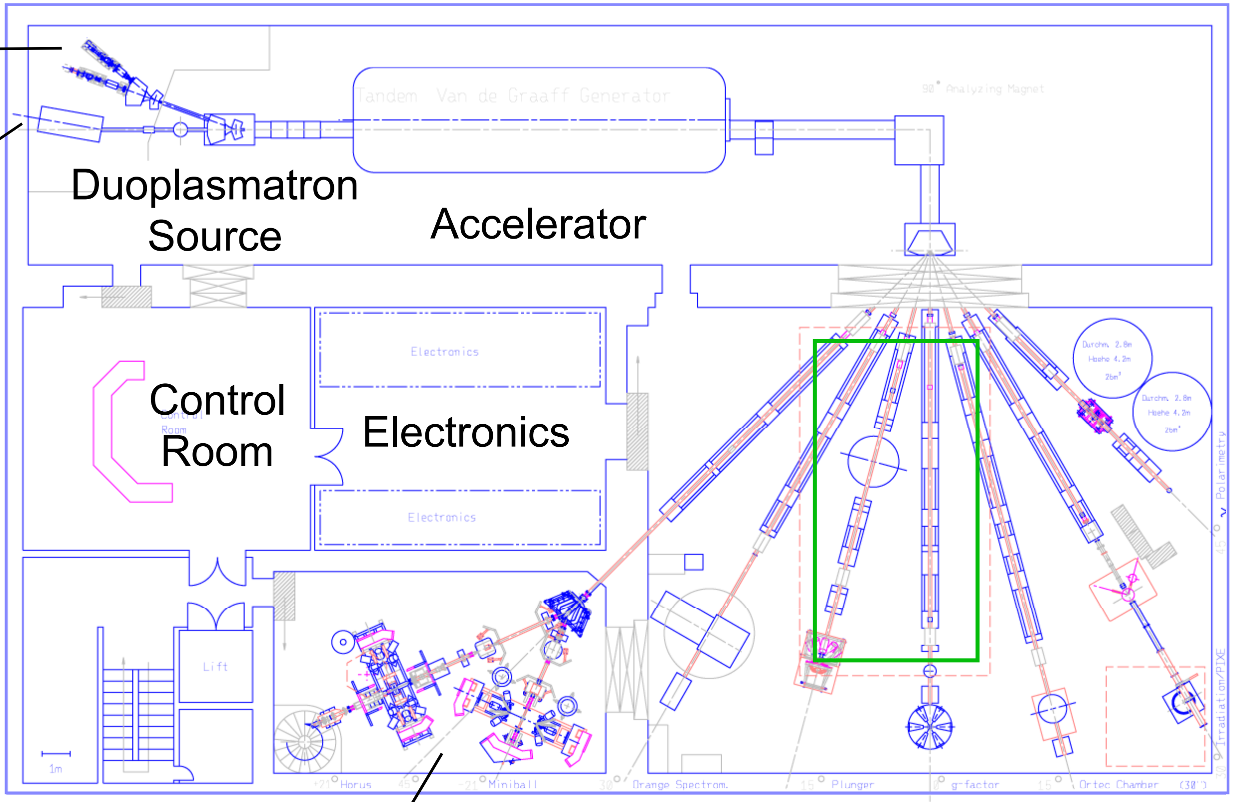
Geology
(M. Melles, M. Staubwasser)

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



Sputter Source

Polarized Ion Source

Duoplasmatron Source

Accelerator

Control Room

Electronics

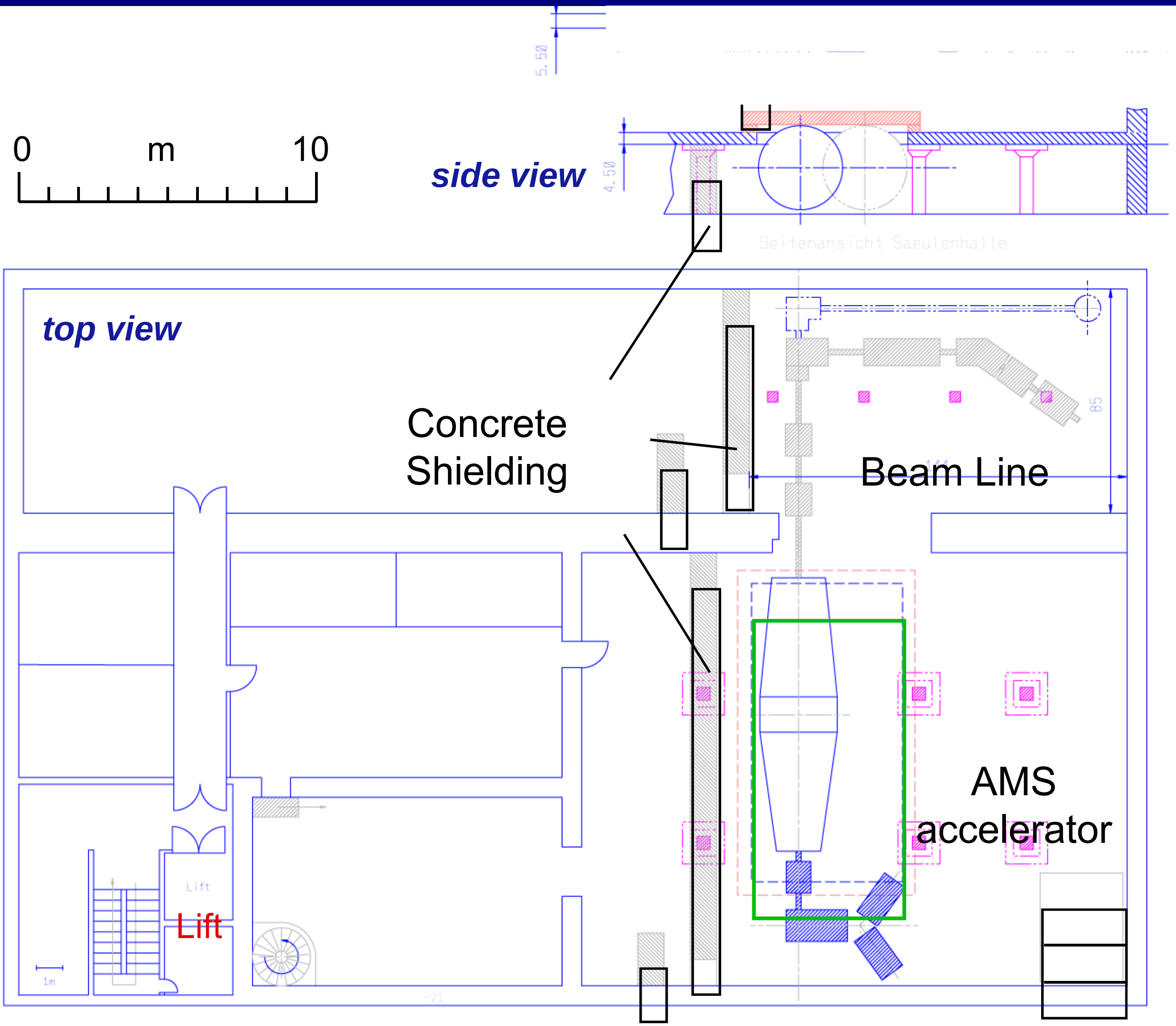
γ-ray Spectrometers

Experimental Hall

0 m 10

Universität zu Köln

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



Funded by DFG and University of Cologne

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

Total investment: about 9 M€

Annual running costs: about 0.3 M€

<u>Additional</u> personnel: 2 Professors, 2 Scientists, 3 Technicians, 4 Operators

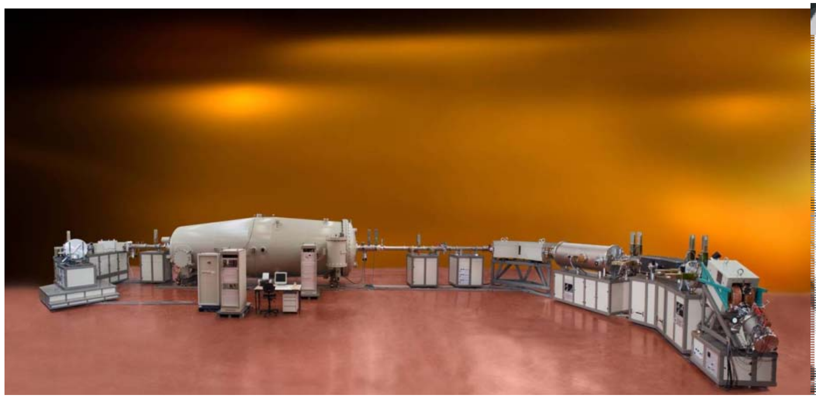
A. Dewald, J. Jolie, and A. Zilges, Nuclear Physics News 18 (2008) 26

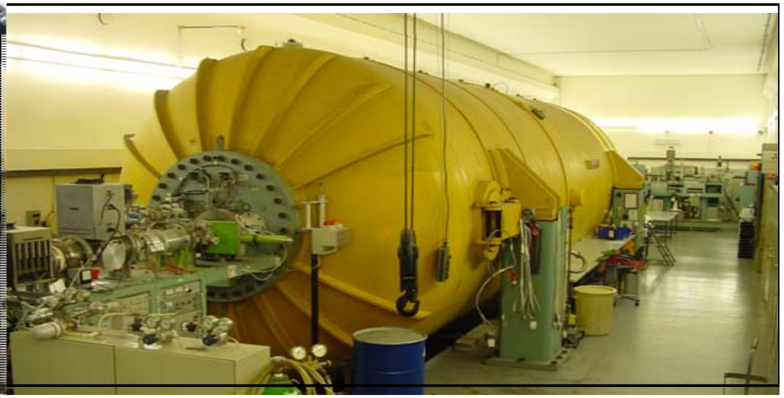
Funded by DFG and University of Cologne

Facilities at the Universität zu Köln

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

COME AND SEE (AND USE) !





Experimental techniques to investigate the *p* process of nucleosynthesis

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L. Kern, S. Müller, D. Savran,
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More information and references: www.zilges.de