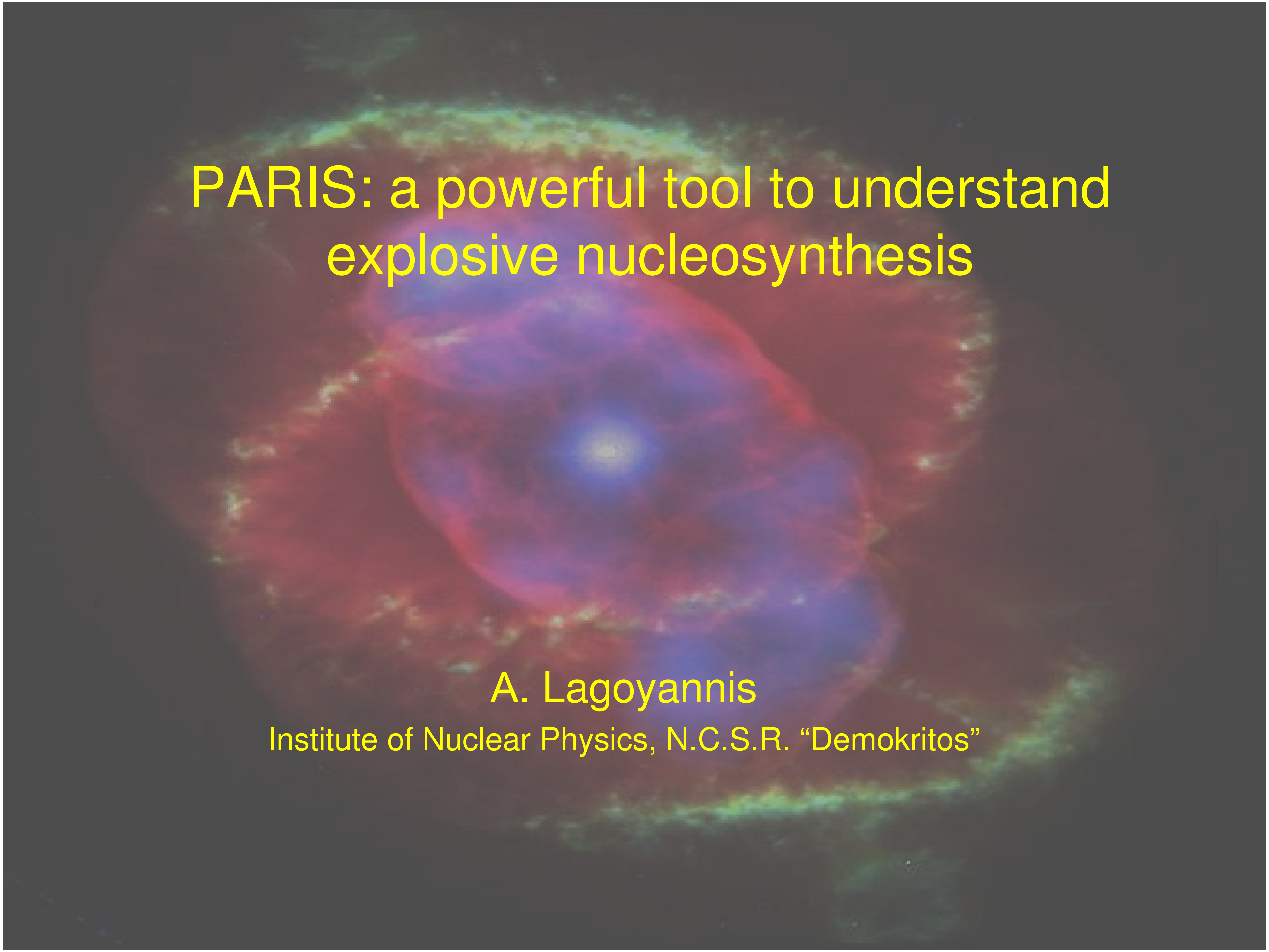
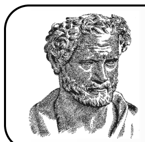


PARIS: a powerful tool to understand explosive nucleosynthesis

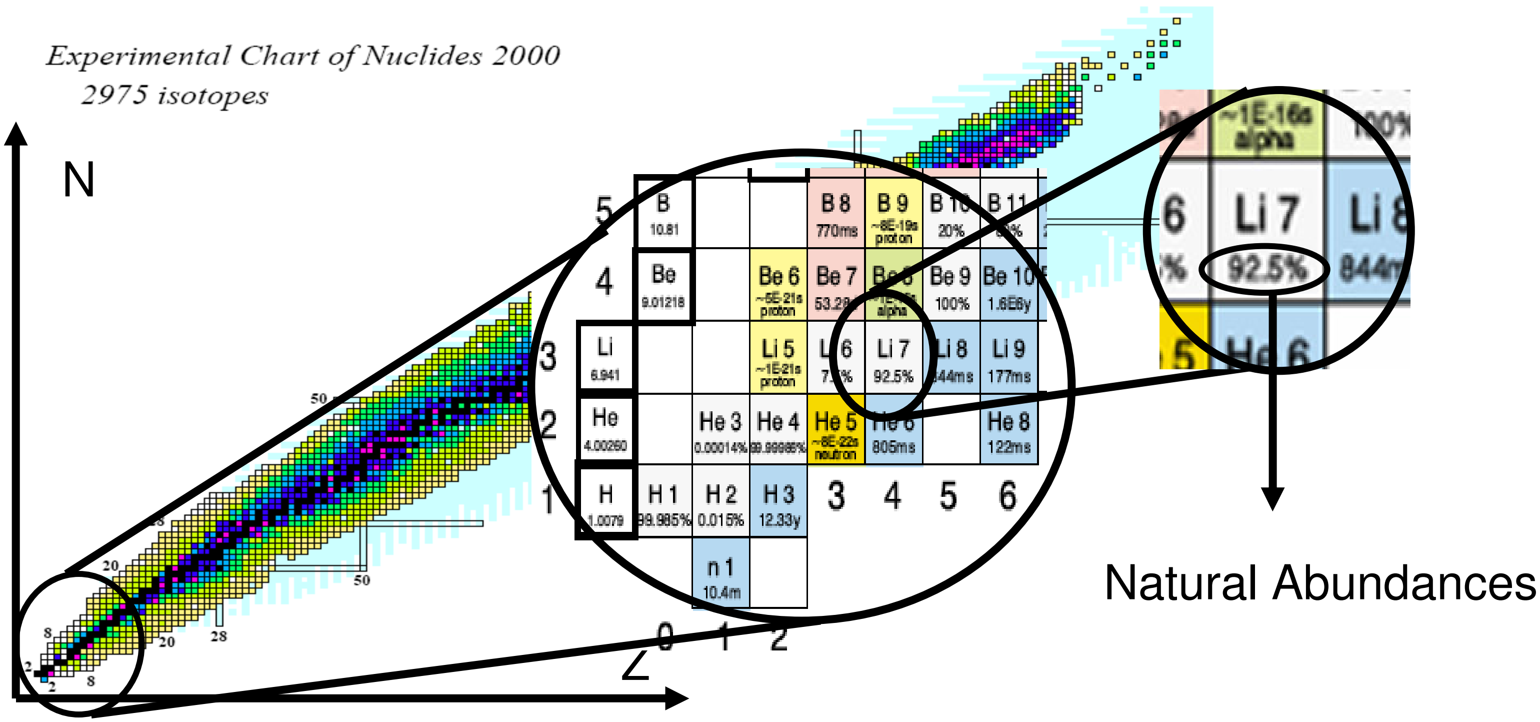
A. Lagoyannis
Institute of Nuclear Physics, N.C.S.R. “Demokritos”

Outline

1. The problem
2. Ways of coping with the problem (so far) and their limitations
3. Need for new tools and/or methods
4. Extension of the problem to RIB's
5. PARIS : a very promising solution

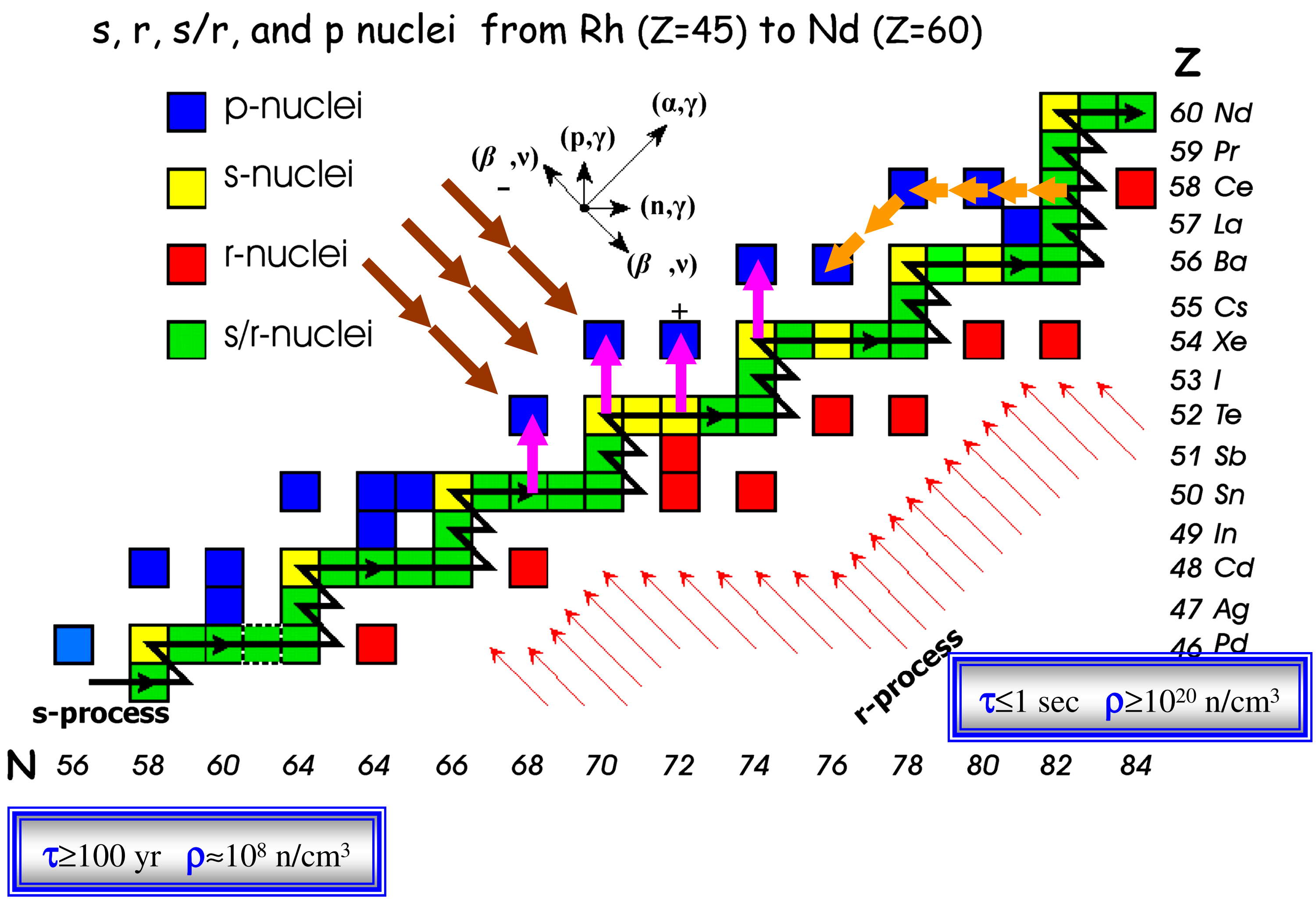


Natural abundances



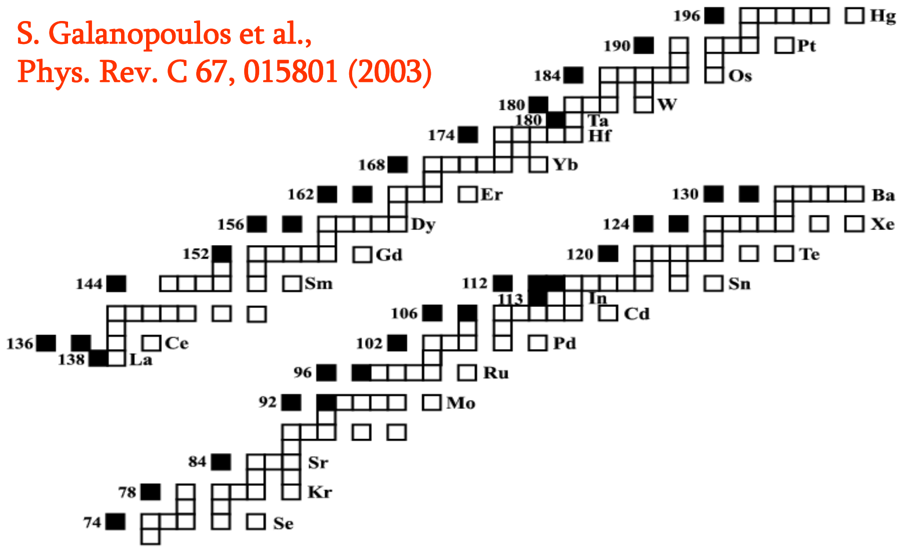
1. Earth samples analysis
2. Photosphere of Sun spectrometry
3. Meteorites analysis

Pathways for heavy-element nucleosynthesis

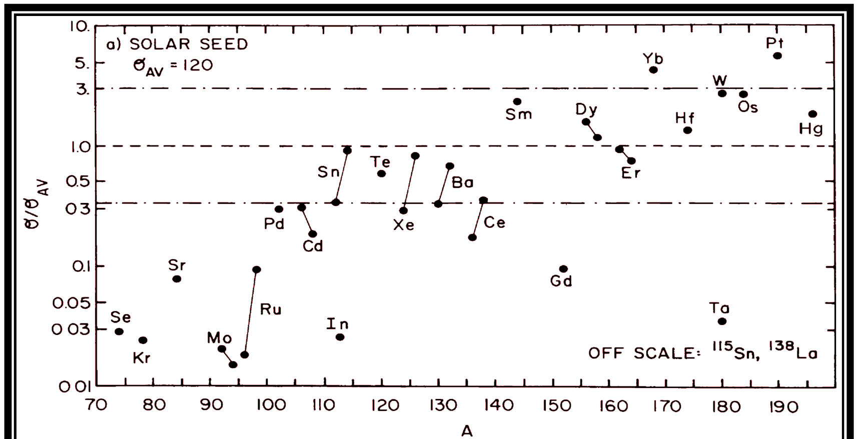


p nuclei and p-nuclei abundances

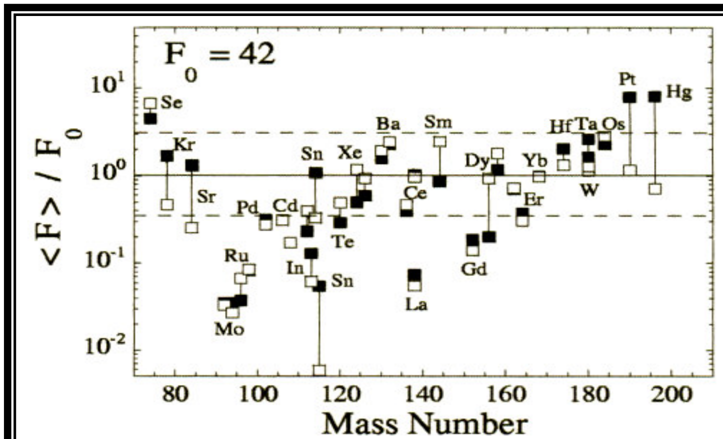
S. Galanopoulos et al.,
Phys. Rev. C 67, 015801 (2003)



p nucleus	(%)	p nucleus	(%)	p nucleus	(%)
^{74}Se	0.89	^{114}Sn	0.65	^{156}Dy	0.06
^{78}Kr	0.35	^{115}Sn	0.34	^{158}Dy	0.10
^{84}Sr	0.56	^{120}Te	0.096	^{162}Er	0.14
^{92}Mo	14.84	^{124}Xe	0.10	^{164}Er	1.61
^{94}Mo	9.25	^{126}Xe	0.09	^{168}Yb	0.13
^{96}Ru	5.52	^{130}Ba	0.106	^{174}Hf	0.162
^{98}Ru	1.88	^{132}Ba	0.101	^{180}Ta	0.012
^{102}Pd	1.02	^{138}La	0.09	^{180}W	0.13
^{106}Cd	1.25	^{136}Ce	0.19	^{184}Os	0.02
^{108}Cd	0.89	^{138}Ce	0.25	^{190}Pt	0.01
^{113}In	4.3	^{144}Sm	3.1	^{196}Hg	0.15
^{112}Sn	0.97	^{152}Gd	0.20	abundances	



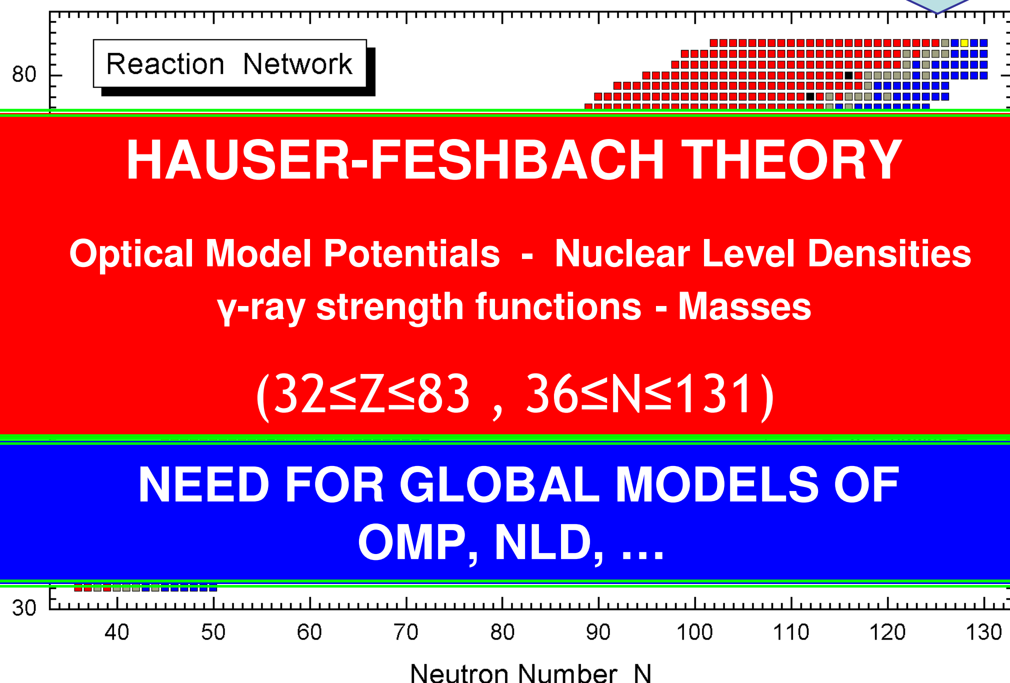
Woosley and Howard, Ap. J. Suppl. 36, 285 (1978)



S. Goriely et al., A&A 375, 35 (2001)

Reaction network

Initial "stellar" conditions → Key reactions: $^{22}Ne(\alpha,n)^{25}Mg$, $^{12}C(\alpha,\gamma)^{16}O$ ………… → seed abundances **s process** → Reaction network → p-nuclei abundances **p process**



HAUSER-FESHBACH THEORY

Optical Model Potentials - Nuclear Level Densities

γ-ray strength functions - Masses

$(32 \leq Z \leq 83\ ,\ 36 \leq N \leq 131)$

NEED FOR GLOBAL MODELS OF OMP, NLD, …

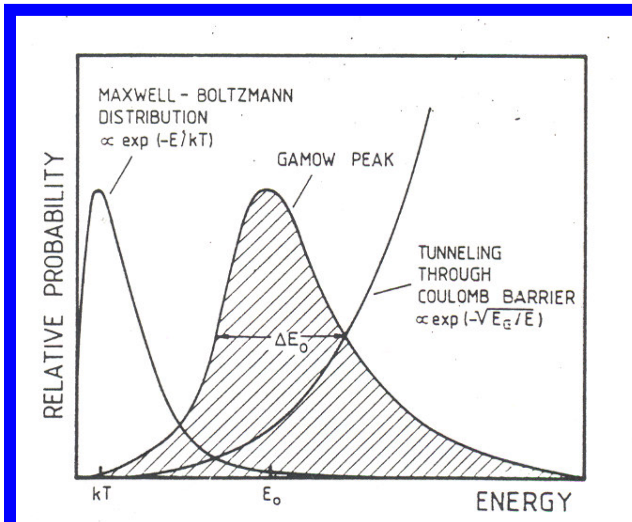
Almost 2000 nuclei are involved in this ...rk powered ...re than 20000 ...ions

...(γ,p), (γ,α), ..., α-captures, ...ays, ...tures

...uge number ...oss sections have to be known

HAUSER-FESHBACH THEORY is required !

Gamow peaks and windows: the astrophysically relevant energies



charged-particle induced reactions

$$E_0 = (bkT/2)^{2/3}$$

$$b^2 = E_G = 2\mu\pi^2 \frac{e^4 Z_t^2 Z_p^2}{\hbar^2}$$

$$\Delta E = \sqrt{\frac{16 E_0 kT}{3}} \exp(-3E_0/kT)$$

reaction	barrier (MeV)	E_0 (keV)	T (K)
p + p (sun)	0.55	5.9	1.5×10^7
α + ^{12}C (red giants)	300	56	1.5×10^8
^{12}C + ^{12}C (massive stars)	10.44	1500	$\approx 1\times10^9$
p + ^{74}Se (p process)	7.9	2800	$\approx 3\times10^9$

(p,γ) reactions: E_{CM} = 1 - 5 MeV

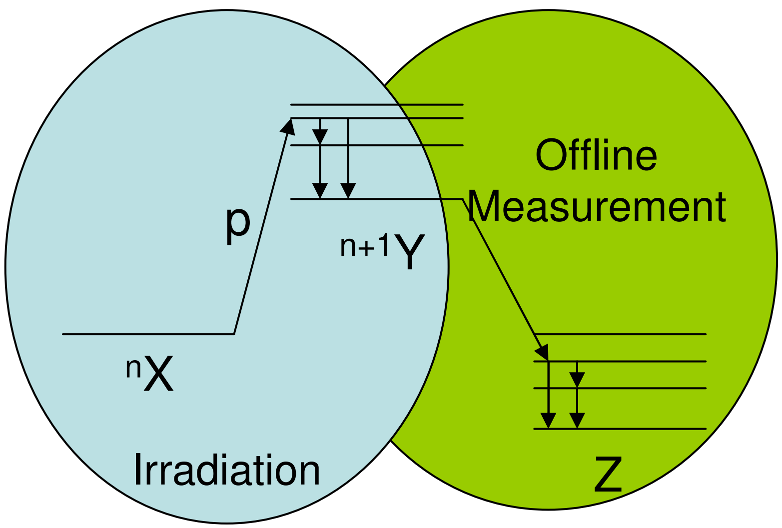
(α,γ) reactions: E_{CM} = 6-12 MeV

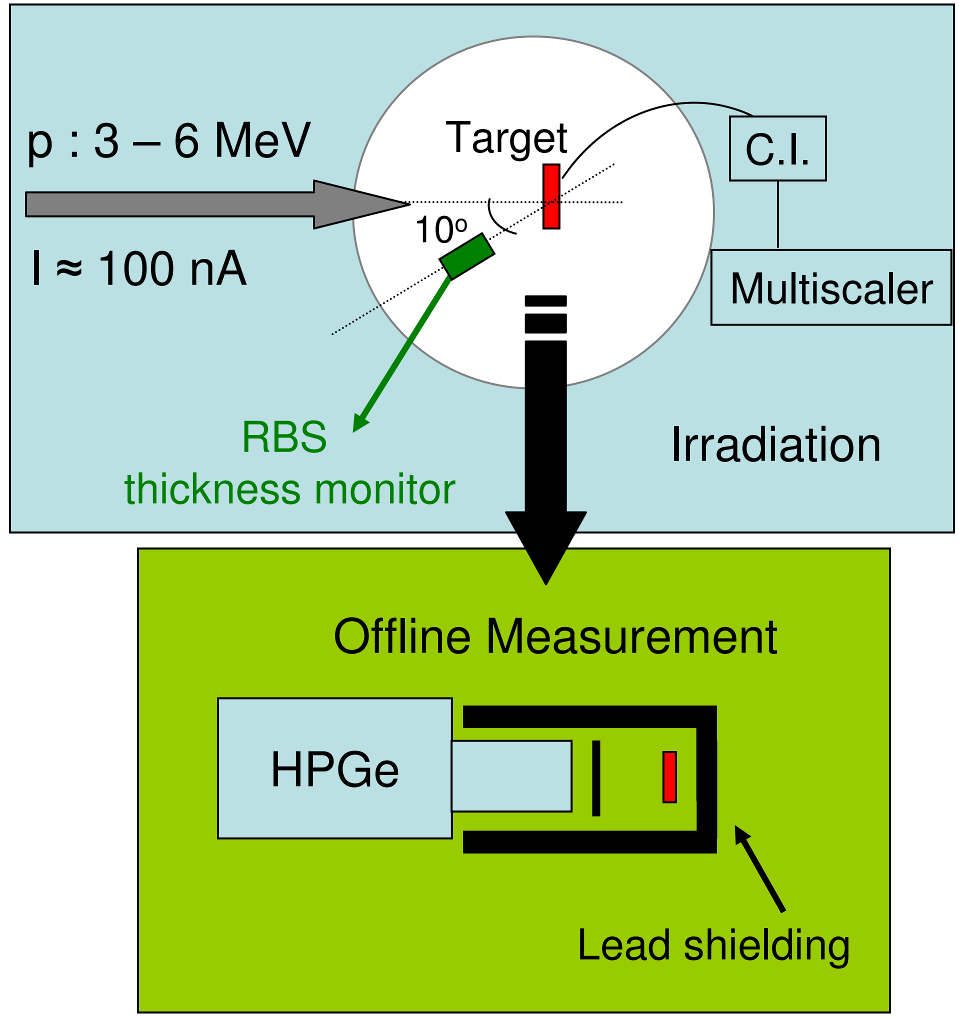
OUR GOAL → To measure the cross section **σ** at these energy regions

Activation: Principle and Setup

Requirements

1. Radioactive product
2. Suitable lifetime (30min - 1 day)



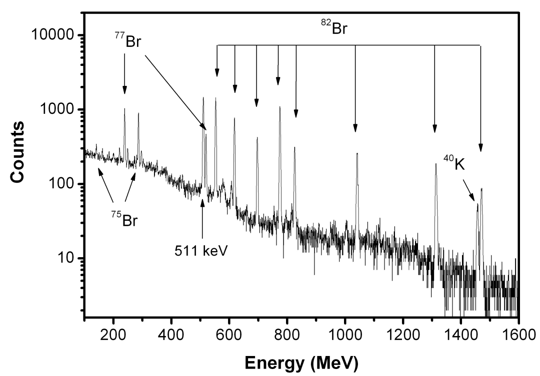


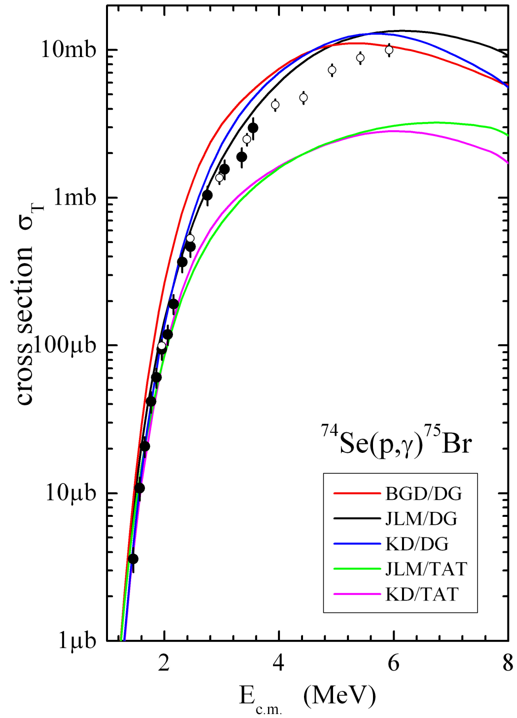
Activation: The $^{74}Se(p,\gamma)^{75}Br$ example

$^{74}Se(p,\gamma)^{75}Br$

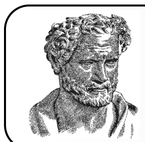
E_p = 3 – 6 MeV ξ=604 μg/cm^2

$T_{1/2}(^{75}Br)$=96.7 min $t_{irrad} \approx$ 4.5 h

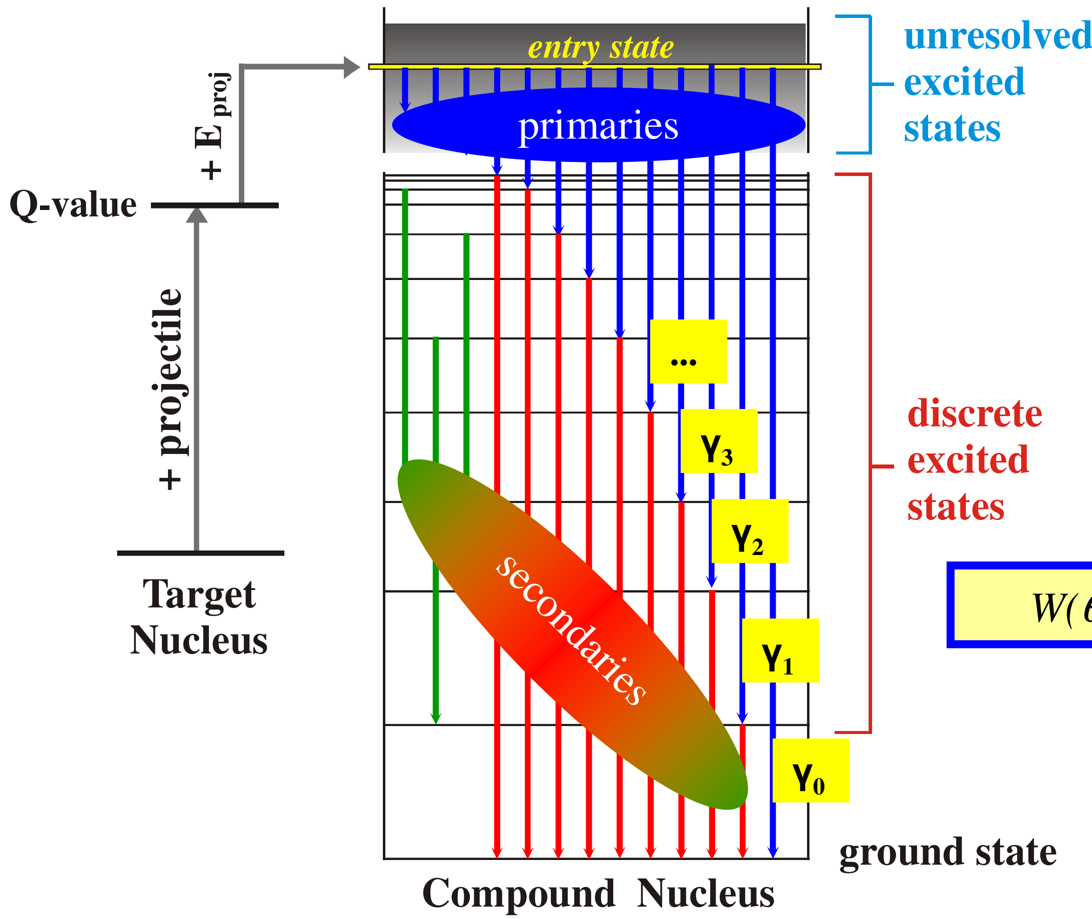




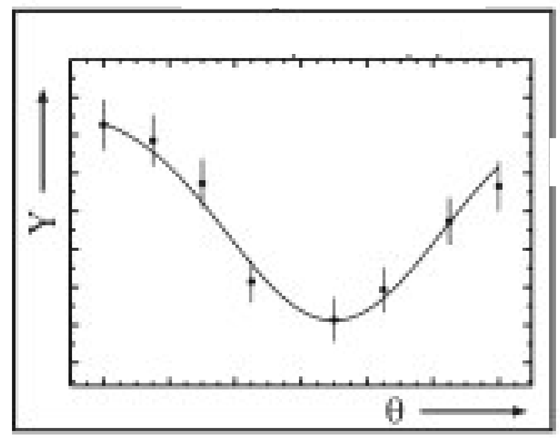
$$\sigma = \frac{C_\gamma \cdot \lambda}{eff_\gamma \cdot I_\gamma \cdot N_0 \cdot e^{-\lambda t_w} \cdot (1-e^{-\lambda t_m}) \cdot (1-e^{-\lambda \Delta t}) \cdot \sum_{i=1}^{n} \{\Phi_i \cdot e^{-(n-i)\lambda \Delta t}\}}$$



γ angular distribution measurements: The principle



Angular distribution for $\gamma_0, \gamma_1, \ldots$



$$W(\theta)=A_0(1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta))$$

$$\sigma = \frac{A}{N_A N_p \xi} \sum_j A_{0,j}$$

γ angular distribution measurements: The $^{78}Se(p,\gamma)^{79}Br$ example

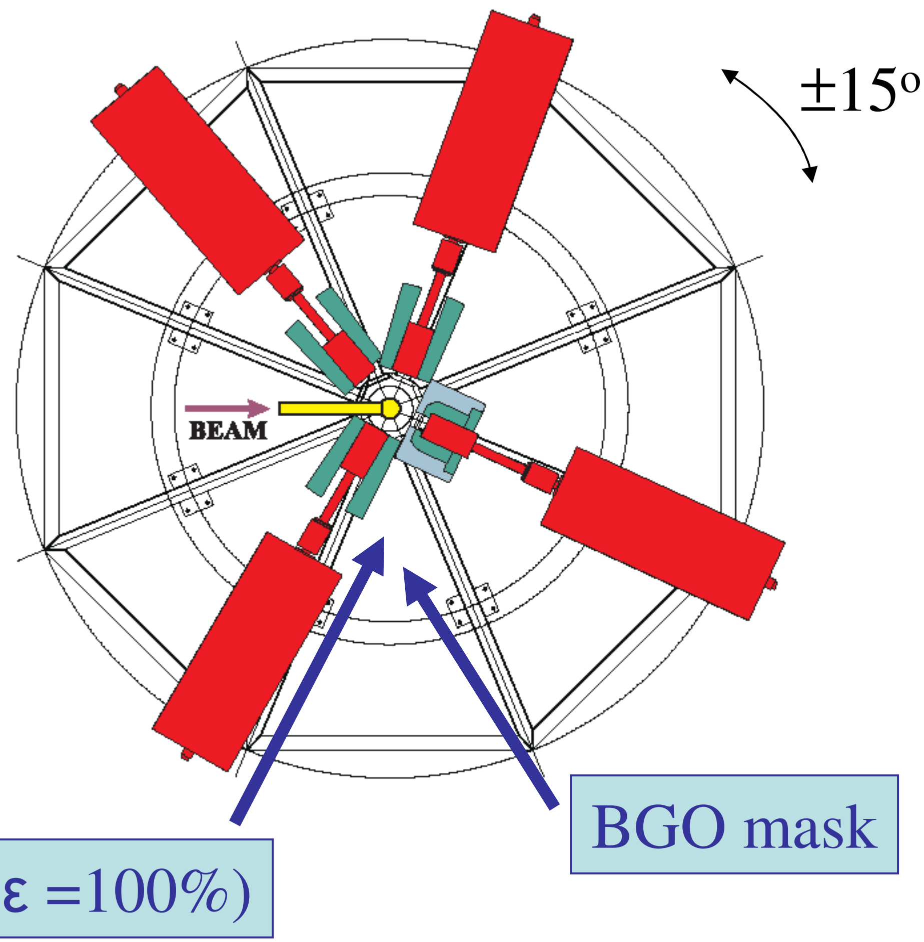
Experiment at the 4 MV Dynamitron accelerator at IfS Stuttgart

$^{78}Se(p,\gamma)^{79}Br$

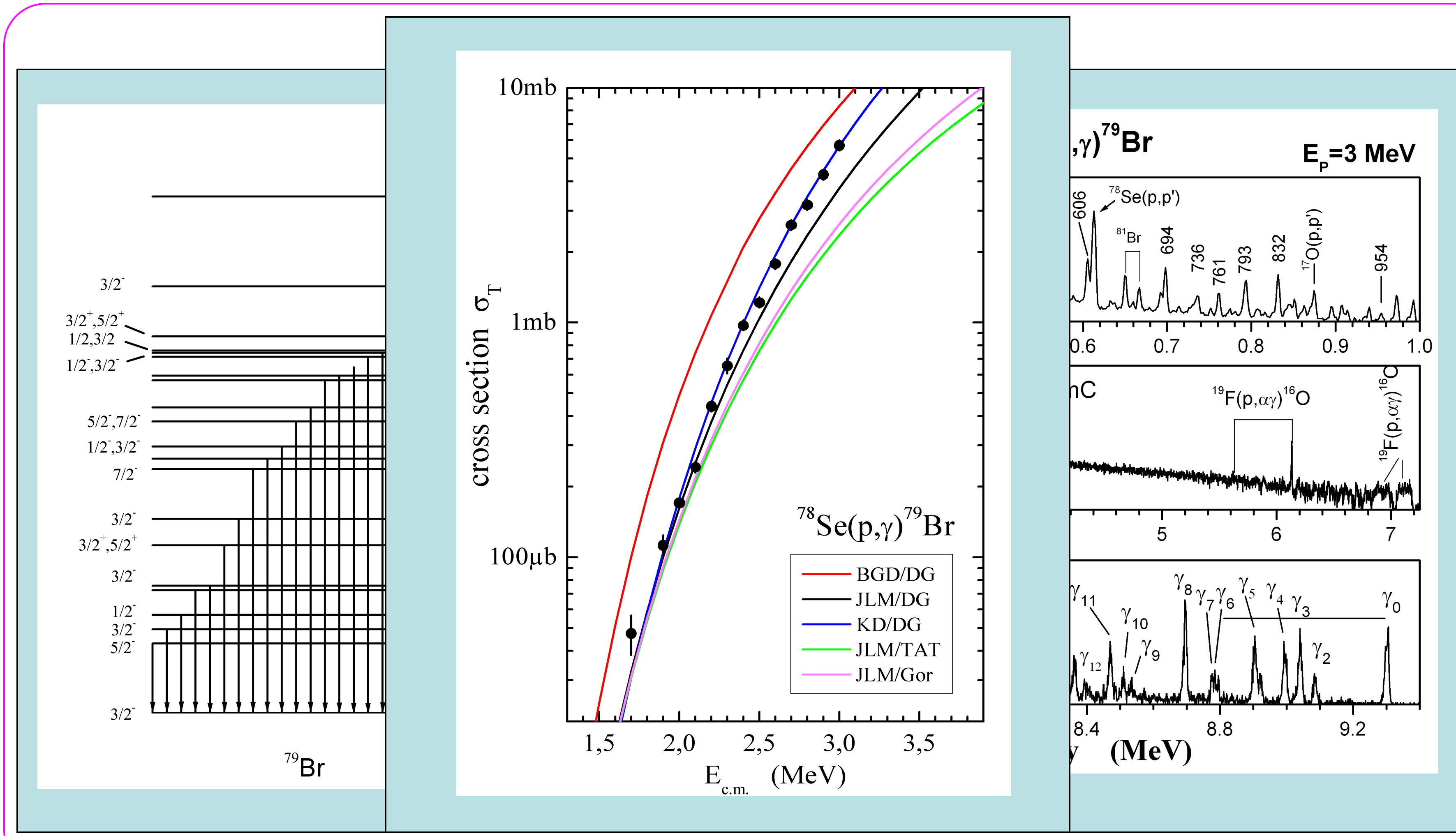
$E_p = 1.5 \sim 3.5$ MeV

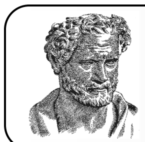
^{78}Se – metallic: 85 μg/cm^2 (enr. 97.8%)

all targets on Ta backing



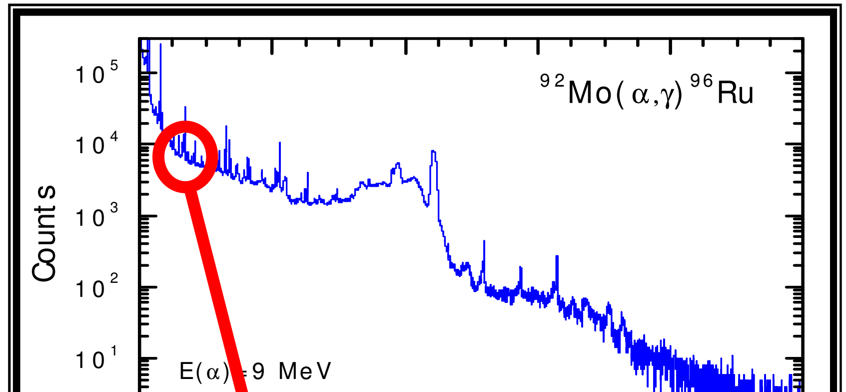
γ angular distribution measurements: The $^{78}Se(p,\gamma)^{79}Br$ example





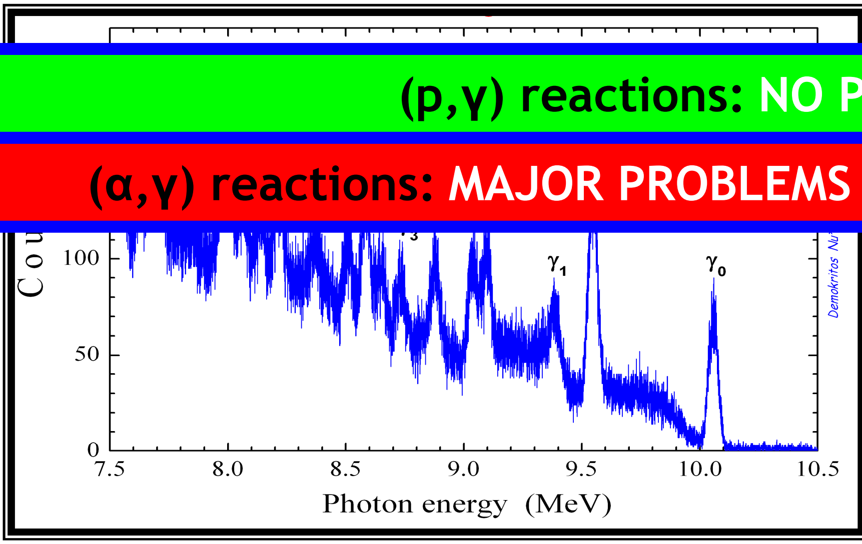
γ angular distribution measurements: the (α,γ) problem

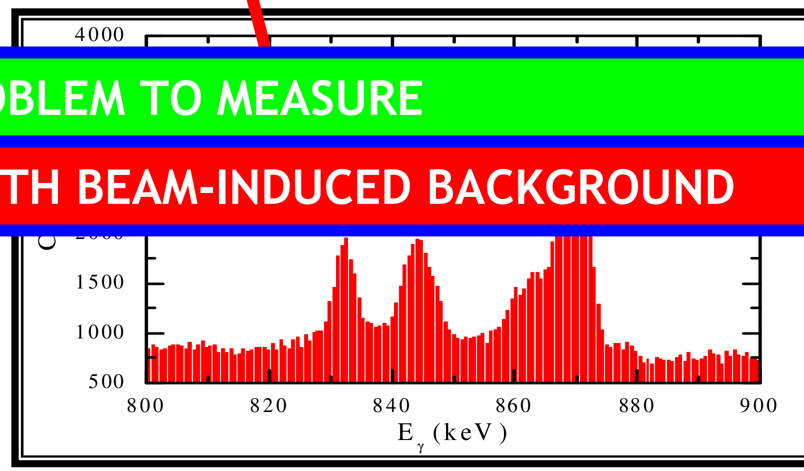
MINIBALL @ IKP/Cologne



(p,γ) reactions: E_{CM} = 1 - 5 MeV , σ = 1 μb ÷ 1 mb

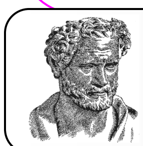
(α,γ) reactions: E_{CM} = 6-12 MeV , σ = 0.1 ÷100 μb



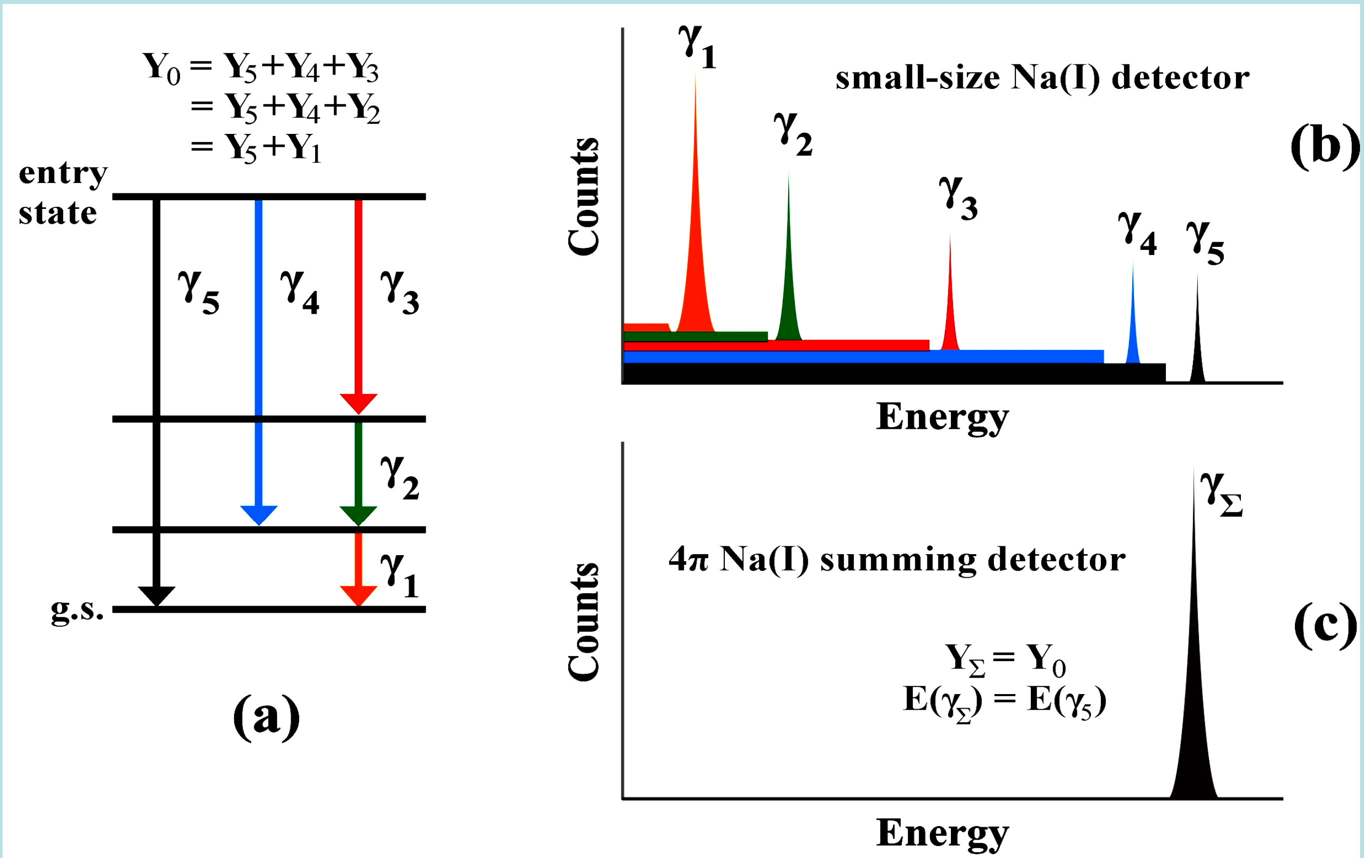


(p,γ) reactions: NO PROBLEM TO MEASURE

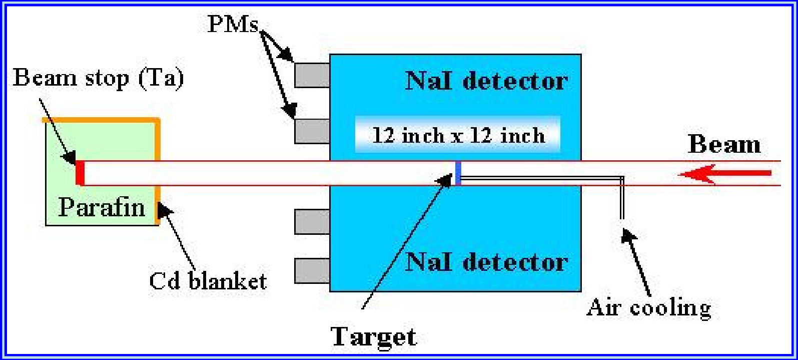
(α,γ) reactions: MAJOR PROBLEMS WITH BEAM-INDUCED BACKGROUND



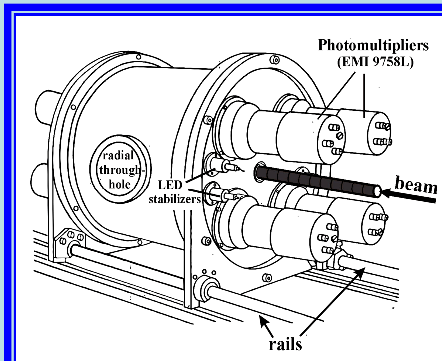
The 4π γ-summing method: The principle

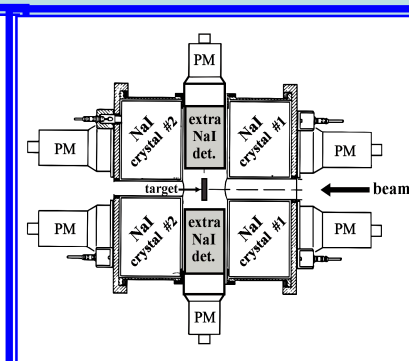


The 4π γ-summing method: The setup

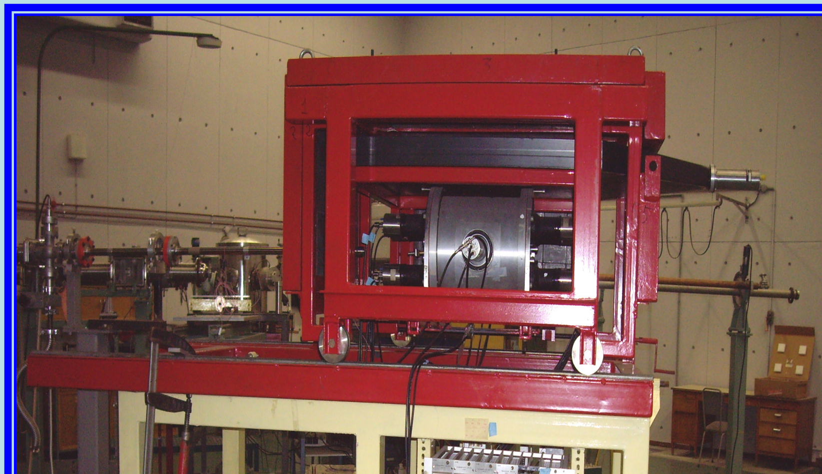


@ DTL-Bochum





@ INP-Demokritos



The 4π γ-summing method: The $^{92}Mo(\alpha,\gamma)^{96}Ru$ example

$^{92}Mo(\alpha,\gamma)\ ^{96}Ru$

$E_\alpha = 6 - 12$ MeV

$\xi = 398$ μgr/cm^2

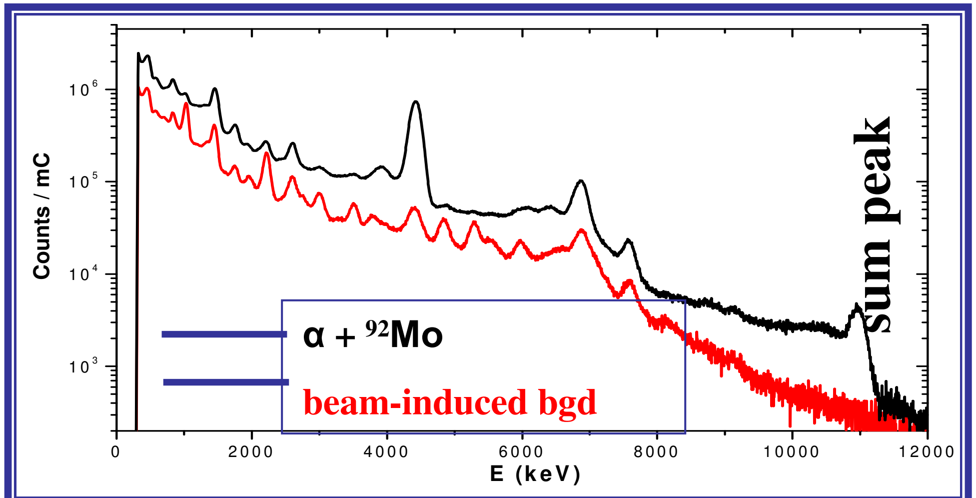
$\sigma = (Y/\varepsilon) * (1/\xi) * (A/N_A)$

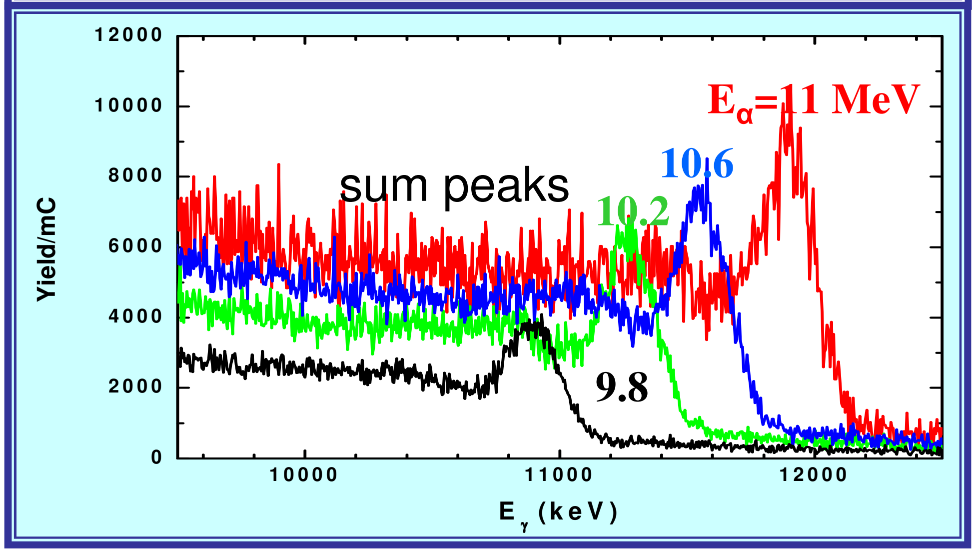
BUT $\varepsilon = f(E,M)$

Solutions (up to now):

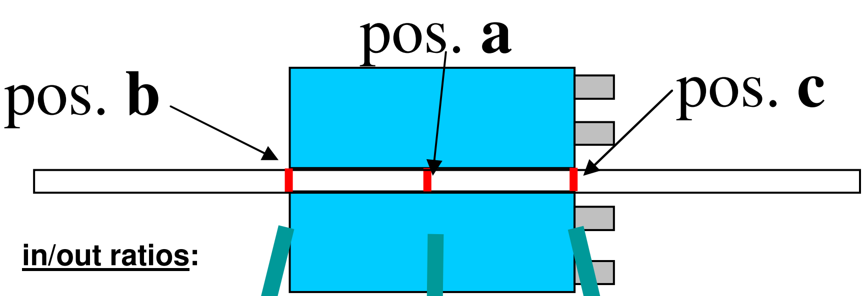
- Theoretical calculations
- Simulation

No "real" experimental solution





The 4π γ-summing method: Efficiency calculation



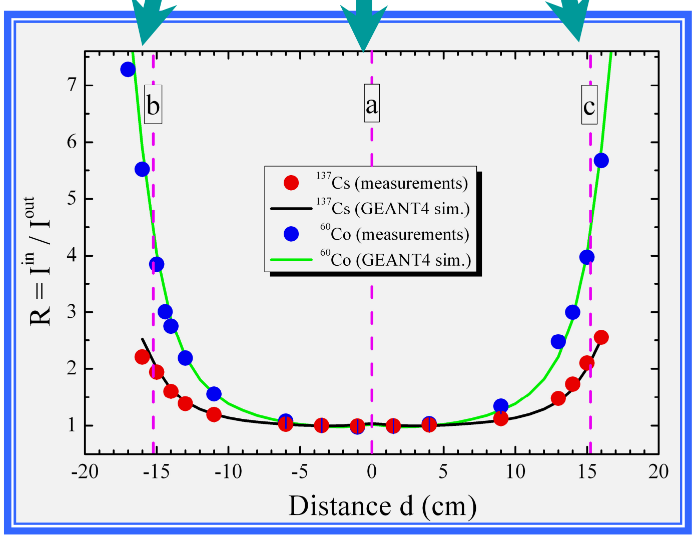
in/out ratios:

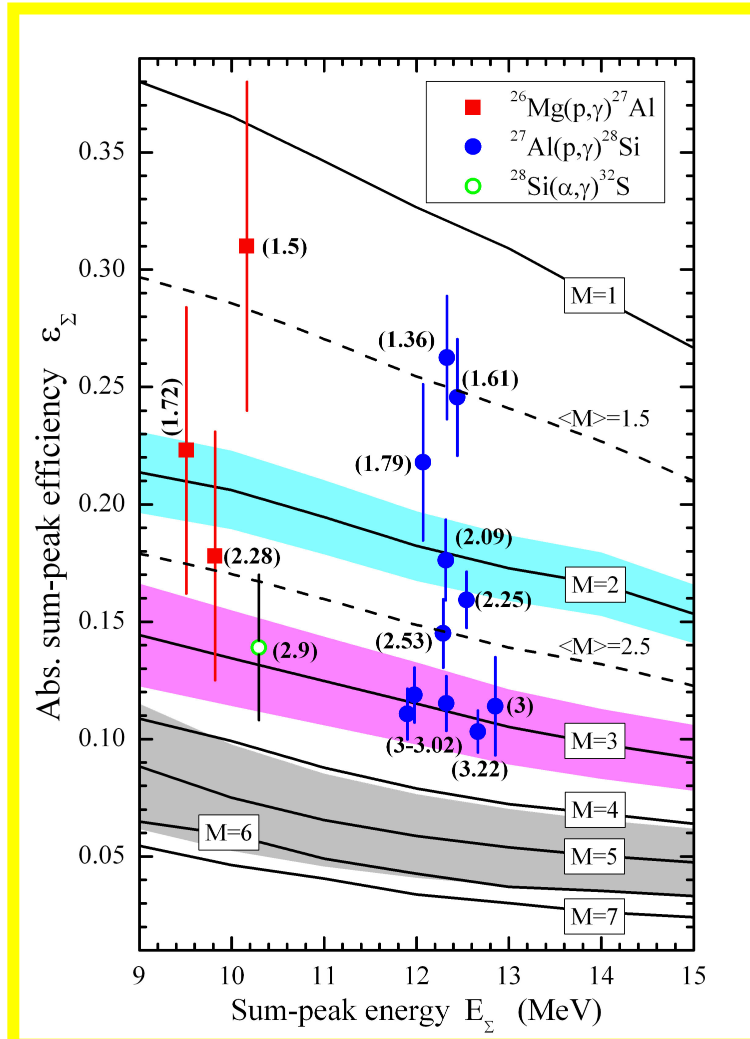
M=1 → R = 2

M=2 → R = 2 × 2 = 4

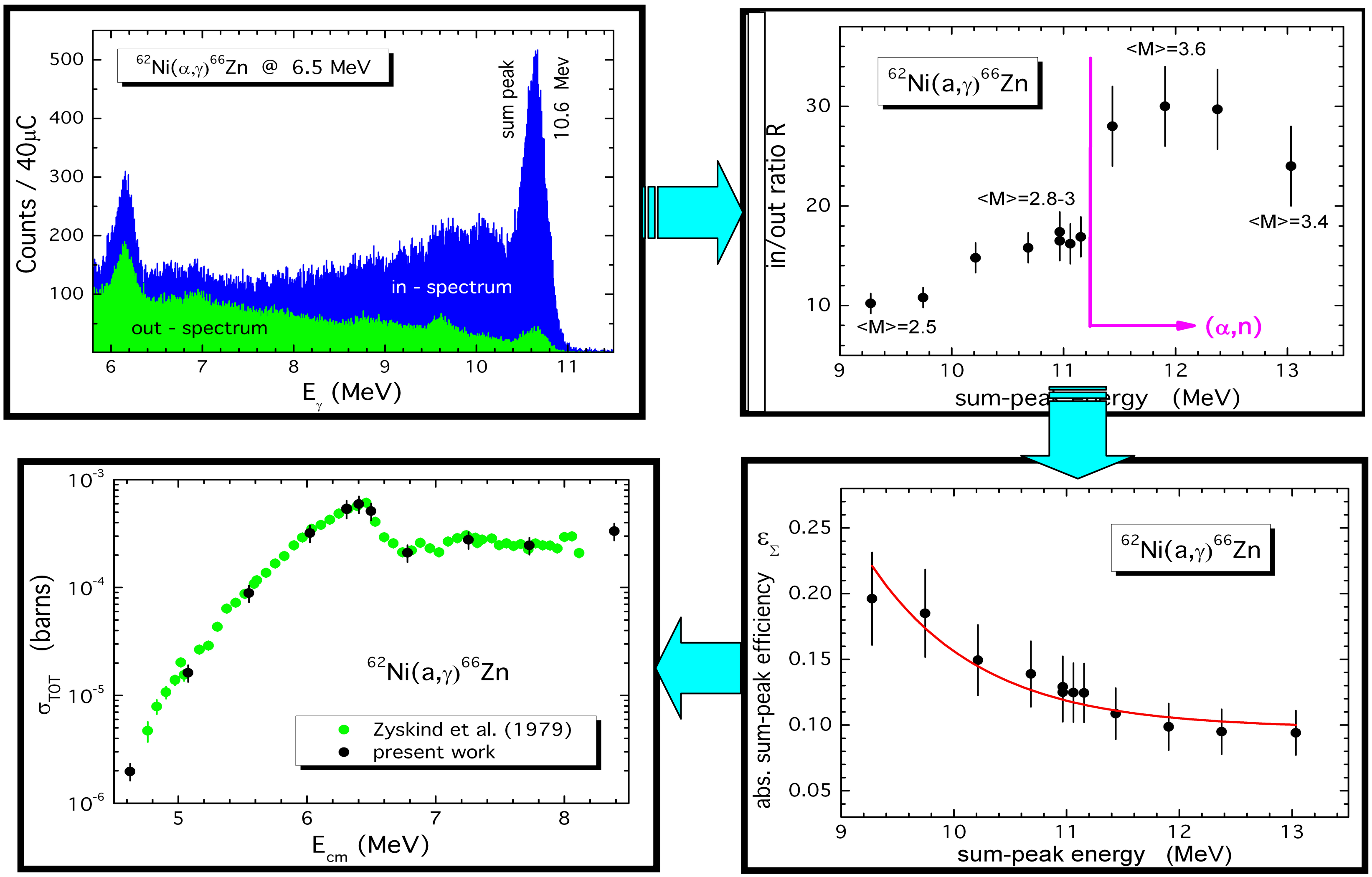
M=3 → R = 2 × 2 × 2 = 8

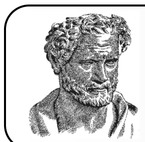
M=4 → R = 2 × 2 × 2 × 2 = 16



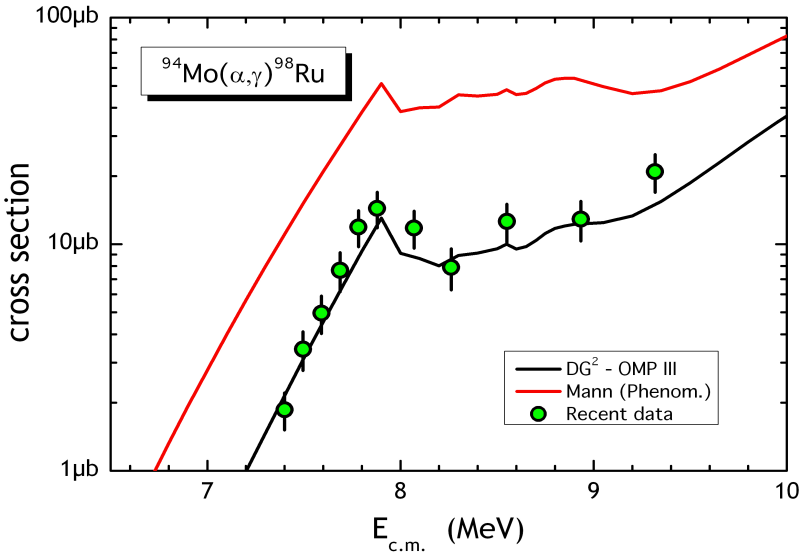


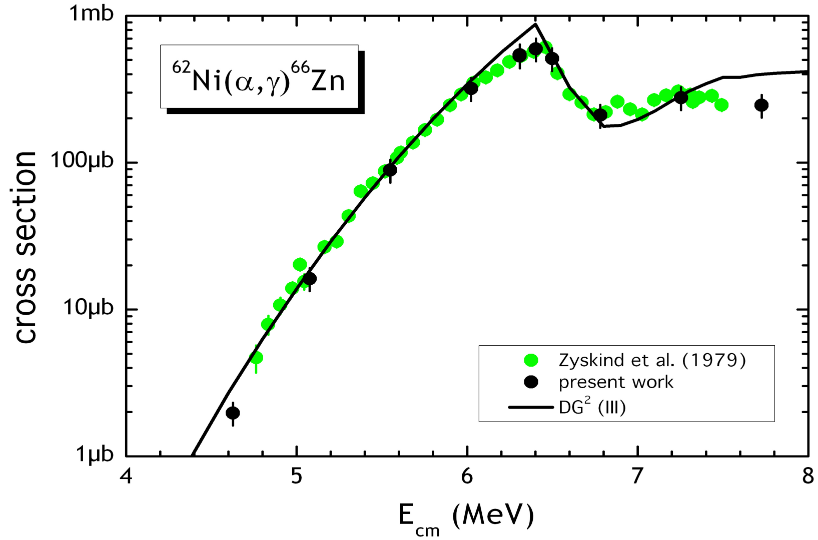
The 4π γ-summing method: Efficiency check with known reactions

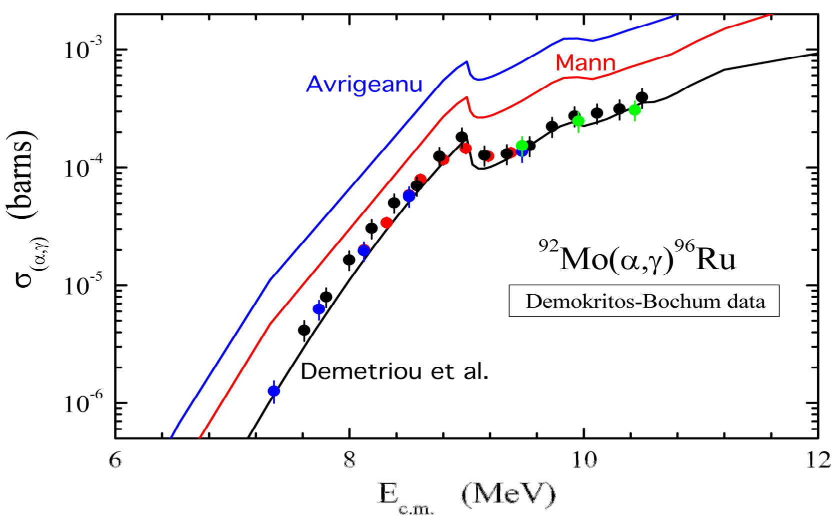


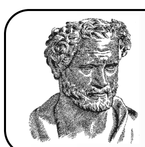


(α,γ) results: Comparison with theory





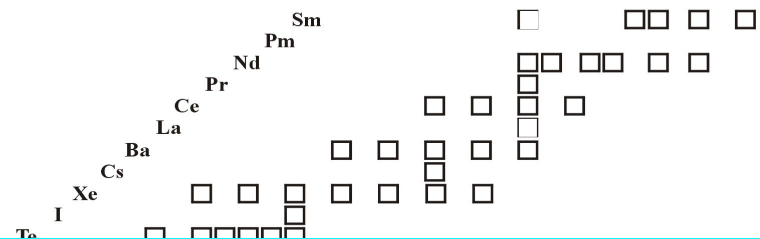




Alpha-particle capture reaction cross-section systematics

Measurements of low-energy (α,γ) reactions

(α,γ) cross section data: 10 isotopes



Summary

The global α-potential of Demetriou, Grama, Goriely seems to be working well in mass region A ≤ 100.

However very few data exist in higher mass regions where uncertainties are large.

But from experimental point of view such measurements are very challenging: need high current α beams + target development + efficient γ - arrays.

Perspectives: Explore the unstable mass regions using RIB's

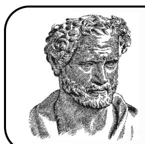
Capture reactions in inverse kinematics

	Projectile		Target				
Instead of	^{4}He	+	^{78}Kr	$\longrightarrow$	^{82}Sr	+	γ
we do	^{78}Kr	+	^{4}He	$\longrightarrow$	^{82}Sr	+	γ

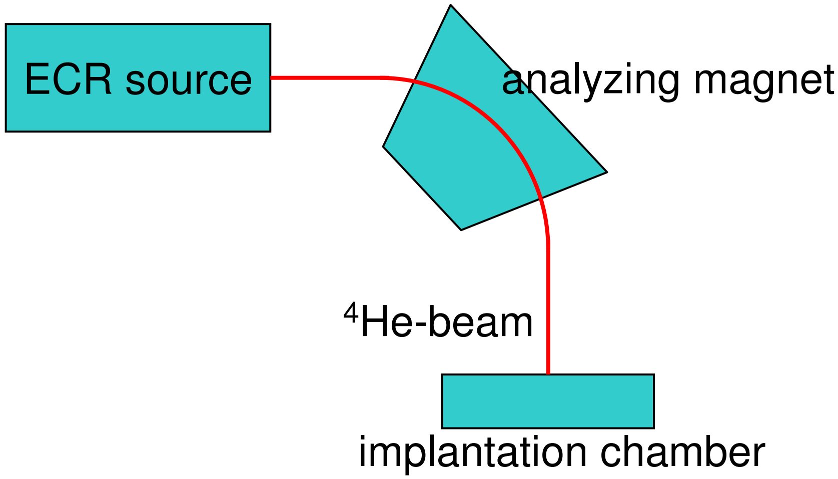
Experimental challenges

1. Target preparation
   - helium implanted targets
   - helium gas targets
2. Detection
   - γ (γ – spectroscopy)
   - ^{82}Sr (particle detection)

Detection apparatus ?



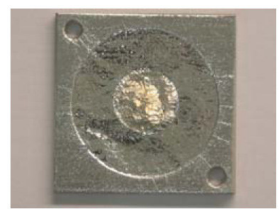
Capture reactions in inverse kinematics: The target



Implantation in Al-foils (50 µg/cm²)

Implantation energy 10-20 keV

Implantation fluence 10^{17}-10^{18} atoms/cm²

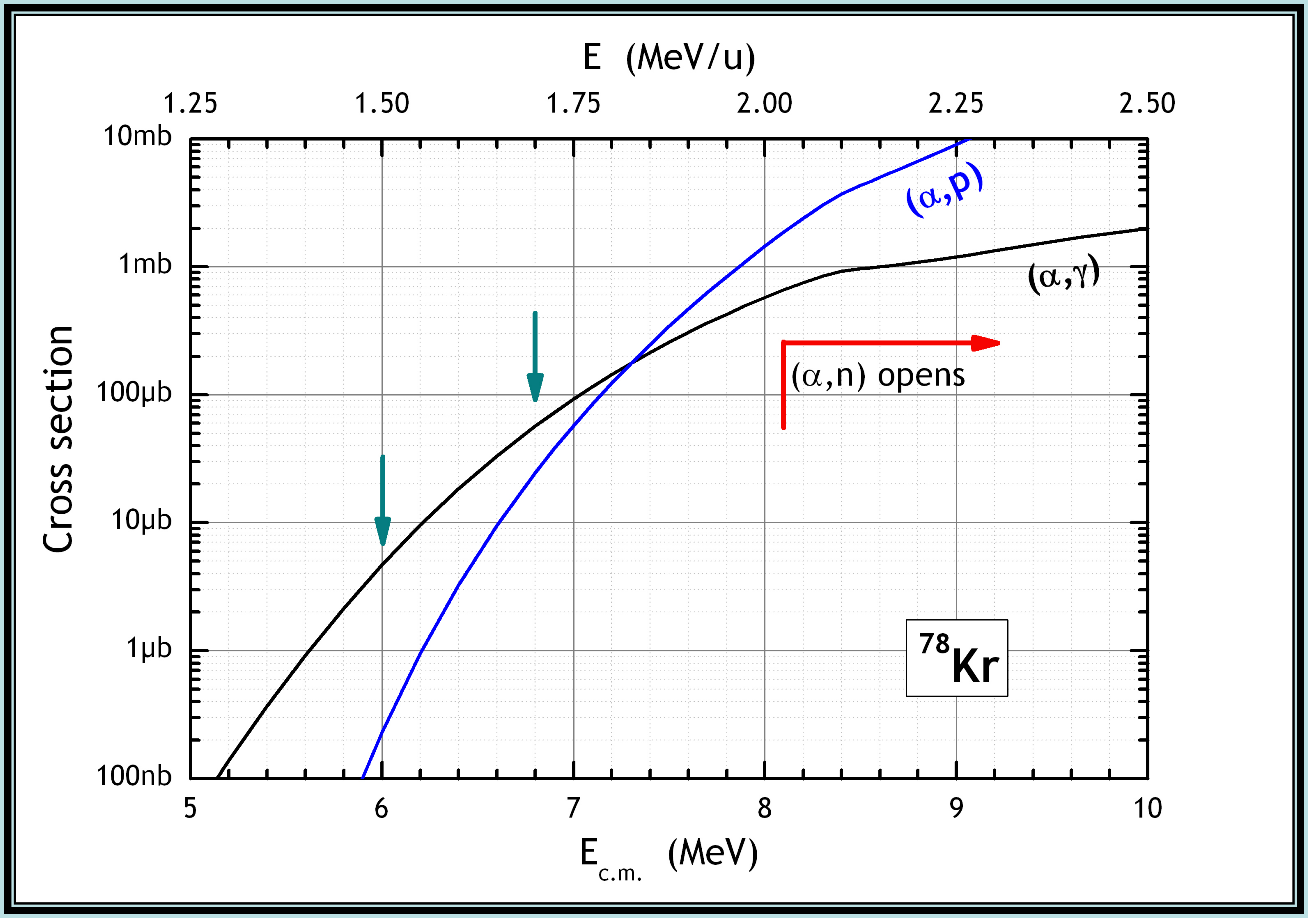


^{4}He
(≈ 10^{18} at/cm²)
implated in
^{27}Al
(≈50 µg/cm²)

e.g. 3µA ^{4}He-beam → 14 h needed for 10^{18} atoms/cm²

Capture reactions in inverse kinematics

The $^{4}He(^{78}Kr,\gamma)^{82}Sr$ case



Capture reactions in inverse kinematics: γ - spectroscopy

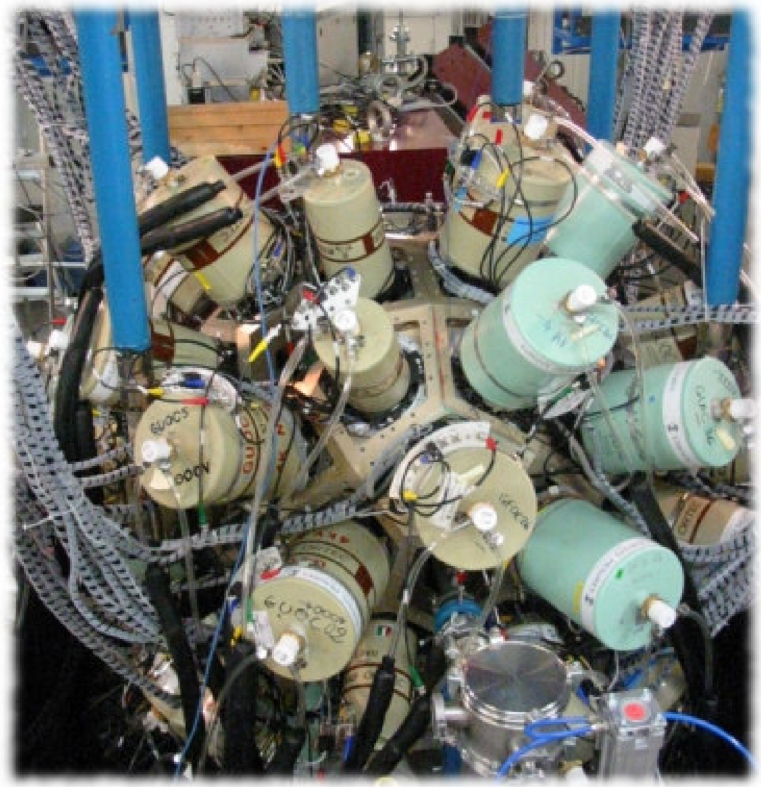
Experiment at Jyväskylä

$^{4}He(^{78}Kr,\gamma)^{82}Sr$

Beam: ^{78}Kr

Target: ^{4}He implanted Al-foils

Detection of γ's with JUROGAM



array of 43 Compton-suppressed HPGe detectors

[redacted]