Atomki nuclear astrophysics activities

Atomki:

Instititute for Nuclear Research,

Hungarian Academy of Sciences

ATOMKI associated partner of NAVI

Institut für Kernphysik
Institute for Nuclear Physics
Theoretical Nuclear Astrophysics
Prof. Dr. Gabriel Martinez Pinedo

Nuclear Astrophysics Virtual Institute
Spokesperson for the
Nuclear Astrophysics Virtual Institute

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Date 6 September 2014

Dear Dr. Fulop,

On Behalf of the Nuclear Astrophysics Virtual Institute (NAVI) it is a pleasure for me to welcome the ATOMKI nuclear astrophysics group as associated partner.

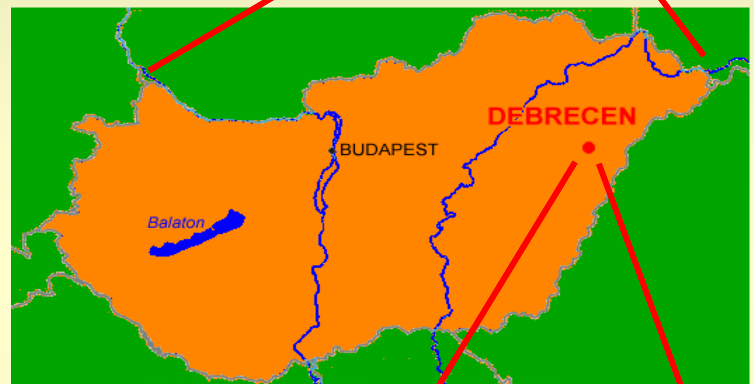
The Nuclear Astrophysics Virtual Institute (NAVI) was setup on September 2011 funded by the Helmholtz Association with the objective of coordinate the nuclear astrophysics activities in Germany. It has been recently very positively evaluated by an international panel and our funding is currently secured till August 2016. NAVI coordinates the nuclear astrophysics activities of three Helmholtz Centers (GSI, FZJ, HZDR), five different German universities (Bonn, Darmstadt, Frankfurt, Giessen, Würzburg), the Frankfurt Institute for Advanced Studies, the Max-Planck Institut für Kernphysik Heidelberg with colleagues from France (GANIL and IPHC), Switserland (Basel University) and the United States (JINA). It combines theoretical and experimental research focused on two main topics: stellar hydrogen and helium burning and r-process nucleosynthesis. The experimental research includes work on stellar reaction cross sections at underground laboratories like the Felsenkeller in Dresden as well as at the fore-front radioactive ion-beam facilities in Europe (GSI and GANIL) and in the US (NSCL at MSU). In addition to ATOMKI we have also as associated partners the nuclear astrophysics groups at the University of Edinburgh and ITEP (Moscow) and the Center for Nuclear Astrophysics in Shanghai that aims to coordinate Nuclear Astrophysics in China in similar way that NAVI does in Germany.

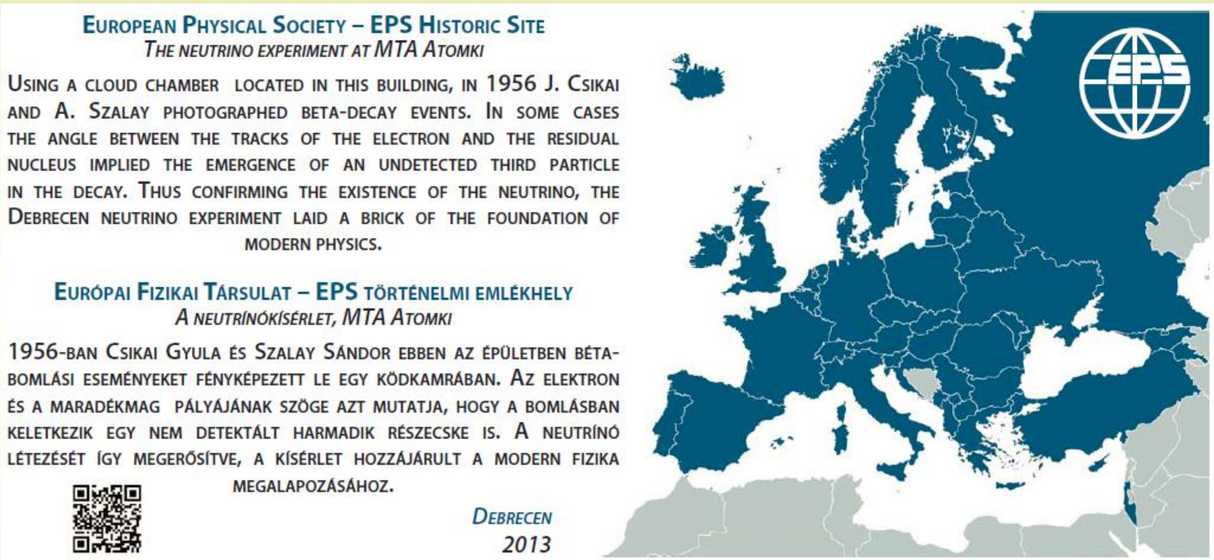
NAVI will benefit from the p-process expertise of ATOMKI and we look forward to many successful collaborations.

Sincerely,

Gabriel Martínez Pinedo

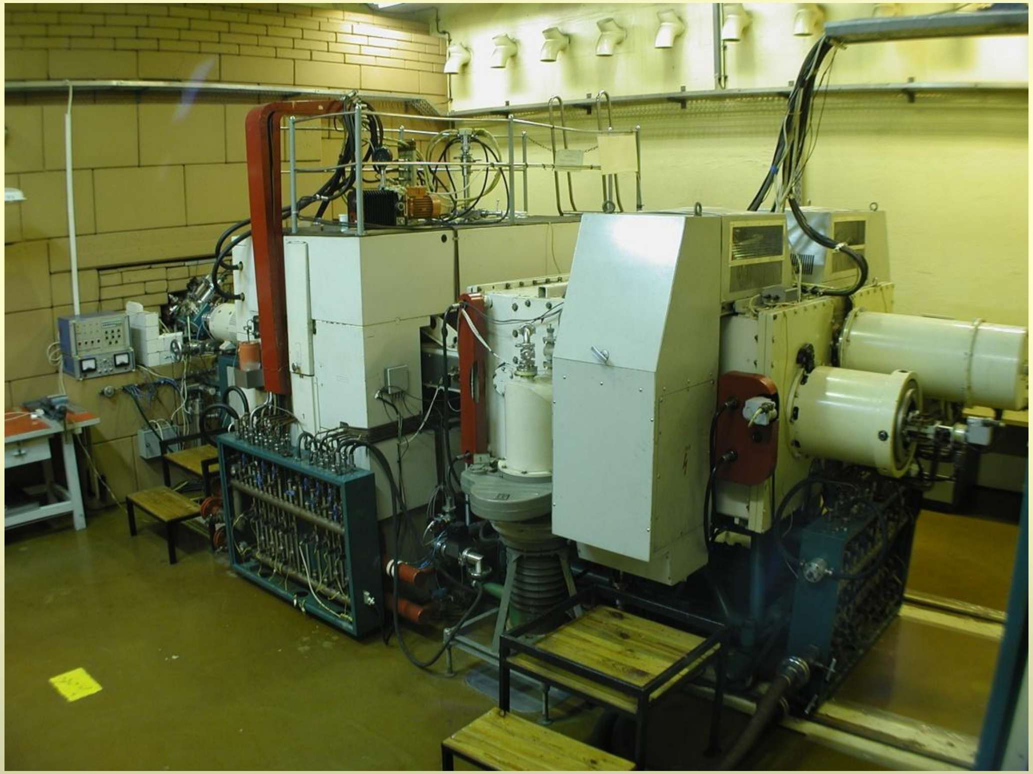
Atomki, Debrecen, Hungary





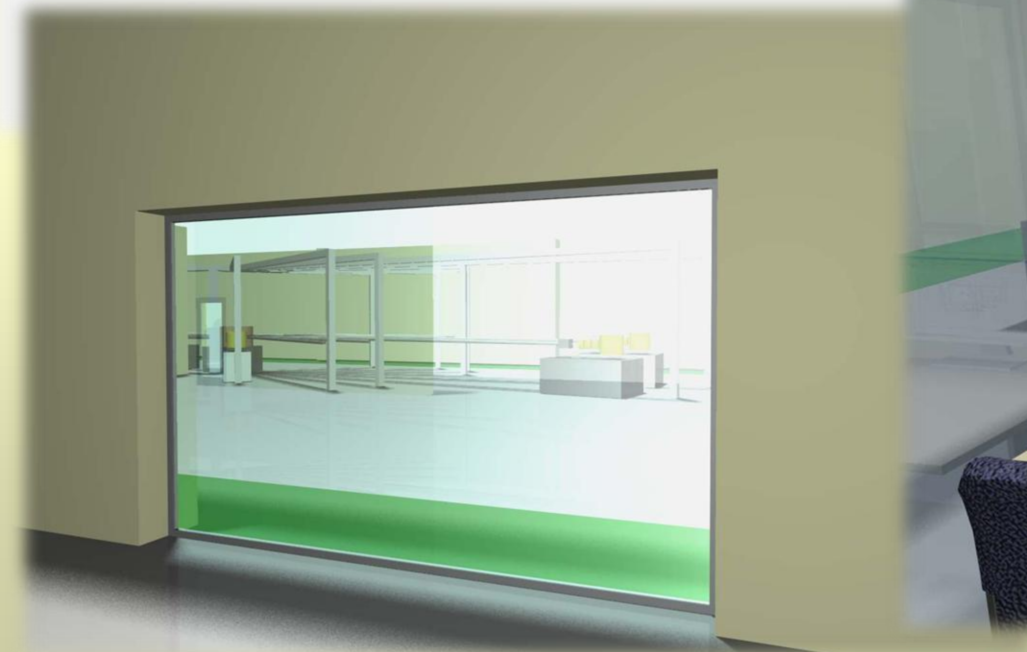
ATOMKI Accelerator Centre

- **Running:**
  - Compact cyclotron K=20
  - 5MV electrostatic accelerator
    - Microbeam (OXFORD)
  - 1MV electrostatic accelerator
- **Recently installed:**
  - Accelerator Mass Spectrometer
    - (ETH Zürich + Isotoptech SME)
- **Under installation:**
  - 2MV tandem (HV)

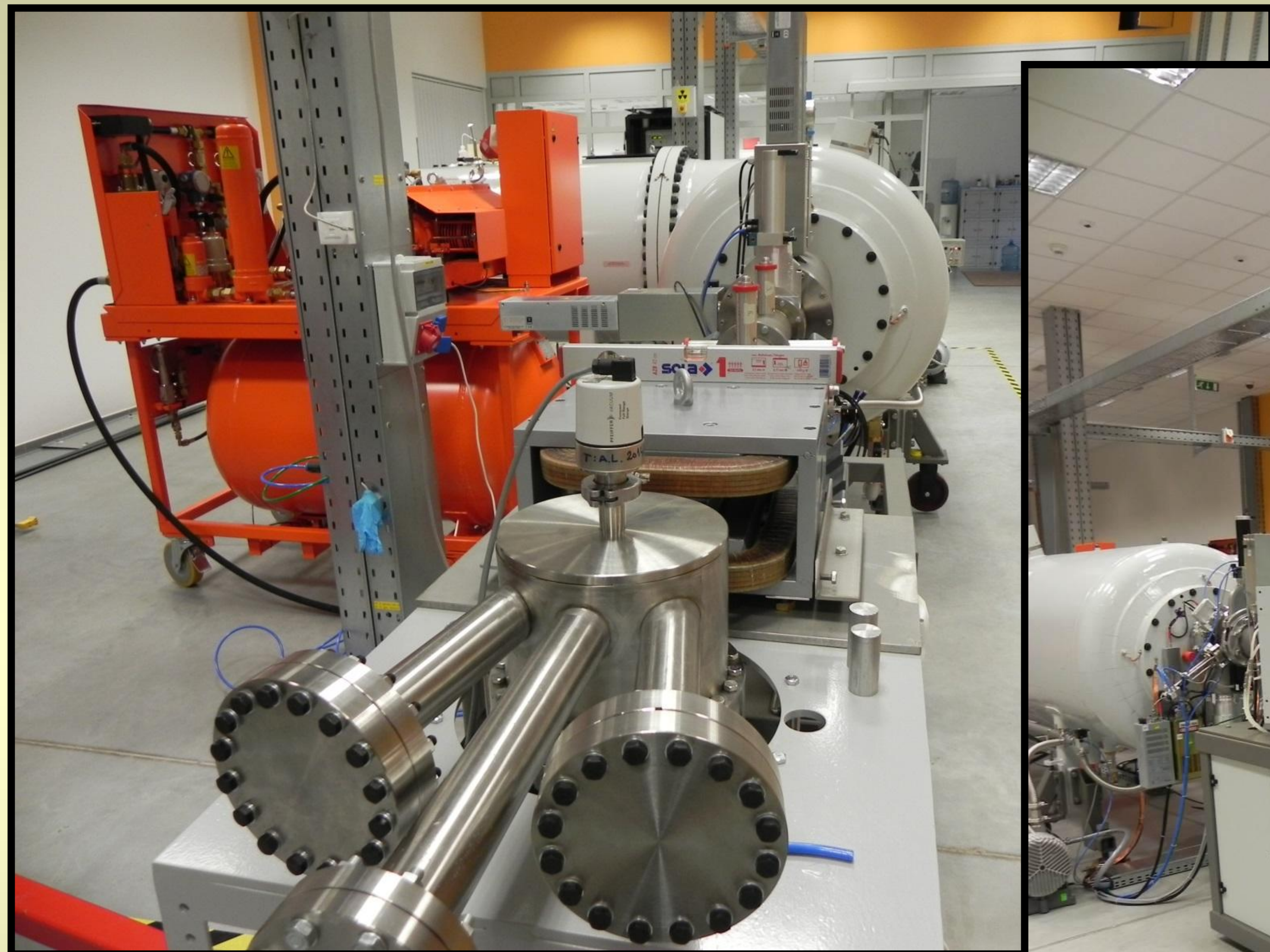


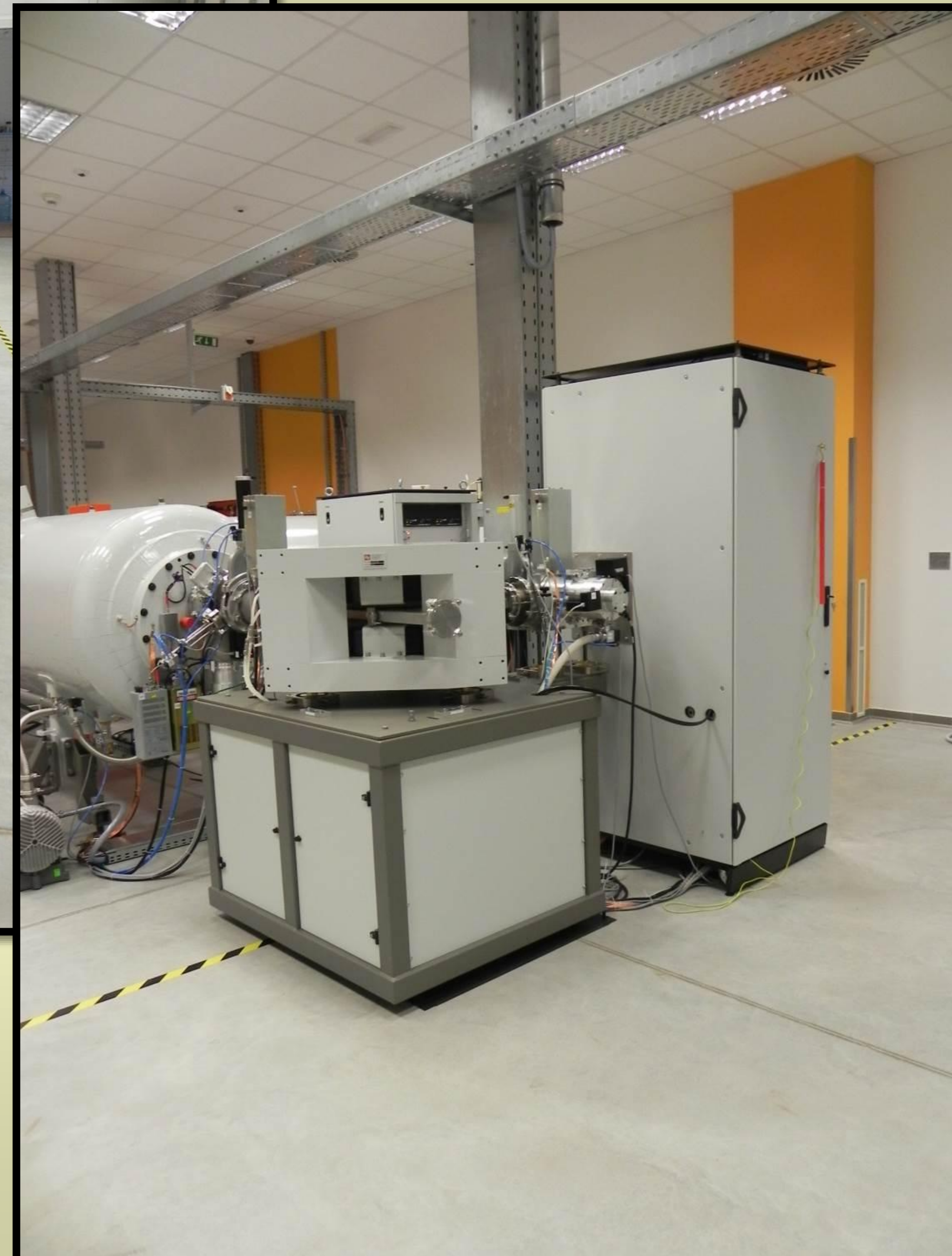
AMS system for ^{14}C: archaelogy, climate, medical applications

2MV Tandem




1/2 TON

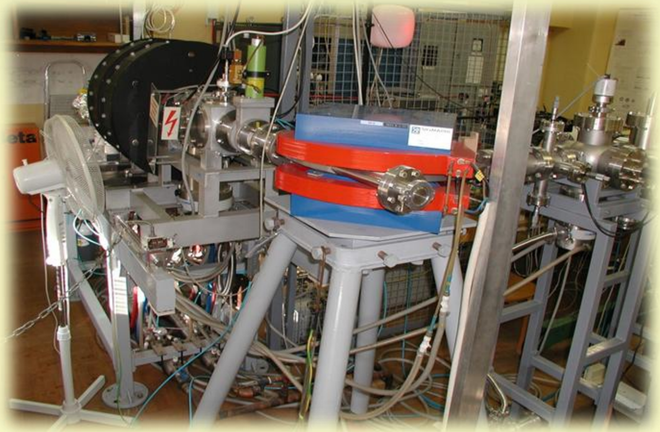




Other facilities

- Standalone ECR
- ESCA
- SNMS/XPS
- Hot chemistry lab.
- Isotope separator
- Mini-PET camera
- ^{60}Co irradiation
- TIER-3 GRID

atomic physics



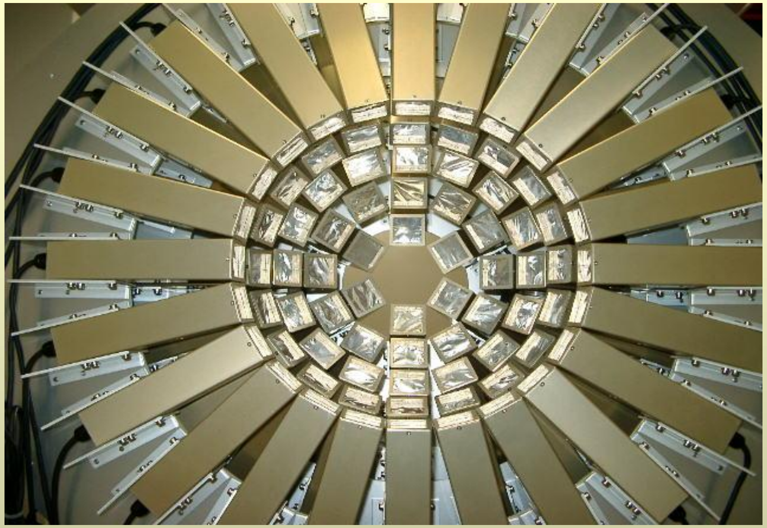
surface science

computing

radiochemistry

Atomki astrophysics topics

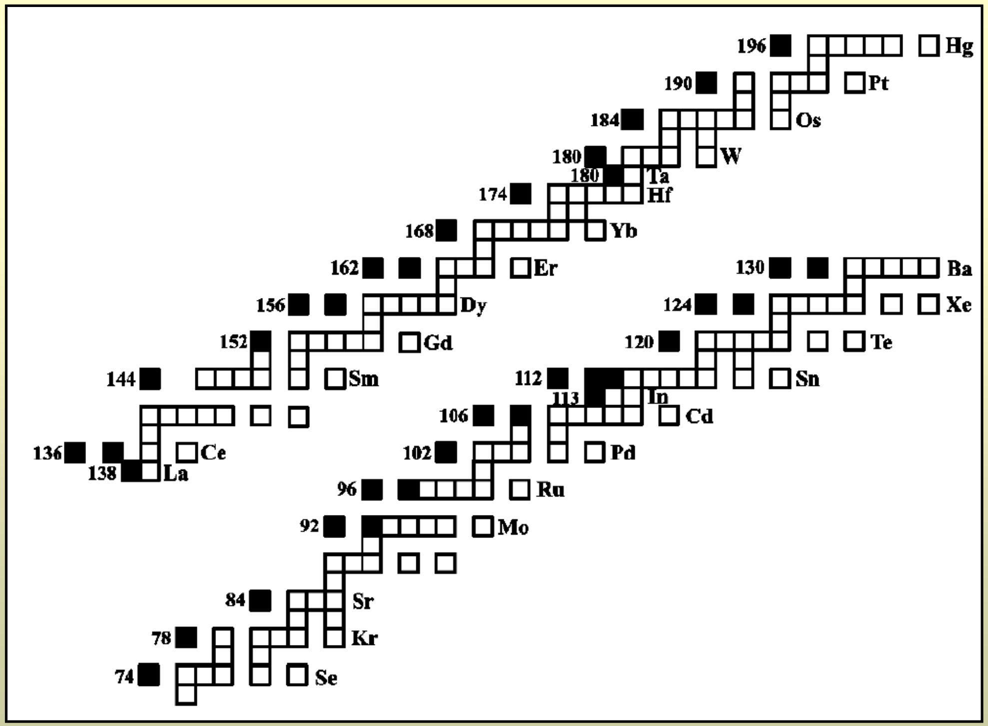
- LUNA related
  - Same experiments at higher energies eg $^{3}He(\alpha,\gamma)^{7}Be$
  - Different experiments at higher energies eg $^{6}Li(^{3}He,d)^{7}Be$
  - Auxiliary experiments (half-lives, stopping power)
  - Feasibility studies (target properties)

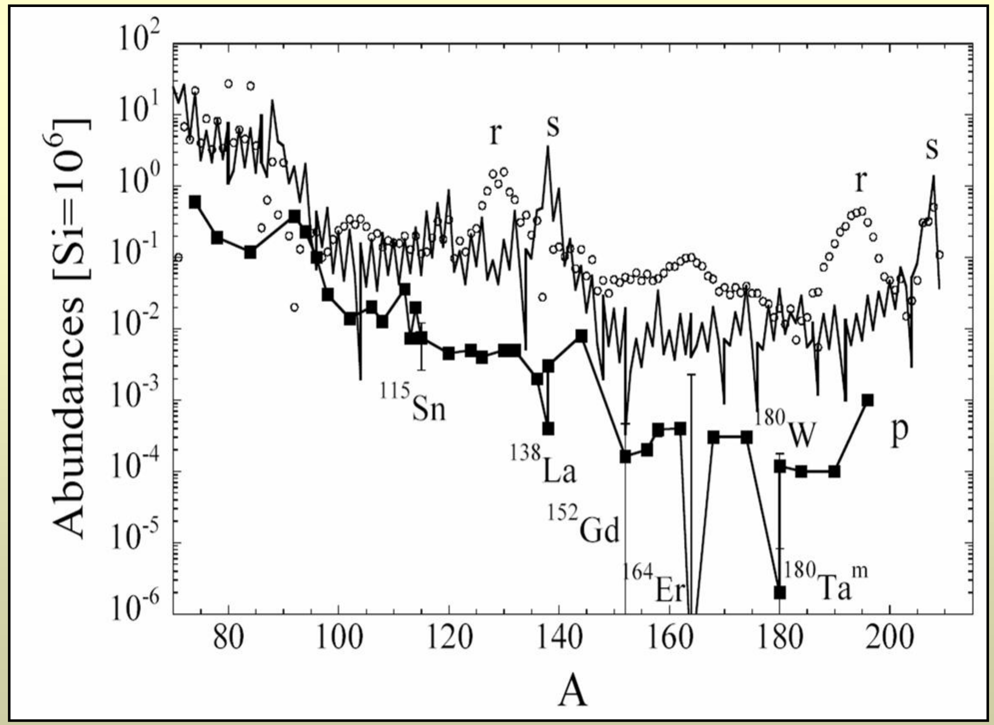


- RIKEN RIB related
  - SAMURAI: Coulomb dissociation
  - BRIKEN: beta delayed neutron emission
  - Target chamber, detector development
- P-process studies (ERC + Eurogenesis + NAVI)

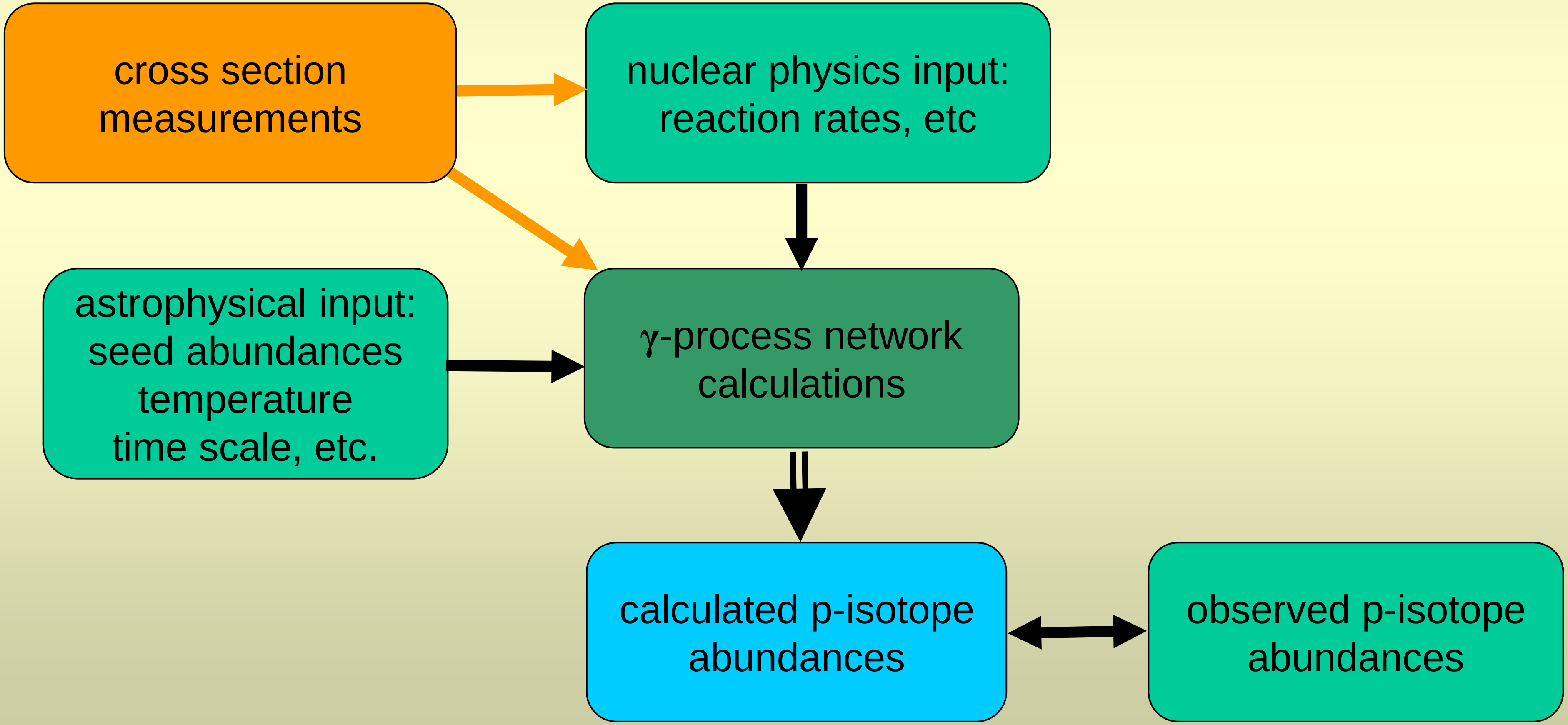
Heavy element nucleosynthesis: a weak p-branch

- s- & r-processes → 99% of abundances
- p-process → 1%





γ-process model calculations



Input parameters of the statistical model

level density

masses, etc.

optical model potential

cross section measurements

nuclear physics input: statistical model calculations

astrophysical input: seed abundances temperature time scale, etc.

γ-process network calculations

calculated p-isotope abundances

observed p-isotope abundances

- **Large networks**
- **Lack /too many of key reactions**

→ Trend investigations

→ Global studies

More data is needed

ATOMKI for p-process

ATOMKI aims:

Improve nuclear inputs for the gamma-process

- Comprehensive analysis of nuclear data
  - Elastic alpha scattering
  - Alpha- and proton- induced reactions
- Extension of reaction database for heavy nuclei

Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

p-process data viewer

Enter your isotope of interest or click it on the chart of nuclides below (drag the chart with your mouse)

Isotope: 70Ge all reactions

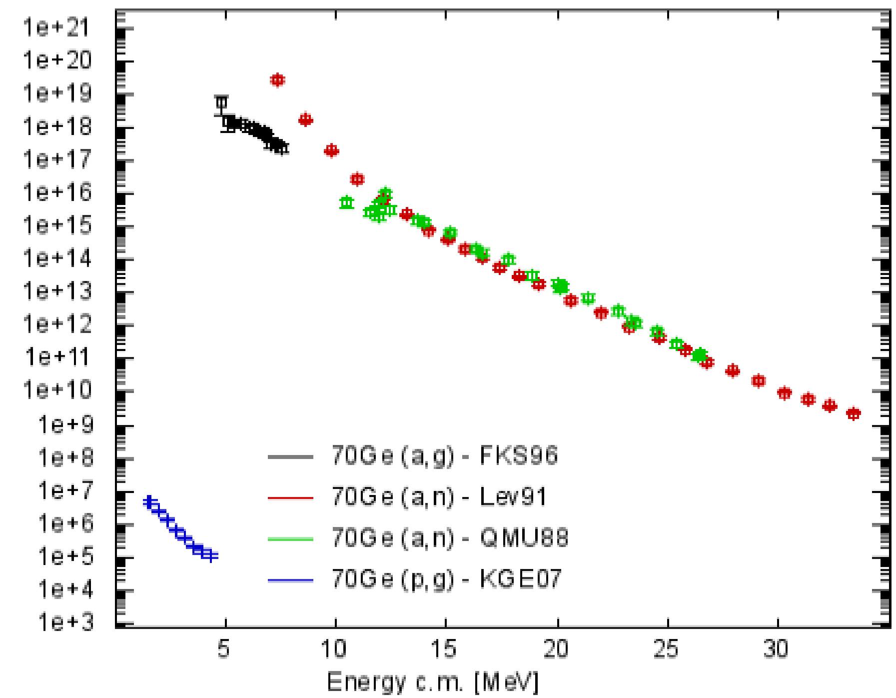
zoom out zoom in

Gamow window (T9=2-3): 3777.3 - 7807.6 MeV

^{70}Ge(*,)

^{70}Ge

Cross section [barn]
S-factor [MeV barn]



T. Szücs and I. Dillmann

(p,γ) vs. (α,γ)

(p,γ): Higher cross sections, lower mass range

– Gamow window can be reached (no extrapolations)

– Highly enriched targets available

– Test ground for new methods (ESR, Coulomb breakup, …)

– More data available (trend investigations)

(α,γ): lower cross sections, higher mass range

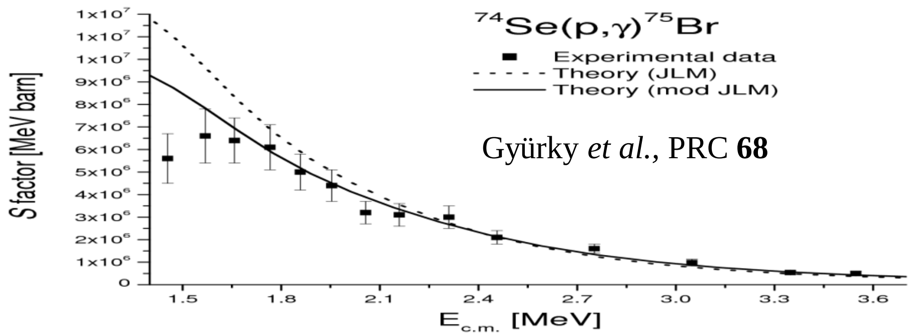
– Experiments above Gamow window

– Expensive targets

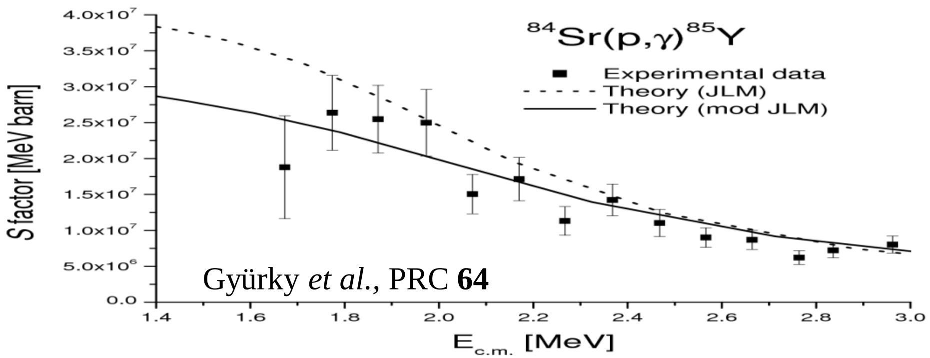
– Auxiliary α-potential studies to improve global potentials

An improved proton optical potential

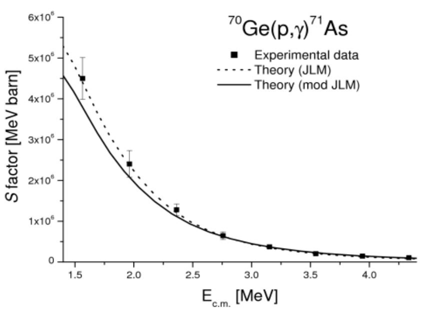
Increased imaginary strength by 70%

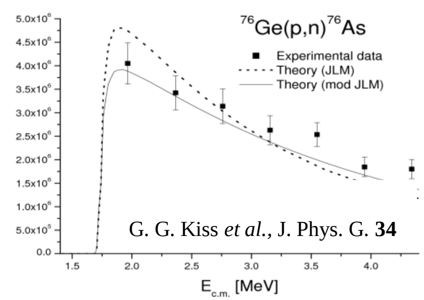


Gyürky *et al.*, PRC **68**

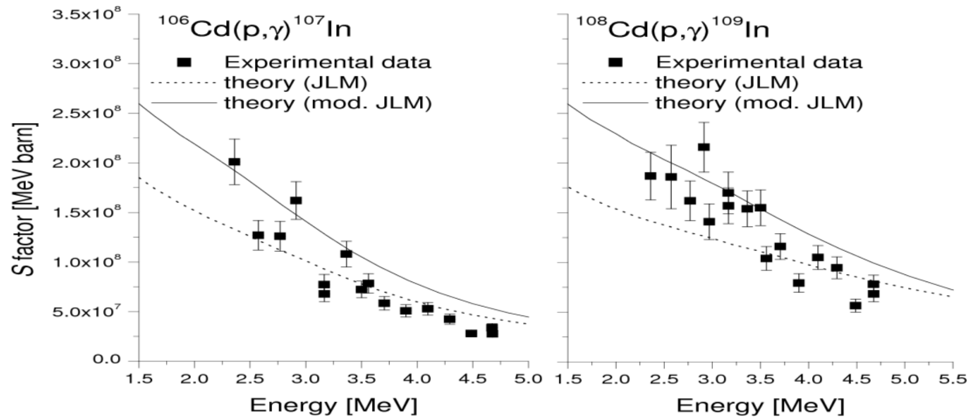


Gyürky *et al.*, PRC **64**

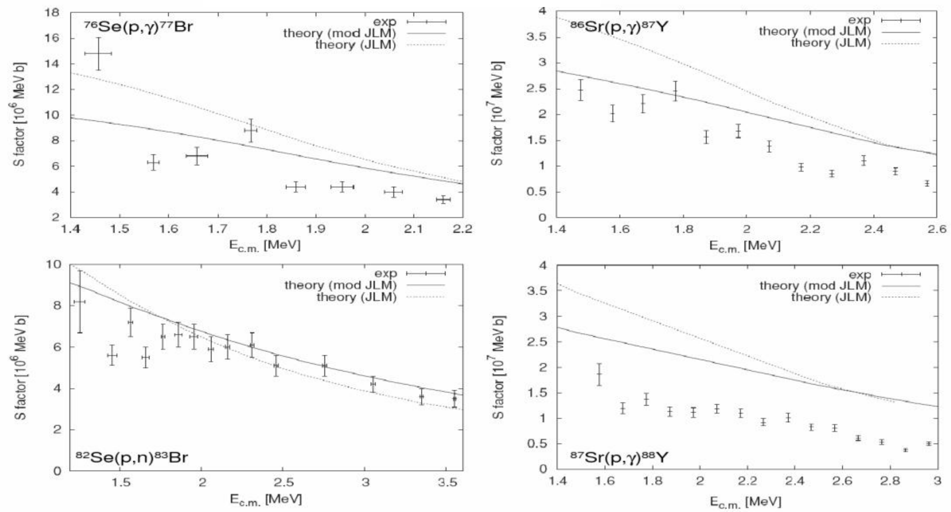




G. G. Kiss *et al.*, J. Phys. G. **34**



Gyürky *et al.*, J. Phys. G **34**



G. G. Kiss *et al.*, PRC **76**

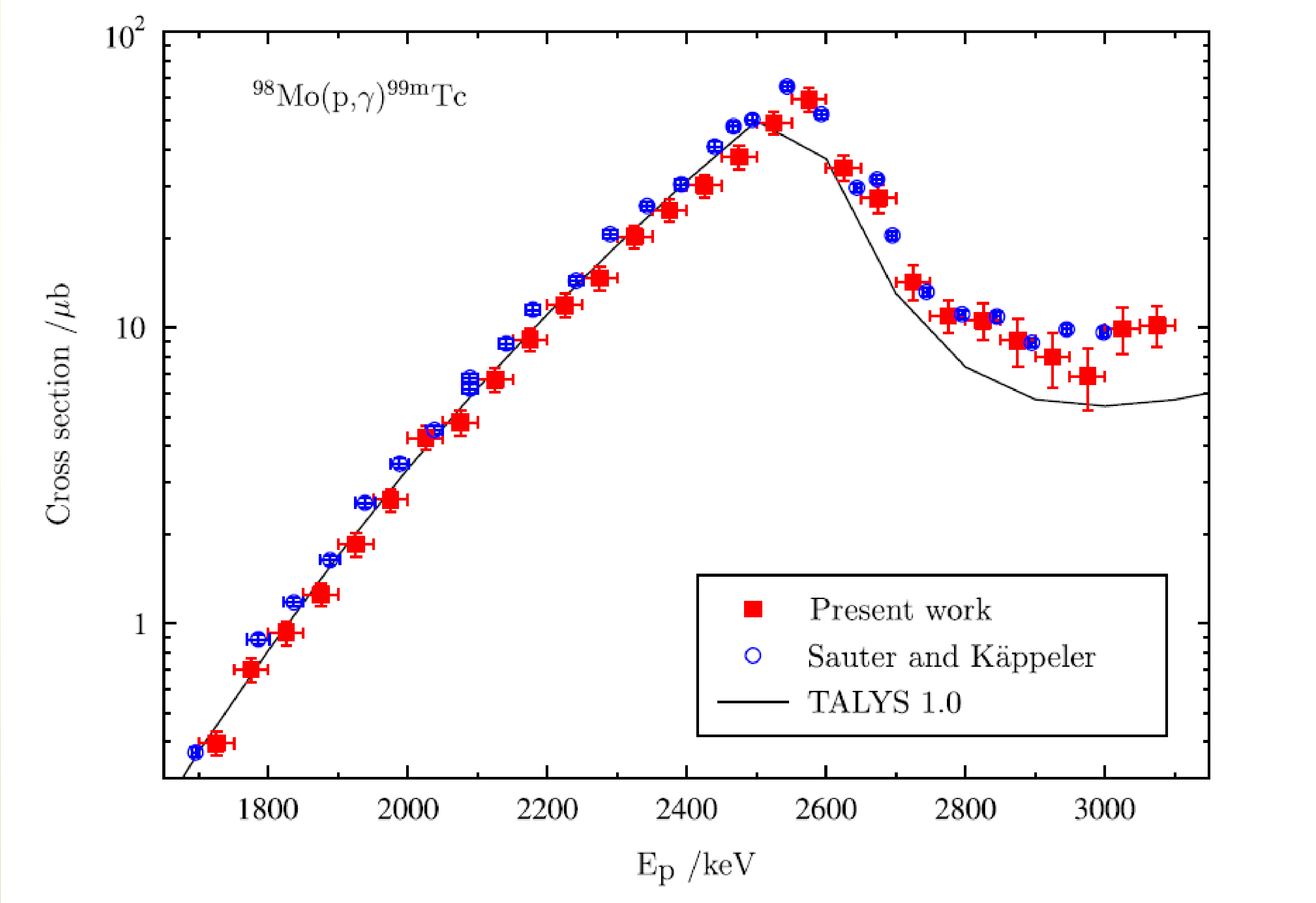
^{92}Mo(p,γ) thick target experiment

- Low mass: statistical model valid?
- Experiment of the Kappeler group: scattered data
- Target preparation problems

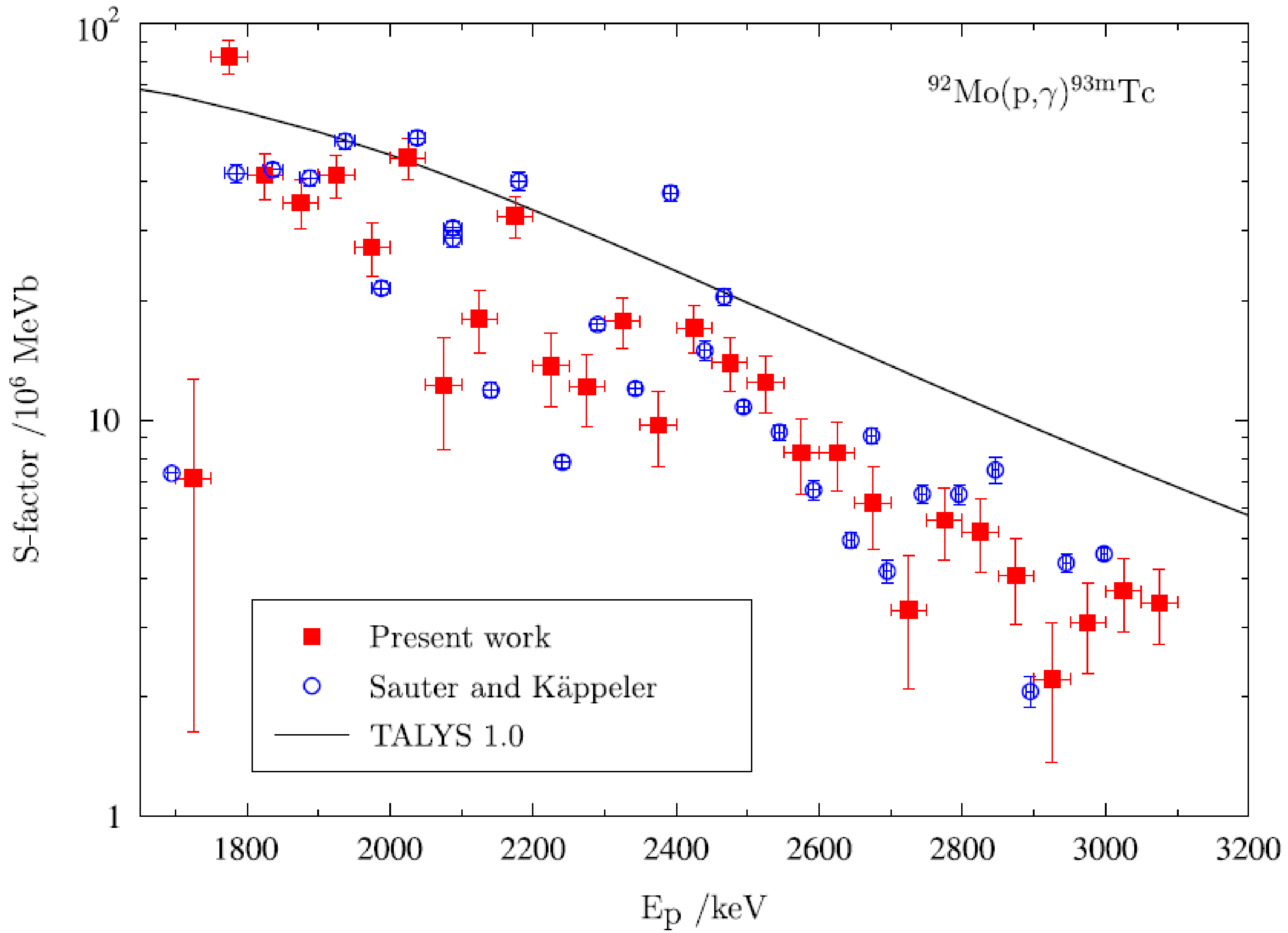
Reaction	Produced isotope	Half-life [hour]	Gamma-energy [keV]	Gamma-intensity [%]
^{92}Mo(p, γ)	^{93g}Tc	2.75 ± 0.05	1363	66.2 ± 0.6
			1477	8.67 ± 0.47
			1520	24.4 ± 0.8
^{92}Mo(p, γ)	^{93m}Tc	0.725 ± 0.017	392	58.9 ± 0.9
			2645	13.3 ± 0.6
^{98}Mo(p, γ)	^{99m}Tc	6.0067 ± 0.0005	141	89.0 ± 0.3

Gyürky et al.: NPA 922 (2014)

$^{92}Mo(p,\gamma)$ thick target experiment

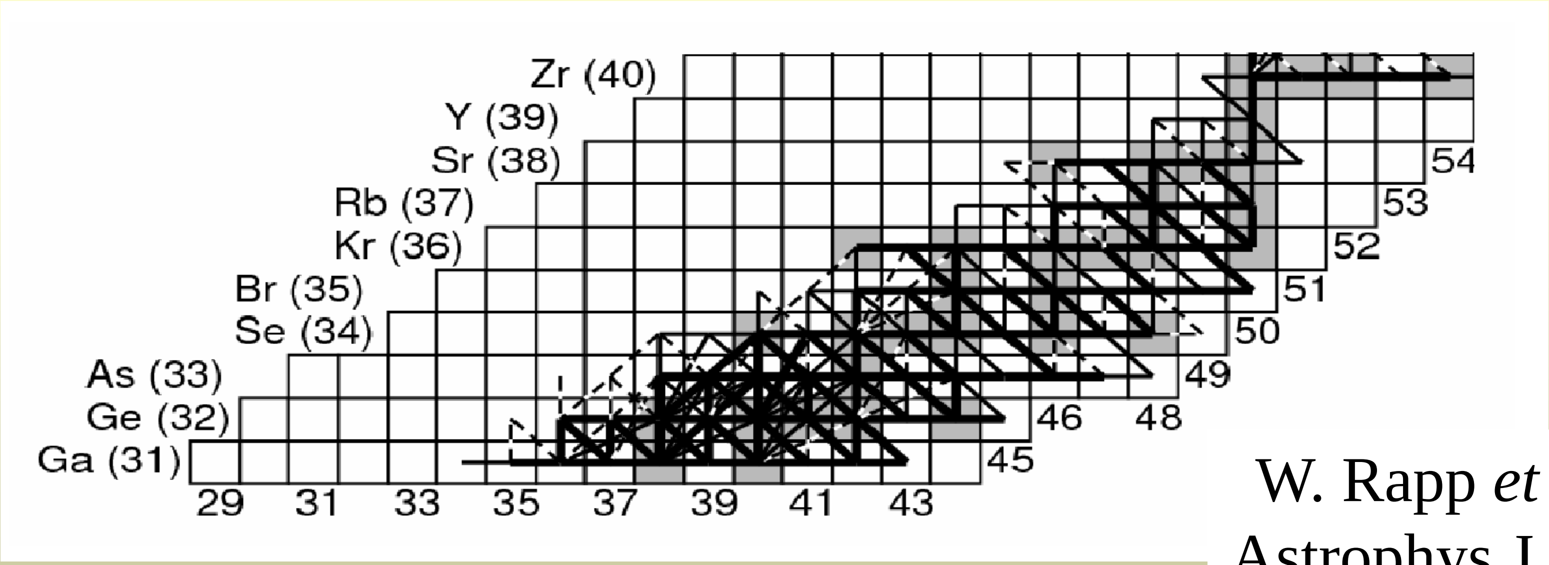


$^{92}Mo(p,\gamma)$ thick target experiment



(p,n) reactions

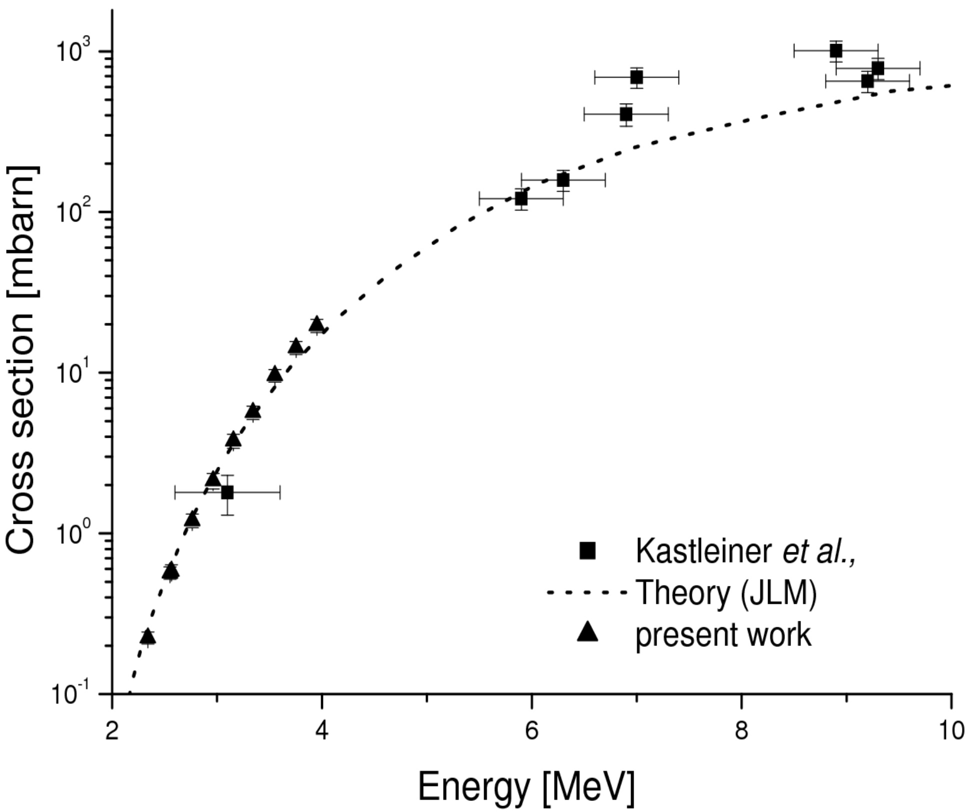
- Direct role in heavy element nucleosynthesis
- Can be used to disentangle p- and γ-strength
- Can be combined with (p,γ) activation experiments

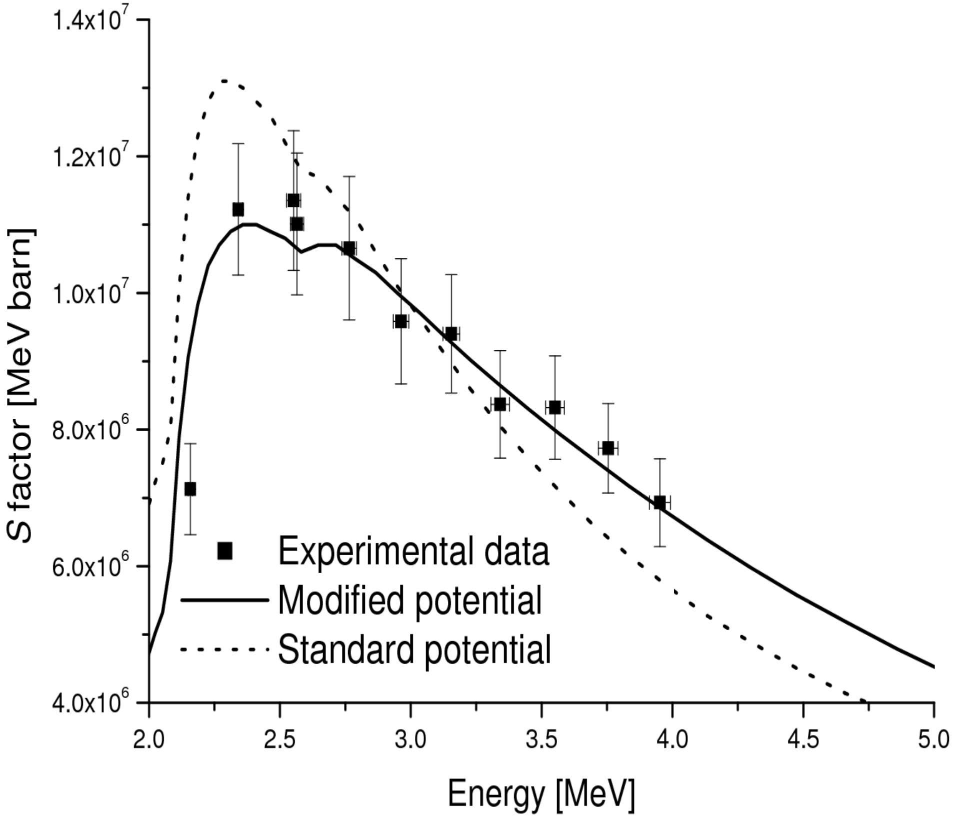


W. Rapp *et al.*, Astrophys J. **653**

Example: ^{85}Rb(p,n)^{85}Sr

G.G. Kiss et al: PRL **101,** 191101 (2008)





(p,γ) vs. (α,γ)

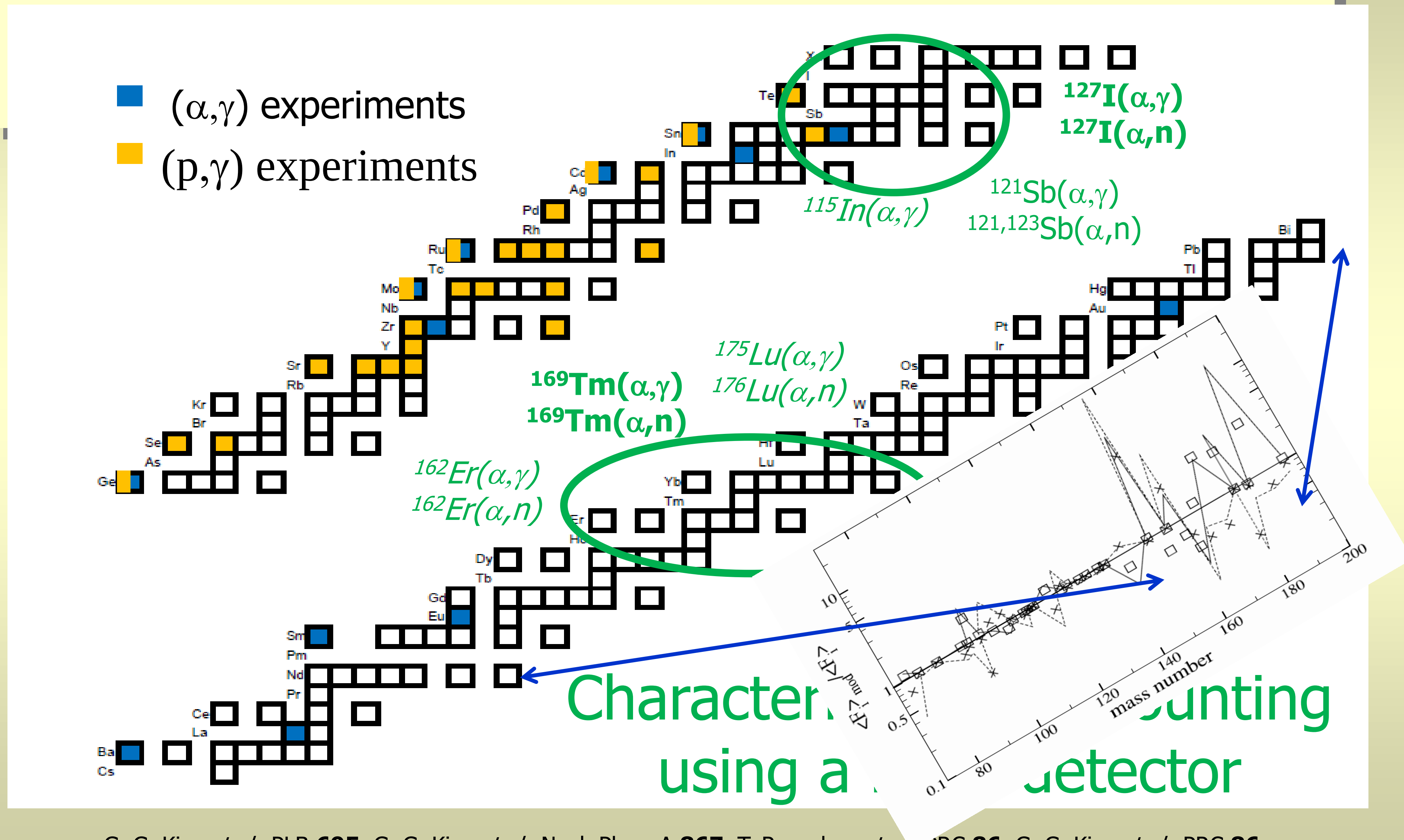
(p,γ): Higher cross sections, lower mass range

- Gamow window can be reached (no extrapolations)
- Highly enriched targets available
- Test ground for new methods (ESR, 4π summing…)
- More data available (trend investigations)

(α,γ): lower cross sections, higher mass range

- Experiments above Gamow window
- Target problems
- Auxiliary α-potential studies to improve global potentials
- (α, n), (α, p) channels also important

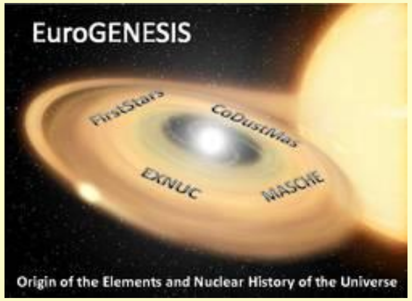
Available sub-Coulomb database



G. G. Kiss *et al.*, PLB **695,** G. G. Kiss *et al.*, Nucl. Phys. A **867,** T. Rauscher *et al.*, PRC **86,** G. G. Kiss *et al.*, PRC **86**

Activation method: serious limitations

- Poorly known nuclear parameters (branching, $T_{1/2}$)
  - Ancillary exp.
- Too long halflife
  - AMS: ^{142}Nd(α,γ)^{146}Sm ($T_{1/2}=10^8$ y) @ANL
- Inadequate branching ratios (no γ-transition)



Characteristic X-ray detection might help

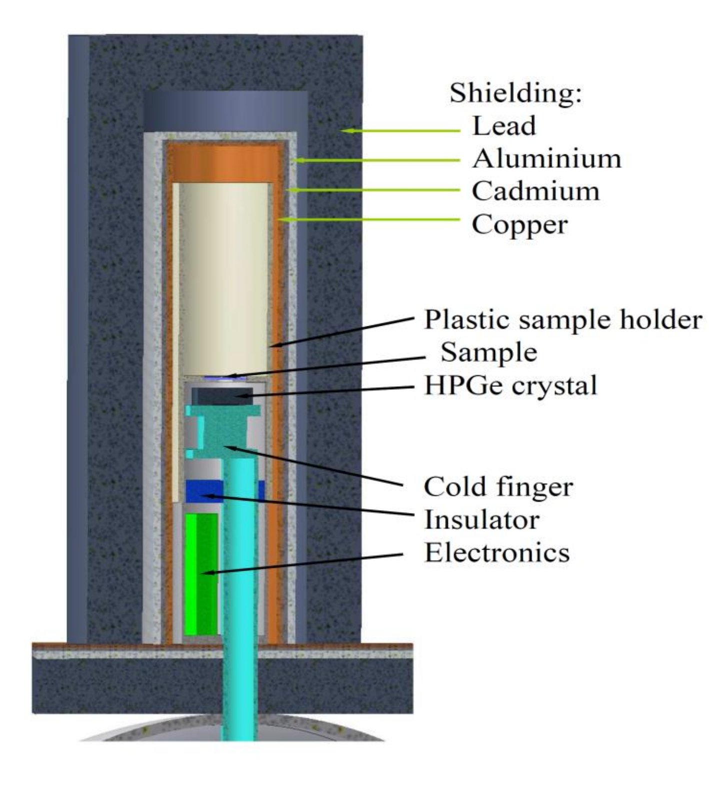
Case study: $^{169}Tm(\alpha,\gamma/n)^{173/172}Lu$

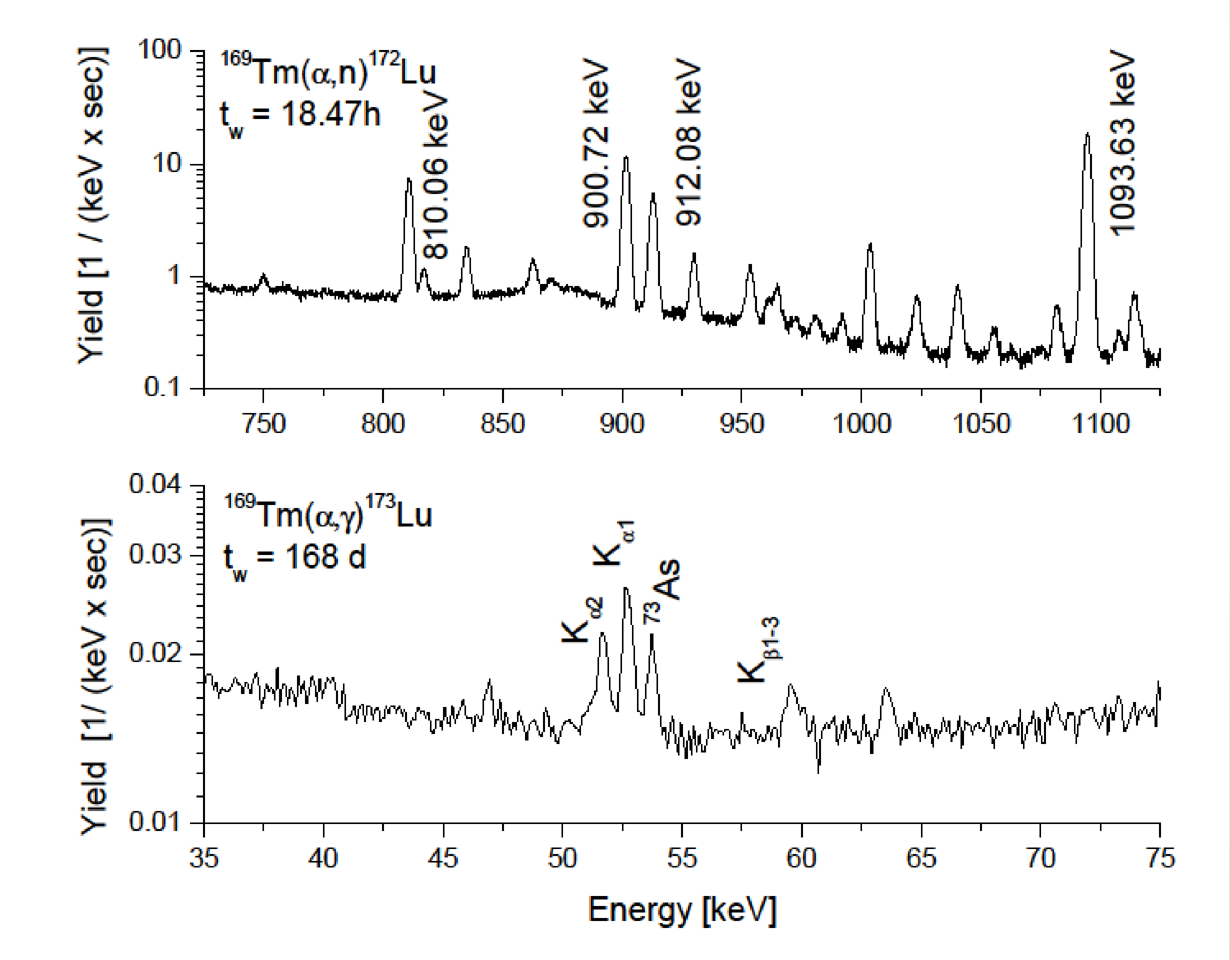
decay characteristics:

Residual nucleus	Decay mode	Half-life [d]	Energy [keV]	Relative intensity per decay [%]
^{173}Lu	ϵ 100%	500 ± 3.65	51.35 ($K\alpha_2$)	43.8 ± 1.4
			52.39 ($K\alpha_1$)	76.3 ± 2.4
^{172}Lu	ϵ 100%	6.7 ± 0.04	51.35 ($K\alpha_2$)	31.5 ± 0.9
			52.39 ($K\alpha_1$)	54.9 ± 1.5
			810.06	16.6 ± 0.9
			900.72	29.8 ± 1.3
			912.08	15.3 ± 0.7
			1093.63	63.0 ± 3.0

$^{169}Tm(\alpha,\gamma)^{173}Lu$ - $^{169}Tm(\alpha,n)^{172}Lu$

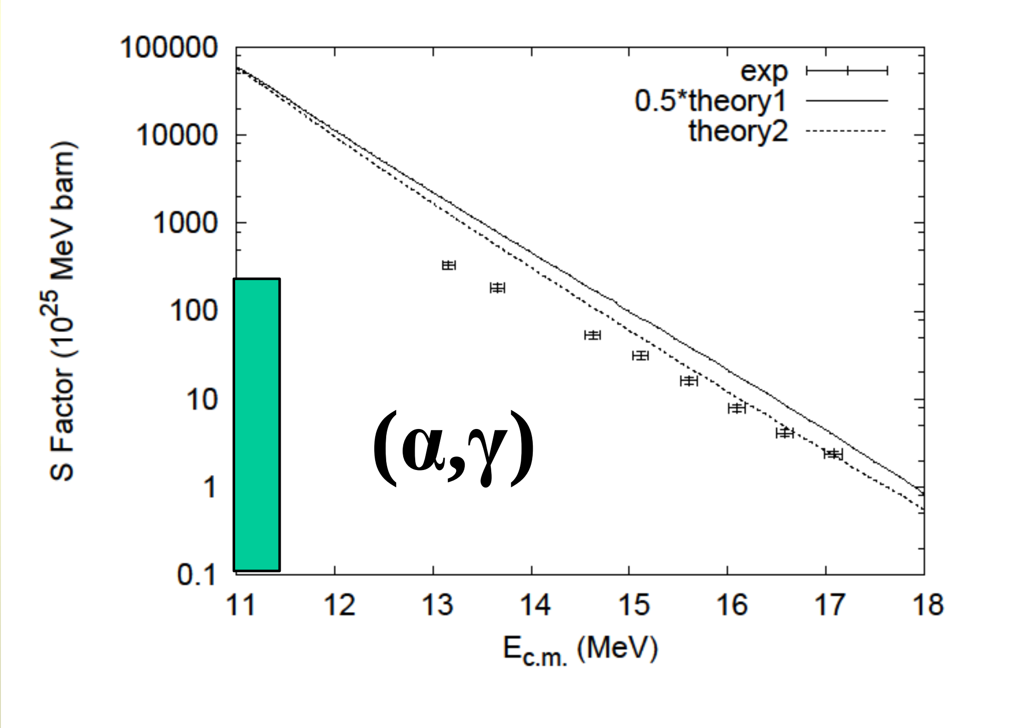
LEPS detector

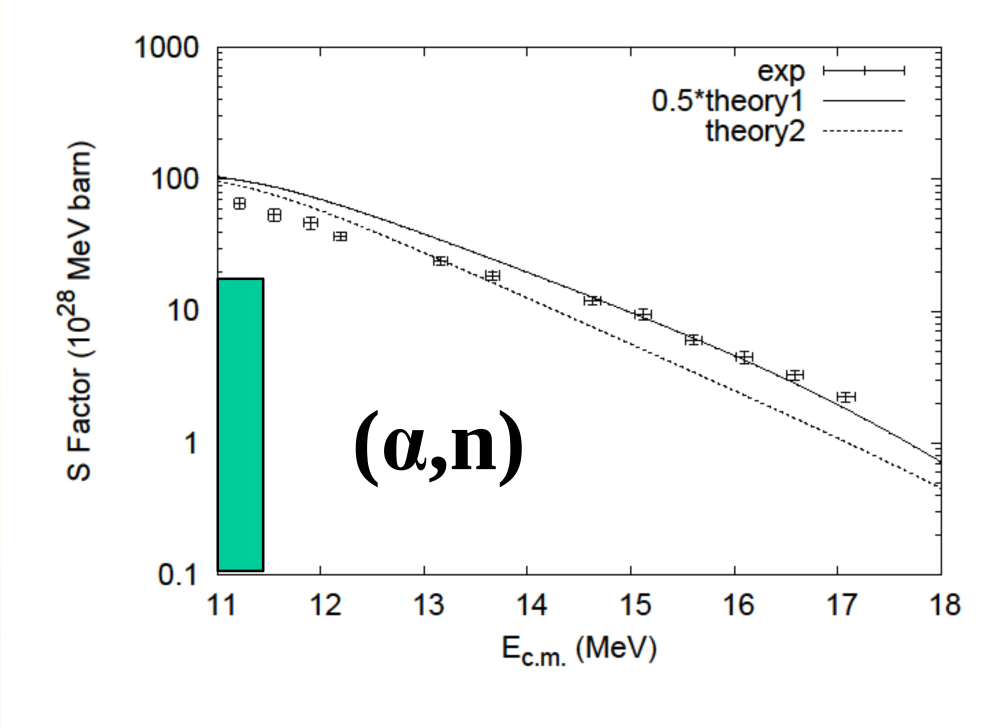




$^{169}Tm(\alpha,\gamma)^{173}Lu$ - $^{169}Tm(\alpha,n)^{172}Lu$

Curves: NON-SMOKER^{WEB} with different α-potentials





G.G. Kiss et al: Phys. Lett. B695 (2011) 419

X-ray detection: (α,γ) possibilities at heavy mass

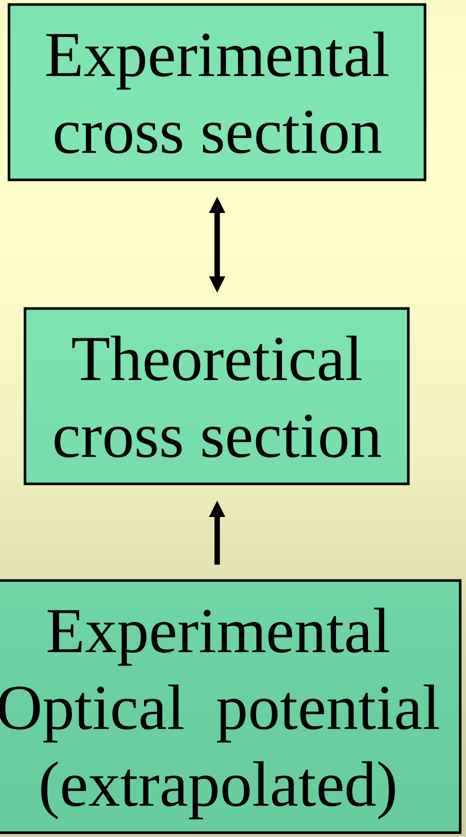
Target nucleus	Target Z	Half life [d]	Gamow window [20] ($T_9 = 3.5$ GK) [MeV]	E_{min} HPGe [MeV]	E_{min} LEPS [MeV]
^{156}Dy	66	1.19	8.2 - 12.0	13.7	12.0
^{162}Er	68	2.36	8.5 - 12.1	12.8	11.4
^{175}Lu	71	665	8.6 - 13.0	not possible	15.1
^{191}Ir	77	186.1	8.8 - 12.2	not possible	16.5

(α,α) experiments at low energies

Experimental constraints on the optical model parameters in the A>100 region

- ATOMKI/Darmstadt/Basel collaboration
- Experiments at ATOMKI Cyclotron
- Precision scattering chamber
- ~100% enriched targets
- Experimental constraints on the optical model parameters in the A>100 region

- Alternative: (n,α) studies

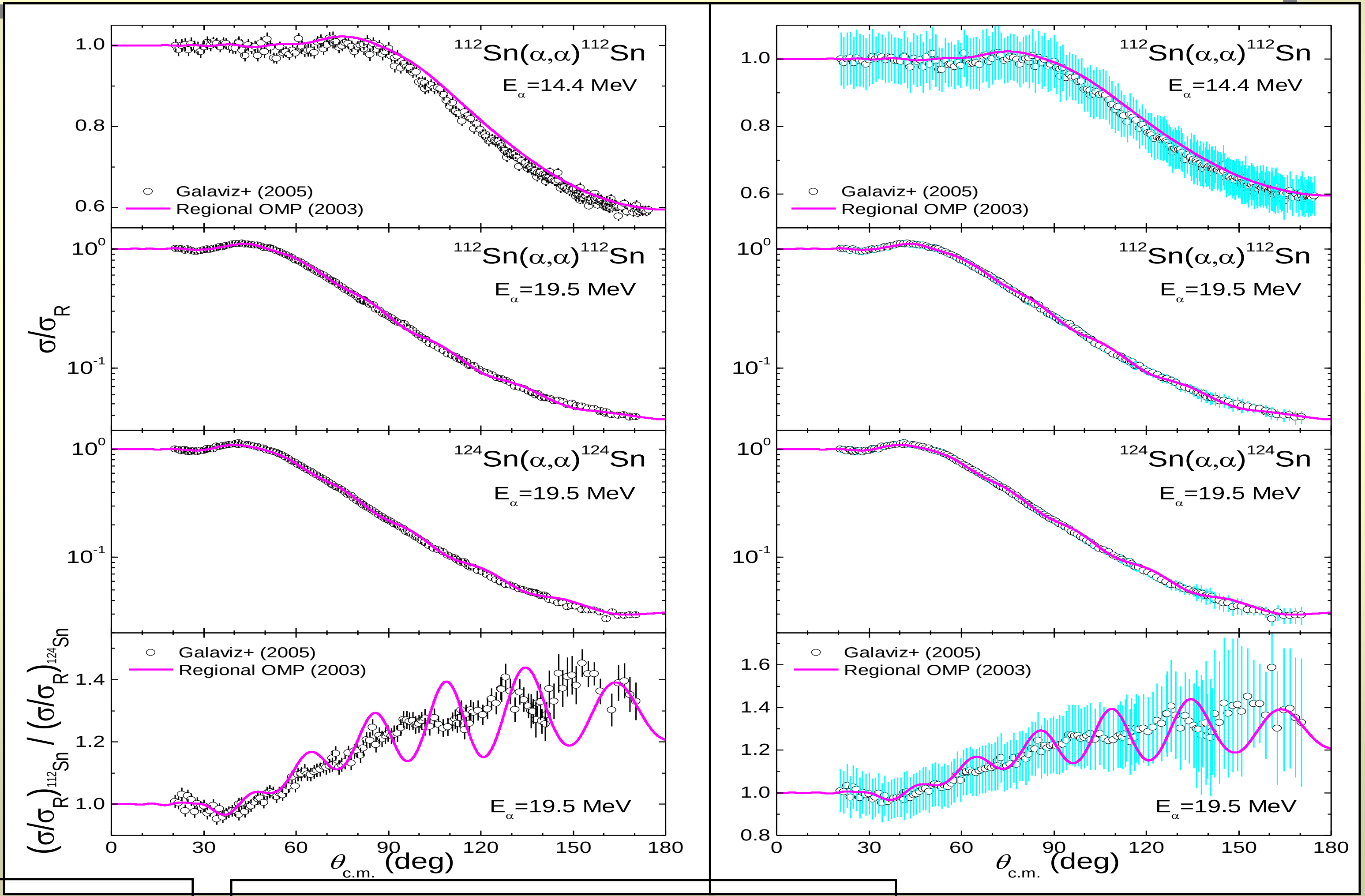


Comprehensive description of $^{112,124}Sn(\alpha,\alpha)$

High precision: uncertainties <3-4%
(data basis average: ~15%)

New features of exp. data

New opportunities also for model understanding



M. Avrigeanu et al, PRC73 (2006)

D. Galaviz et al. PRC71 (2005) 5802

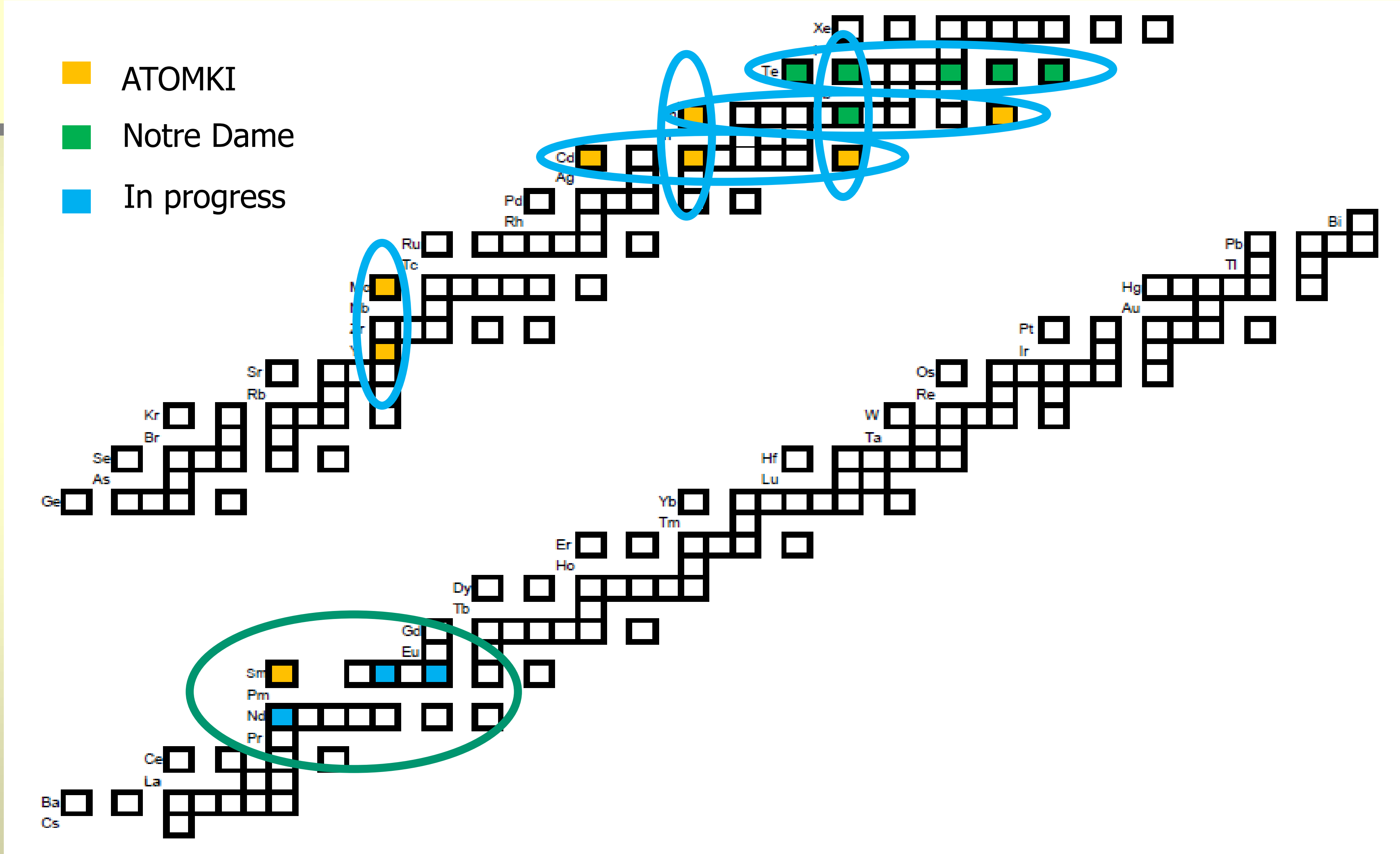
Studied reactions so far

Table 1: Charge and neutron number, energy of the first excited state of the target nuclei, enrichment, and E_{lab} and $E_{c.m.}$ energies for each of the angular distributions studied at ATOMKI in the recent years work.

target nuclei	proton number	neutron number	1st excited state [keV]	enrichment [%]	E_{lab} [MeV]	$E_{c.m.}$ [MeV]	Ref.
^{89}Y	39	50	908.97	100	16.21	15.5	[1]
					19.47	18.6	
^{92}Mo	42	50	1509.51	97.3	13.83	13.2	[2]
					16.42	15.7	
					19.50	18.6	
^{106}Cd	48	58	632.64	96.5	16.13	15.6	[3, 4]
					17.65	17.0	
					19.61	18.9	
^{110}Cd	48	62	657.76	95.7	16.14	15.6	[5]
					19.46	18.8	
^{116}Cd	48	68	513.49	98.3	16.14	15.6	[5]
					19.46	18.8	
^{112}Sn	50	62	1256.85	99.6	14.4	13.9	[6]
					19.5	18.8	
^{124}Sn	50	74	1131.74	97.4	19.5	18.9	[6]
^{144}Sm	62	82	1660.03	96.5	20.0	19.5	[7]

P. Mohr et al.: ADNDT in 2013

Experimental (α,α) database

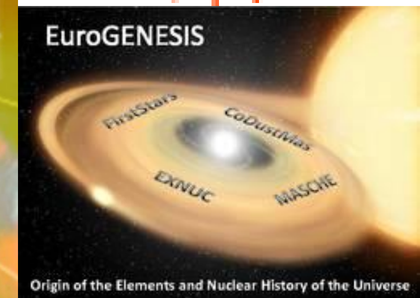


P. Mohr *et al.*, PRC **55**, Zs. Fülöp *et al.*, PRC **64**, D. Galaviz *et al.*, PRC **71**, G.G.Kiss *et al.*, PRC **80**, G.G. Kiss *et al.*, PRC **83** A. Palumbo *et al.*, PRC **85**

Atomki tools to extend p-process data

- **X-ray detection** (lower energies)
- **Thick target method** (full yield integration)
- **Gas cell development** (noble gas targets)
- **Inelastic scattering** (further potential benchmark)
- **TAS** (Total Absorbtion Spectrometer) from Valencia
- **Irradiations for AMS studies**

Supported by ERC, EUROCORES



ATOMKI group members:

- **Z. Elekes**
- **Zs. Fülöp**
- **Gy. Gyürky**
- **Z. Halász**
- **G.G. Kiss (at RIKEN)**
- **A. Ornelas**
- **E. Somorjai (emeritus)**

In collaboration with:

T. Rauscher (statistical model)
I. Dillmann, R.Plag (KADoNIS)
P. Mohr (elastic scattering)
Kocaeii group (cross sections)

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