p-process: status of the experimental program at GANIL

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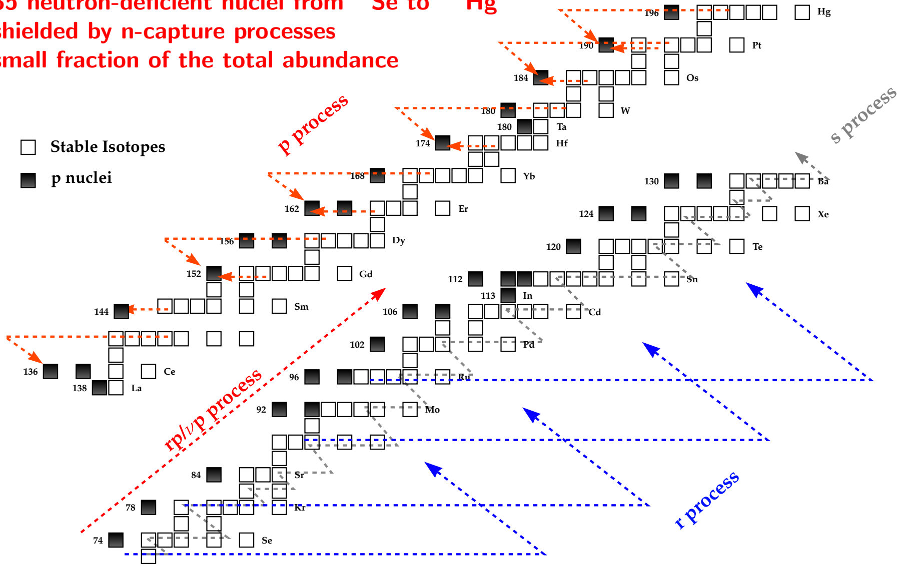
GANIL

Navi Physics Days
February 26-27th, GSI

Outline

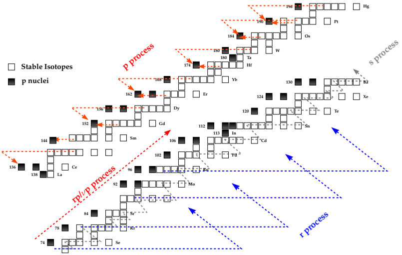
p-nuclei

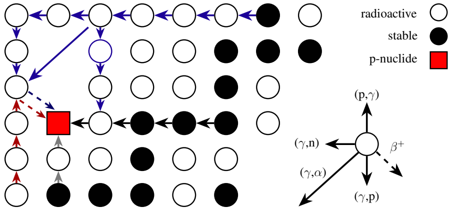
- 35 neutron-deficient nuclei from ^{74}Se to ^{196}Hg
- shielded by n-capture processes
- small fraction of the total abundance

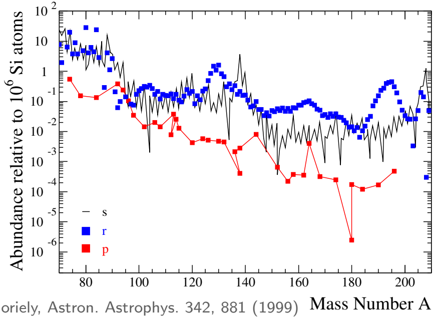


Origin of p-nuclei

- Originally suggested by B^2HF
  (E. M. Burbidge *et al.*, Rev. Mod. Phys. 29, 547 (1957))
  to explain the small fraction of p-nuclei compared to *s* and *r* abundances
- (γ,n), (γ,p),(γ,α) reactions and their inverse in Supernova shock front
- (γ,n) reactions at $T \gtrsim 10^9$ K
  $\Rightarrow$ (γ,p),(γ,α) and inverse maintaining the flow
  $\Rightarrow$ β decay bringing to final p-nuclei abundances
  M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003)







S. Goriely, Astron. Astrophys. 342, 881 (1999)
E. Anders and N. Grevesse, Geochim. Cosm. Acta 53, 197 (1989)

Understanding the p-nuclei abundances

Proposed scenarios

- O/Ne Layers of massive stars ($\approx$ 25 $M_{\odot}$) during Supernova Type II* explosions ($1.7 \leqslant T_9 \leqslant 3.3$)

  S. E. Woosley and W. M. Howard, ApJS 36, 285 (1978)
  M. Rayet *et al.*, Astron. Astrophys. 298, 517 (1995)

- Supernova Type Ia** ($1.5 \leqslant T_9 \leqslant 3.7$)

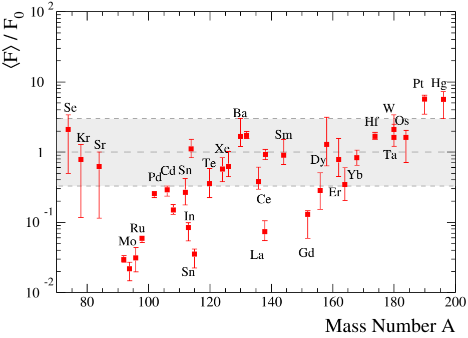
  W. M. Howard *et al.*, ApJL 373, L5 (1991)
  C. Travaglio *et al.*, ApJ 739, 93 (2011)

- Recently : νp-process, neutrino-driven wind ($1.0 \leqslant T_9 \leqslant 3.0$)

  R. D. Hoffman *et al.*, ApJ 460, 478 (1996)
  C. Fröhlich *et al.*, PRL 96, 142502 (2006)

* SNII = Core-Collapse Supernova
** SNIa = Explosion from Dwarf-Giant Binary system

Overproduction Factors
(Th vs Obs Average Abundances)

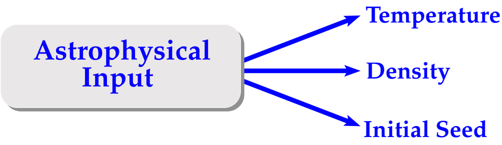


M. Rayet *et al.*, Astron. Astrophys. 298, 517 (1995)

- Most of abundances reproduced within a factor 3
- Mo, Ru, In, Sn, La, Gd still strongly underproduced

Theoretical calculations : Inputs

Reaction network calculations : ∼ 20000 reactions linking ∼ 2000 nuclei



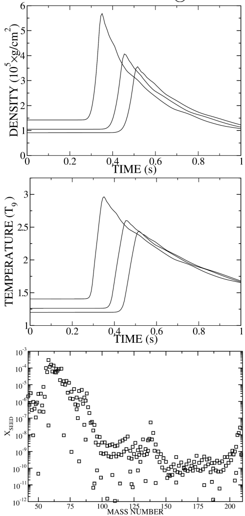
Astrophysical Input

Temperature

Density

Initial Seed

$\mathrm{M} = 25\mathrm{M}_\odot$



M. Rayet *et al.*, Astron. Astrophys. 298, 517 (1995)
W. Rapp *et al.*, ApJ 653, 474 (2006)

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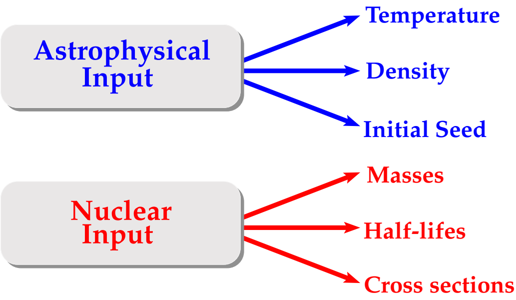
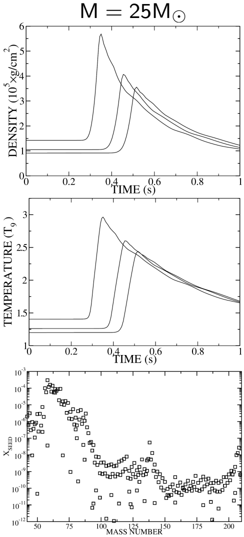


Astrophysical Input

- **Temperature**
- **Density**
- **Initial Seed**

Nuclear Input

- **Masses**
- **Half-lifes**
- **Cross sections**



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Theoretical calculations : Inputs

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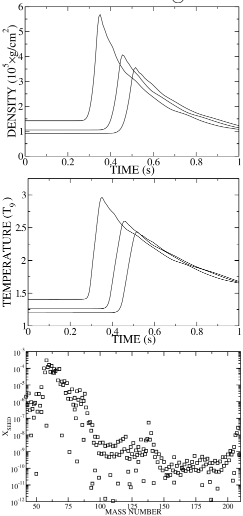
Astrophysical Input
- Temperature
- Density
- Initial Seed

Nuclear Input
- Masses
- Half-lifes
- Cross sections

Hauser-Feshback model (HF)
- Optical Model Potentials (n, p, α)
- Nuclear Level Densities
- Gamma Strenghts

$M = 25M_\odot$



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W. Rapp *et al.*, ApJ 653, 474 (2006)

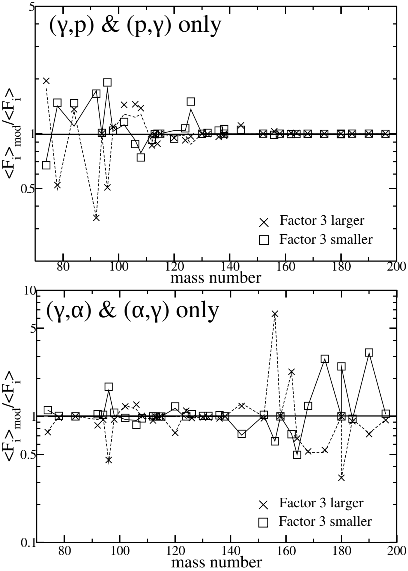
Sensitivity studies

Reaction network calculations

Rapp et al., ApJ 653, 474 (2006)

- Fixed astrophysical input
- Variation of (γ, p), (γ, α) rates and their inverse
- Strong effects observed for specific reactions

  ⇒ Need data in the relevant energy range
- Often better to measure (x,γ) reactions and deduce time-reverse (γ,x) rates

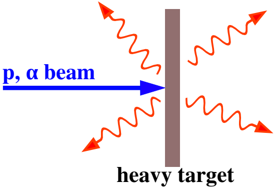


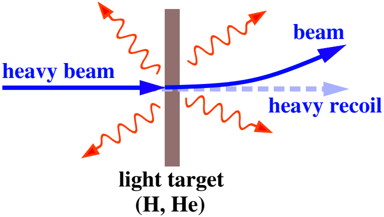
W. Rapp *et al.*, ApJ 653, 474 (2006)

Selected Reactions with strong impact on abundances

(p, γ)	(p, n)	(α, γ)
^{72}Ge$(p, \gamma)^{73}$As	^{76}Ge$(p, n)^{76}$As	^{70}Ge$(\alpha, \gamma)^{74}$Se
^{74}Ge$(p, \gamma)^{75}$As	^{75}As$(p, n)^{75}$Se	^{92}Mo$(\alpha, \gamma)^{96}$Ru
^{77}Br$(p, \gamma)^{78}$Kr	^{85}Rb$(p, n)^{85}$Sr	^{102}Pd$(\alpha, \gamma)^{106}$Cd
^{83}Rb$(p, \gamma)^{84}$Sr†	^{86}Kr$(p, n)^{86}$Rb	^{106}Cd$(\alpha, \gamma)^{110}$Sn

Experimental techniques





Direct kinematics measurements

- Intense p/α low-energy beams
- Recoils are stopped in the target or backing
- Not applicable for (most) radioactive targets
- Techniques : In-beam (Angular Distribution, γ-summing) and Activation
- Facilities : Mostly Tandem/Linac (Bochum, Atomki, Demokritos, **SPIRAL2-NFS** etc)
- Equipments : X and γ-ray detectors

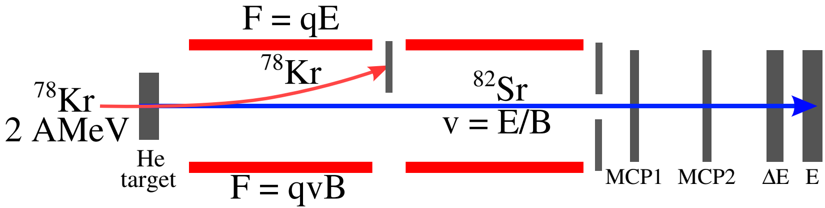
Inverse kinematics measurements

- Stable/radioactive beams
- Recoil separators, storage rings
- Gas (often windowless) targets
- Techniques : In-beam and Activation
- Facilities : TRIUMF, MSU, GSI, GANIL-SP2
- Equipments : DRAGON, **LISE-FULIS**, **GSI-ESR**

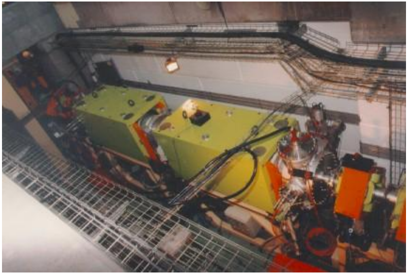
Inverse kinematics measurements @ GANIL

$X(\alpha,\gamma)$ and $X(\alpha,n)$ reactions using LISE Wien Filter (FULIS)

LoI S. Harissopulos, F. de Oliveira, PhD of P. Ujic

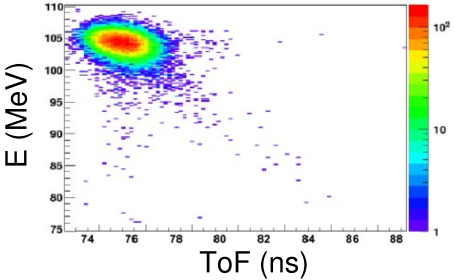


- Velocity selection ⇒ beam rejection
- Ideally collecting all the charge states
- $\Delta v \sim 5\ \%$ between primary beam and CN
- ToF vs ΔE Identification using a Ionisation Chamber (up to 10^5 pps)

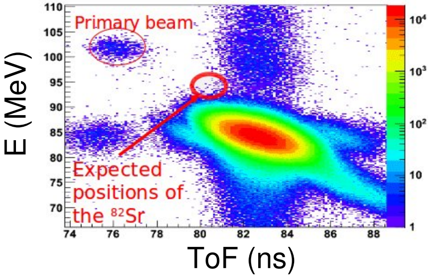


Beam-rejection tests with a solid He-implanted thin target

Low intensity ^{78}Kr beam, WF off



Set-up for ^{82}Sr selection, WF on



- ^{4}He ions implanted in a 0.2-μm Al target ($N_0(He) \approx 10^{16}$cm^{-2})
- Primary beam rejection factor $\sim 10^{10}$
- Intense locus cannot be explained by scattering on He and Al (2000 pps observed, 150 expected)
- Inhomogeneities + dust particles (1-10 μm) ⇒ beam energy loss calculations give ∼ 2000 pps in the intense locus ! ⇒ **need a "windowless" gas target**
- July 2014 : development tests for a windowless gas target + new design to obtain $N_0 \gtrsim 10^{16}$cm^{-2}
- New in-beam test scheduled on July 2015 : ^{58}Ni+p/α @ 4.7 AMeV

Direct kinematics measurements with proton and α beams @ NFS

(G. Randisi, B. Bastin)

Opportunities with NFS

- SPIRAL2-Ph1 will provide **intense p/α** beams at **energies relevant for astrophysics**
  - 1 to 100 pμA for Day-One experiments
  - $E_{lab} \gtrsim 0.75$ AMeV
- **Unique opportunity at NFS to measure σ down to nb**

List of "Day-One" measurements

(p,γ)	(p,n)	(α,γ)
^{72}Ge$(p,\gamma)^{73}$As	^{76}Ge$(p,n)^{76}$As	^{70}Ge$(\alpha,\gamma)^{74}$Se
^{74}Ge$(p,\gamma)^{75}$As	^{75}As$(p,n)^{75}$Se	^{92}Mo$(\alpha,\gamma)^{96}$Ru
^{77}Br$(p,\gamma)^{78}$Kr$^{(rt)}$	^{85}Rb$(p,n)^{85}$Sr	^{102}Pd$(\alpha,\gamma)^{106}$Cd
^{83}Rb$(p,\gamma)^{84}$Sr$^{(rt)}$	^{86}Kr$(p,n)^{86}$Rb	^{106}Cd$(\alpha,\gamma)^{110}$Sn

Blue : relevant energy window is partially/not covered

Red : No Data ! !

Black : Already measured

$^{(rt)}$ Radioactive target ⇒ not possible in direct kinematics

Activation (AC)

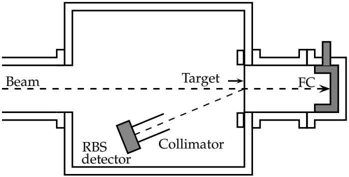
Advantages

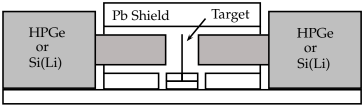
- **Lower background** compared to in-beam measurements (no in-beam radiation)
- Selectivity (especially in case of E.C.)
- Possibility to further reduce background using $\gamma - \gamma$ or $X - \gamma$ coincidences.

Drawbacks

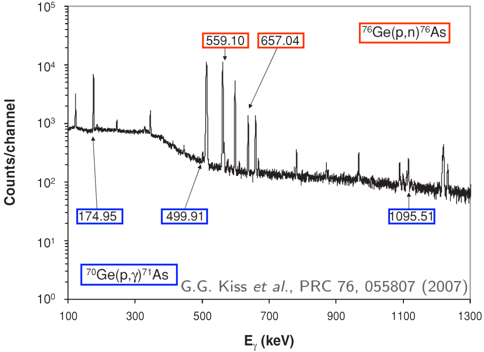
- Possible **only for radioactive products**
- Difficult for long $T_{1/2}$ ($\gtrsim$ 1 month)
- On-line/off-line setup (shielding needed for off-line)

IRRADIATION SETUP





OFF-LINE SETUP



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

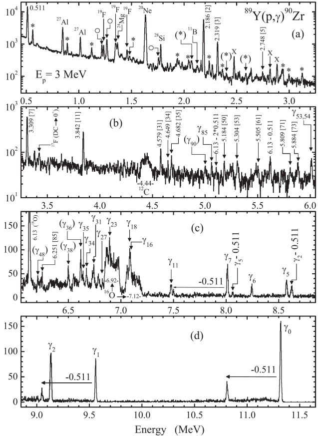
In-beam : angular distributions (AD)

Advantages

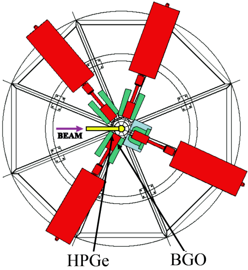
- $d\sigma(\theta)/d\Omega \Rightarrow$ spins + partial cross sections $\Rightarrow$ constraint on HF calculations
- γ Identification
- **High resolution**

Drawbacks

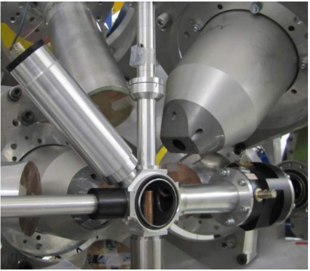
- Low efficiency
- Need High angular coverage (Ω,θ)
- **High in-beam background** from isotopic contaminations/chemical impurities from target/backing $\Rightarrow$ **target enrichment** required



S. Harissopulos *et al.*, PRC 87, 025806 (2013)



Stuttgart HPGe Array



HORUS array (Köln)

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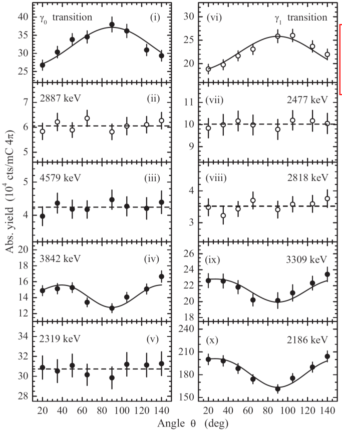
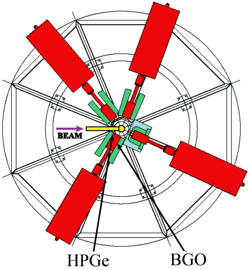
S. Harissopulos *et al.*, PRC 87, 025806 (2013)



$$\Rightarrow W(\theta) = A_0\left[1+\textstyle\sum_k a_k P_k(\theta)\right] \;\Rightarrow\; \sigma = \frac{A}{\rho x\, N_A}\textstyle\sum_i A_0^i$$



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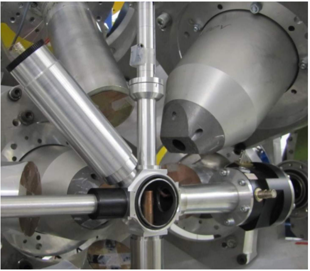


HORUS array (Köln)

In-beam : γ-summing (GS)

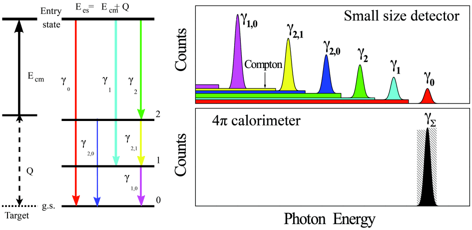
Advantages

- **High geometrical efficiency** ($\sim 4\pi$)
- Direct measurement of the total integrated cross sections
- Fast measurement

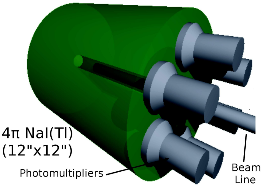
Drawbacks

- **Complex response function** $\Rightarrow$ detailed simulations required (sum peak efficiency ε_Σ)
- **High Background** (as for AD method + large Compton) $\Rightarrow$ target enrichment required
- No γ-ID for a single transition
- Lower resolution compared to AD method

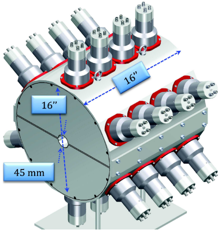
4π spectrometer working principle



$$\boxed{\sigma = \frac{A}{\rho x\, N_A}\,\frac{I_\Sigma}{N_{inc}\,\varepsilon_\Sigma}}$$



4π NaI(Tl) Bochum



SuN Detector (MSU)

In-beam : γ-summing (GS)

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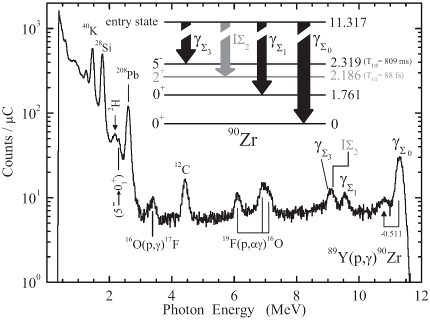

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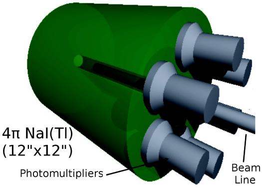

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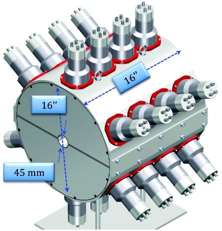


SuN Detector (MSU)

How to improve accuracy ?

Need to measure accurately $1\ \text{nb} \leqslant \sigma \leqslant 1\ \text{mb} \quad \Rightarrow \quad I_{p,\alpha} \geqslant 1\ \text{p}\mu\text{A} \quad , \quad \rho x < 1\ \text{mg/cm}^2$

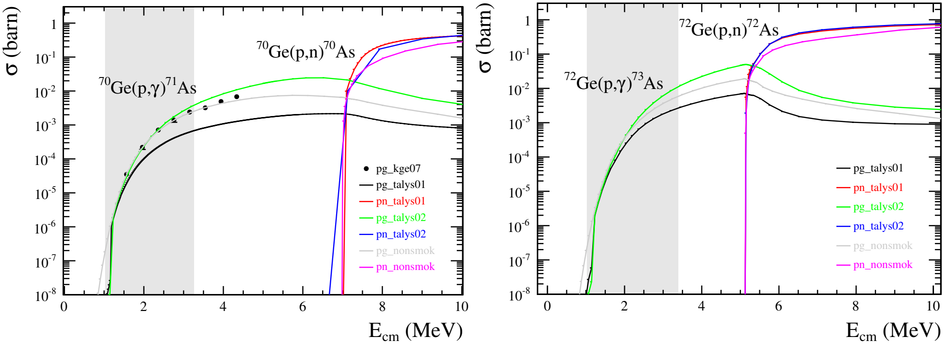
1. γ detection ⇒ high efficiency needed ⇒ large coverage
2. Low background ⇒ high isotopic/chemical purity for target/backing
3. Selectivity (Channel/transition ID)
4. Versatility (Stable/radioactive products)

	AD	GS	AC
Efficiency	x	✓	x
Low bckg	x	x	✓
Selectivity	✓	x	✓
Versatility	✓	✓	x

1^{st} campaign : activation measurements

^{72}Ge(p,γ) : cross section calculations

Theoretical calculations $\sigma(p+^{70,72}Ge)$: TALYS vs NON-SMOKER



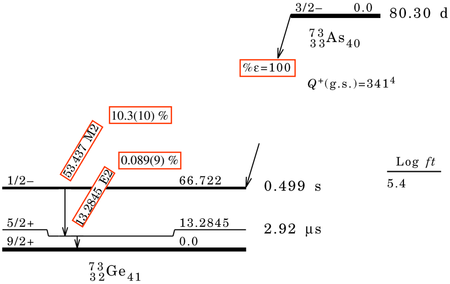
- Different OMPs/NDLs for TALYS
  1. Phenomenological : Koning-Delaroche OMP, Fermi-Gas NLD
  2. Semi-microscopic : JLM (folding) OMP, Goriely's (Skyrme) NLD
- Cross-check with NON-SMOKER (JLM+Fermi) & ^{70}Ge(p,γ) exp. data

  G. G. Kiss *et al.*, PRC 76, 055807 (2007)
- Shaded area ⇒ Relevant Energy Range for $1.5 \leqslant T_9 \leqslant 3.5$

  T. Rauscher, PRC 81, 045807 (2010)

^{72}Ge(p,γ) : activation

- ^{73}As decays 100% by E.C. ($T_{1/2} = 80.3$ days)
- **E_γ =53 keV,** $I_\gamma = 10.3(10)\% \Rightarrow \boldsymbol{\sigma}$
- In addition : ^{73}Ge X-rays
  $k_\alpha = 9.85 - 9.89$ keV, $I_X^{tot} = 90.3(23)\%$
  $\Rightarrow$ **off-line X-γ coincidences**



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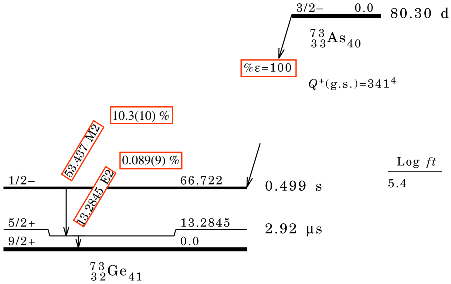
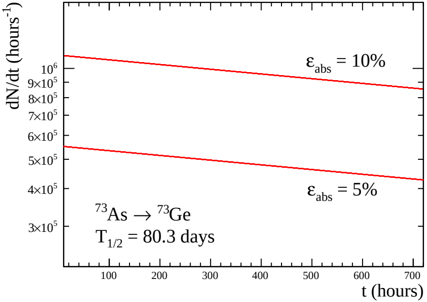
$$\left.\begin{aligned}
\sigma_{th}(2\,\mathrm{MeV}) &= 200 - 300\ \mu b \\
I_p &= 1\ p\mu A \\
T_{irr} &= 10\ h \\
\mathrm{Enrich} &= 95\% \\
\rho x &= 300\ \mu g/cm^2 \\
+10\mu m &\ \ \mathrm{Al\ backing}^{*} \\
\varepsilon_{abs} &= 5 - 10\% \\
BR_\gamma &= 10.3\%
\end{aligned}\right\} \Rightarrow \begin{array}{l} A_0 = 5.5 \cdot 10^5/h \\ \Delta A_0(1h) \geqslant 200/h \\ (@\ \varepsilon_{abs} = 5\%) \end{array}$$

*only ^{27}Al(p,γ) going to stable $\Rightarrow$ no β-delayed γ's





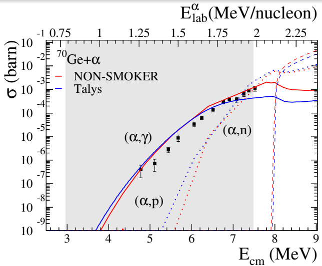
2^{nd} campaign : in-beam measurements

(α,γ) reactions @ NFS (G. Randisi, B. Bastin)

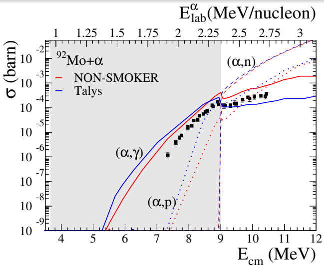
- ^{70}Ge$(\alpha,\gamma)^{74}$Se : **1st step**
- ^{92}Mo$(\alpha,\gamma)^{96}$Ru
- ^{102}Pd$(\alpha,\gamma)^{106}$Cd : **Unmeasured !**
- ^{106}Cd$(\alpha,\gamma)^{110}$Sn

- ^{74}Se,^{96}Ru,^{106}Cd are stable products ⇒ **In-beam Measurement**
- α-capture ⇒ very low cross sections ⇒ **γ-summing for highest efficiency ?**
- Caveat : Need high purity samples + accurate knowledge of the response function !

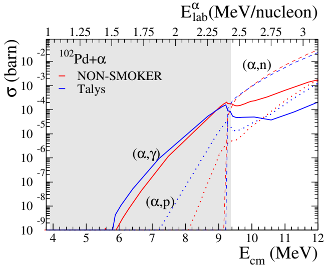
(α,γ) reactions : cross section calculations

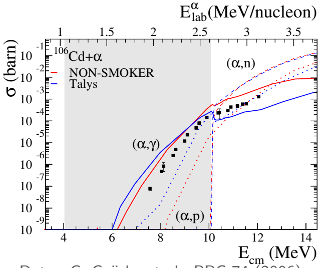


Data : Z. Fülöp *et al.*, ZPA 355 (1996)



Data : P. Demetriou *et al.*, AIP Conf.P. 293 (2009)





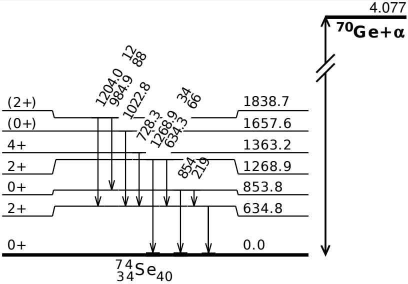
Data : G. Gyürky et al., PRC 74 (2006)

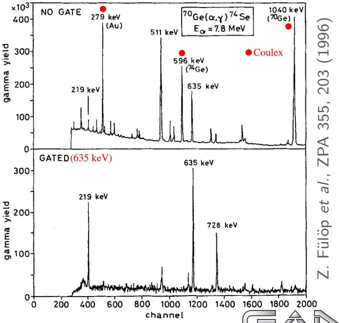
Shaded Area : Relevant Energy Range for $1.5 \leqslant T_9 \leqslant 3.5$

^{70}Ge(α,γ) @ NFS

- Previously measured for $4.7 \leqslant E_{cm} \leqslant 7.4$
  Z. Fülöp *et al.*, ZPA 355, 203 (1996)
- $I_p = 1$ pμA, $\rho x = 36\mu g/cm^2$ on thin Au backing
- $\sigma(4.7\,\text{MeV}) = 0.40(22)\mu b$
- σ **for** $3.5 \leqslant E_{cm} \leqslant 5$ **MeV ?**
- $\sigma_{th}(4\,\text{MeV}) = 1 - 10$ nb
  $\Rightarrow$ **uniquely possible with NFS intensities !**

- 635-keV level fed by most of transitions
  $\Rightarrow$ Small angular-distribution correction needed
- The same kind of setup (2 HPGe's) would allow to measure $\sigma(4\,\text{MeV})$ in $\sim$ 1 UT using $I_p \sim 100$ pμA
- Accuracy strongly dependent on efficiency
  $\Rightarrow$ need simulations
- Experimental response and background with/without target at NFS commissioning





Z. Fülöp *et al.*, ZPA 355, 203 (1996)

Summary & Perspectives

Conclusions

- Reactions with strong impact on p-nuclei abundances have been identified and studied
- Theoretical TALYS/NON-SMOKER calculations have been performed for a series of high-impact reactions
- The effect of different nuclear physics inputs has been studied
- Need cross-section measurements to constrain reaction network calculations
- SPIRAL2-NFS p/α beams : a unique opportunity to measure cross sections at energies relevant for the p-process in direct kinematics
- Several physics cases for an experimental campaign are proposed

Perspectives

- ^{72}Ge(p,γ) activation measurement
- Simulations for in-beam setup for (α,γ) reactions (Master student)
- Proposal for activation measurements @ NFS
- LoI for in-beam measurements @ NFS
- Test for (α,γ) reactions in inverse kinematics @ FULIS (July)

Collaboration

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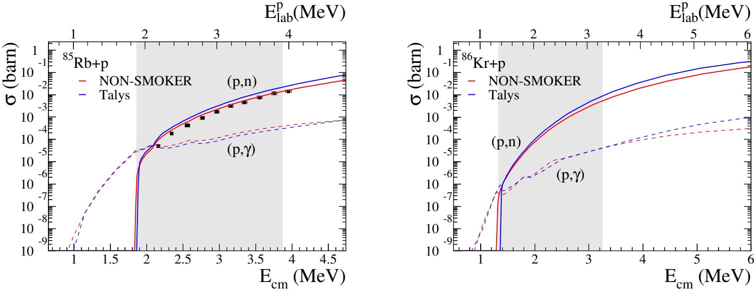
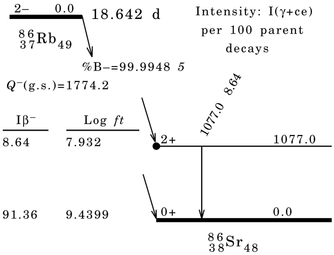
Thank you for your attention

(p,n) reactions : ^{86}Kr(p,n)^{86}Rb



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

- ^{86}Kr(p,n) : low threshold $\Rightarrow$ effect on (p,γ)
- σ_{th}(2MeV) $\approx$ 100μb (Cross-check : ^{85}Rb+p data)
- ^{86}Rb$\xrightarrow{\beta}$^{86}Sr*(E_γ = 1077 KeV) $\Rightarrow$ **can use activation**
- Target is a gas $\Rightarrow$ use a gas cell (recently used for n+^{136}Xe by activation !)
  M. Bhike *et al.*PRC 89, 031602 (2014)
- 10-mm-thick cell @ 100 mbar (+100 μm Al window) $\Rightarrow$ 2.43 · 10^{18} atoms/cm^2



Reminder : Hauser-Feshback Calculations

$$\sigma_p(E_p, \overbrace{E' J' \Pi'}^{residual\ nucleus}) \propto \underbrace{\rho(E', J', \Pi')}_{NLD} \sum_{\underbrace{J\Pi}_{CN}} g_J \sum_{\underbrace{j\pi}_{proj}} \sum_{\underbrace{XL}_{multipolarity}} \frac{\overbrace{T_{pj\pi}}^{OMPs} \; \overbrace{T_{\gamma XL}}^{\gamma - strength}}{\underbrace{T(EJ\Pi)}_{Sum\ over\ ch's}}$$

Tests of a Windowless Gas Target (July 2014)

- Goal : optimize target configuration to obtain $N_0 \geqslant 10^{16} cm^{-2}$
- Measure energy loss of α's on Argon at different pressures/configurations
- $\Delta E = 2 \pm 1$ keV on 5cm-thick cell @ 1 mbar ($\Delta E_{th} = 4 keV$ @ $N_0 = 10^{16} cm^{-2}$)
  $\Rightarrow$ lower gas density in the cell
- Hard to obtain a localized flow at low pressure with differential vacuum
- Need "jet"-type configuration $\Rightarrow$ new design ongoing