PARIS for studying the p-process nuclei

PARIS Collaboration meeting
New ideas for PARIS

B. Rebeiro

Institut de Physique des 2 Infinis de Lyon

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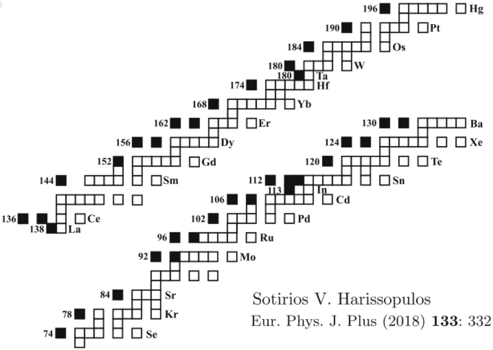
Legnaro, Padova

p-nuclei

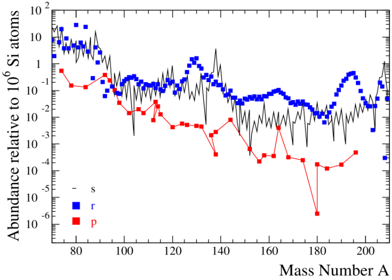
- Majority of heavy nuclei (beyond ^{56}Fe) produced via s- or r- process.
- ~ 35 proton rich nuclei between ^{74}Sr - ^{196}Hg shielded from n-captures..
- produced purely by *p-process* - p-nuclei



Sotirios V. Harissopulos
Eur. Phys. J. Plus (2018) **133**: 332

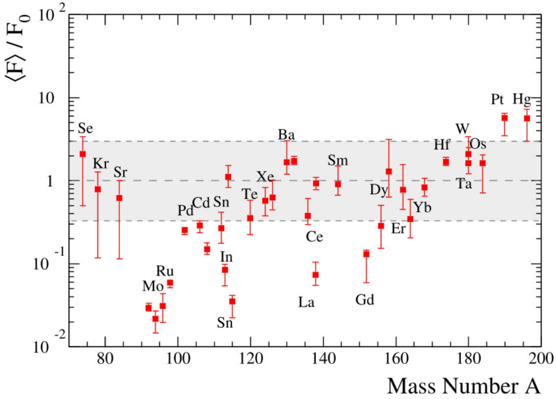
p-process nucleosynthesis

- most favored astrophysical scenario : O/Ne burning layers of massive stars during explosive or pre-explosive phase of Type II Supernovae. Temperature range 1.8 - 3.3 GK.
- Produced by (γ, n) reactions on s- or r-process seed nuclei. Followed by (γ, p) and (γ, α) and if favorable conditions exist, (p, γ).
- Much less abundant than s- or r-process nuclei but non-negligible contribution to solar system abundance.



p-process nucleosynthesis : Do we fully understand it?

- Calculated abundances deviate from observed solar system abundances (from meteorite data).
- While most isotopes agree within a factor of 3 some don't (e.g. Mo, Ru, Sn, La, Gd)



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

p-process nucleosynthesis : Do we fully understand it?

- Abundances calculated via vast network of reactions : $12 \leq A \leq 210$, ~ 2000 nuclei and ~ 20000 reactions
- Various inputs $\Rightarrow$ many uncertainties
  - astrophysical inputs
    - ★ Astrophysical sites
    - ★ temperature
    - ★ initial s- or r-process nuclei seed abundances
  - nuclear physics inputs
    - ★ nuclear masses and half lives
    - ★ γ strength functions
    - ★ optical potential esp. α-OMP
    - ★ reaction rates

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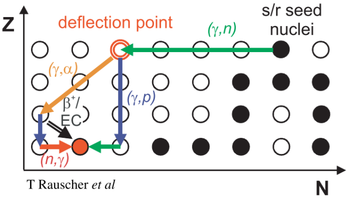
      $A < 130\ (\gamma, p)$

      $A > 130\ (\gamma, \alpha)$



T Rauscher *et al*
Rep. Prog. Phys. **76** (2013) 066201

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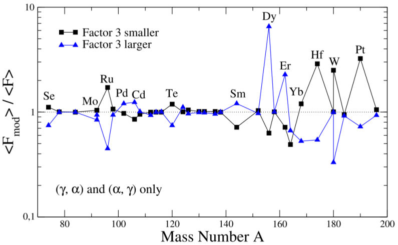
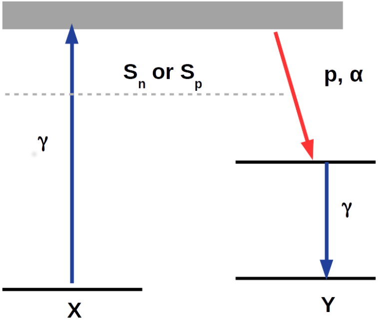


W. Rapp *et al.*, Astrophys. J. **653**, 474 (2006)

Reaction rates need to be measured (where experimentally possible)

Measuring photodisintegration reaction rates

- Very low cross sections, usually μb or less
  - Need extremely efficient set ups
  - intense beams
  - very low backgrounds
- Few facilities with intense γ beams
- In astrophysical environments, target nuclei in excited states.



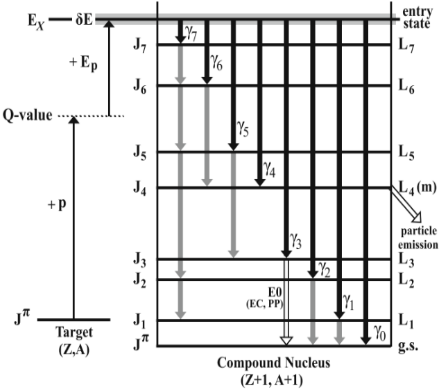
Alternative : Measure reverse reaction i.e. capture cross sections

$$(\gamma, \mathrm{x}) \leftrightarrows (\mathrm{x}, \gamma) \;\; \mathrm{x} = \mathrm{p}, \mathrm{n}, \alpha$$

Use principle of detailed balance to get photodisintegration rates.

Measuring (γ, x) via (x, γ)

- Excited states of nuclei accessible
  - astrophysically more relevant information
- p-process temperatures of 1.8 - 3.3 GK
  - $(p, \gamma) : 1 \leq E_p \leq 5$ MeV
  - $(\alpha, \gamma) : 4 \leq E_\alpha \leq 12$ MeV
  - Low energy accelerators ⇒ intense beams
- Spread in excitation energy
  - target thickness
  - spread in beam energy
- # nuclei produced ⇒ cross section
  1. count the nuclei
  2. count the photons

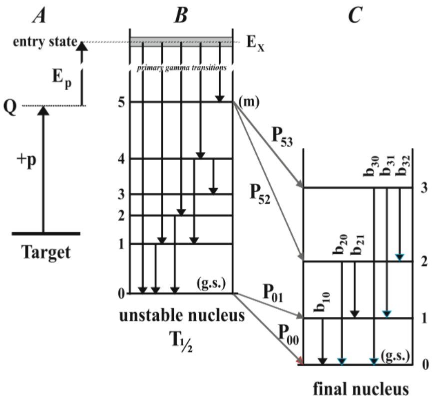


Sotirios V. Harissopulos
Eur. Phys. J. Plus (2018) **133**: 332

Measuring (γ, x) via (x, γ)

1. Count the nuclei ⇒ Activation measurements

- Irradiate then count
- β decay to ground state or β decay to excited state followed by γ transition
- Free from beam induced backgrounds
- Most used technique
- Decaying nucleus should have suitable half life ($\sim$ few days)
- Limited number of isotopes that can be studied



Measuring (γ, x) via (x, γ)

2. Count the photons $\Rightarrow$ In beam measurements

- angular distributions
  - Reaction yield from all γ-transitions feeding the ground state
  - fit angular distributions to Legendre polynomials to obtain absolute A_0 coefficients

$$W(\theta) = A_0 \left(1 + \sum_k \alpha_k P_k(cos(\theta))\right)$$

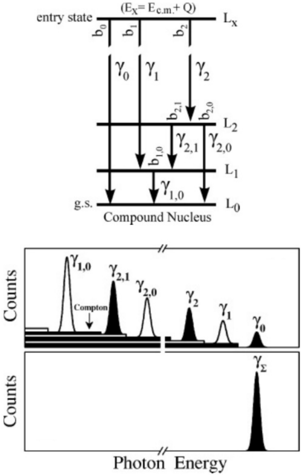
    k_{max} depends on multipolarity of the γ-transition
  - $A_0 \Rightarrow$ reaction yield $\Rightarrow$ cross sections
  - One needs to know detailed level scheme of the resultant nucleus
  - To precisely determine angular distribution of γ_0 (γ from entry level to gs) $\Rightarrow$ high efficiency detectors required.
  - Data analysis extremely time consuming - large number of γ-spectra need to be analyzed with often many γ-transitions
- 4π γ summing
  - Angle integrated cross sections

$4\pi\ \gamma$ summing technique

The technique

- Large volume detector to completely absorb the photons
- Long response time so different photos are indistinguishable
- Measure intensity of the summed peak to get total reaction cross section

$$\sigma_T = \frac{I_{sum}}{\epsilon_{sum}\ N_t\ N_b}$$



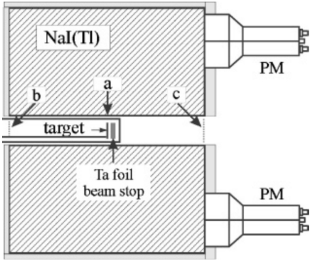
A. SPYROU *et al.*
PHYSICAL REVIEW C **76**, 015802 (2007)

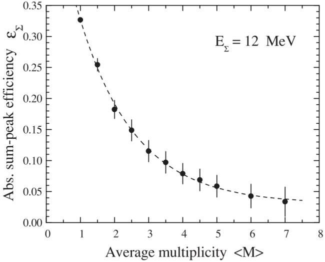
Challenges

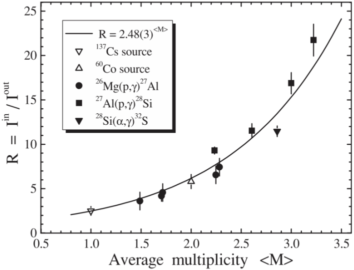
- Efficiency depends on often not well known multiplicity
- Ideal situation does not manifest in reality - background, incomplete absorption, > 1 summed peak ...

$4\pi\ \gamma$ summing technique

- Detector: Large volume NaI crystals
- Need additional techniques to characterize the detector's response function to multiplicity[1]
- $R = \frac{I_a}{I_{edge}}$, $R = \alpha^M$
- Get ϵ_{sum} from Monte Carlo simulations
- for single detection unit, $\epsilon_{sum} \propto \frac{1}{M}$



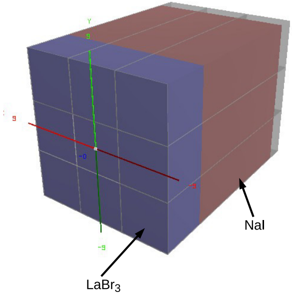




[1] Spyrou *et al.* PRC **76**, 015802 (2007)

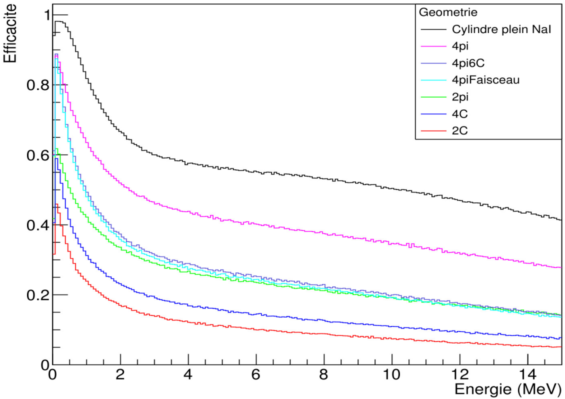
Why 4π γ summing with PARIS?

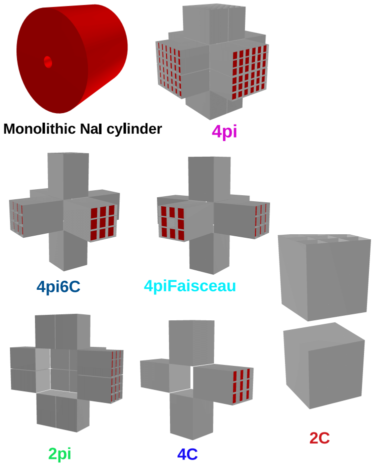
- Detector material ($LaBr_3$ or $CeBr_3$ and NaI) reasonably efficient for low and high energy photons.
- Can act as a 4π calorimeter if enough clusters used
- Provide information about the (often) unknown multiplicity of the γ cascades.
  - correlated with the number of crystals fired



These claims supported by Monte Carlo simulations

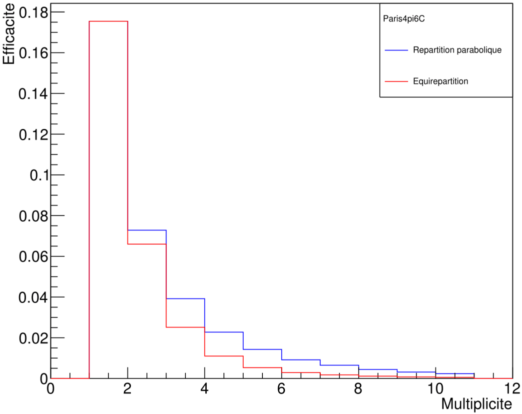
PARIS efficiency for different configurations

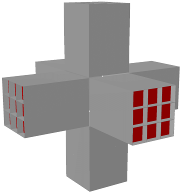


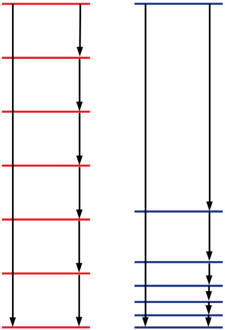


- IP2I Master's students : Arthur Henry and Vincent Lelasseux
  Supervised by O. Stezowski and C. Ducoin

PARIS efficiency: Energy level distribution

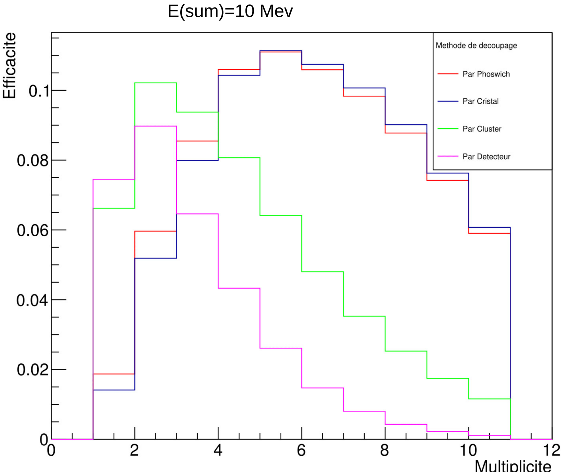


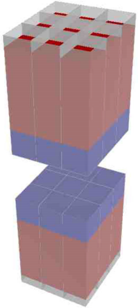




- Efficiency for reconstructing a 12 MeV gamma when the energy levels are spaced equally v/s a parabolic distributions of the energy levels.

PARIS v/s monolithic detectors

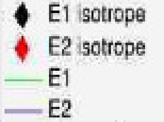




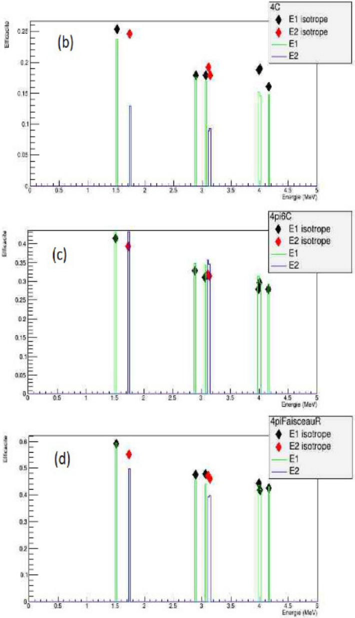
9x2 Phoswich
(9+9)*2 Crystal elements
2 Clusters
1 Detector

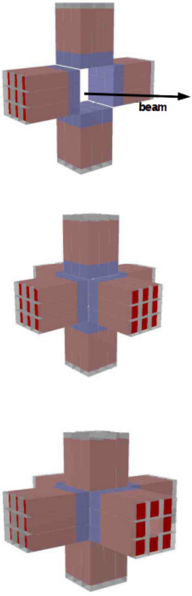
- Efficiency for reconstructing the summing peak for a 10 MeV gamma as a function of the number of cascading gammas

PARIS configurations: efficiency v/s multipolarity

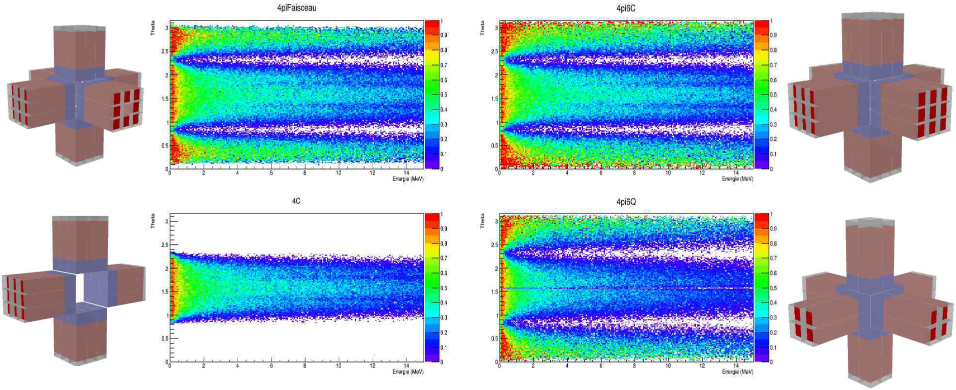


- Most configurations suitable for γ transitions with multi polarity E1
- For E2 transitions, critical detection angles missing.
- Detectors at forward angles required.



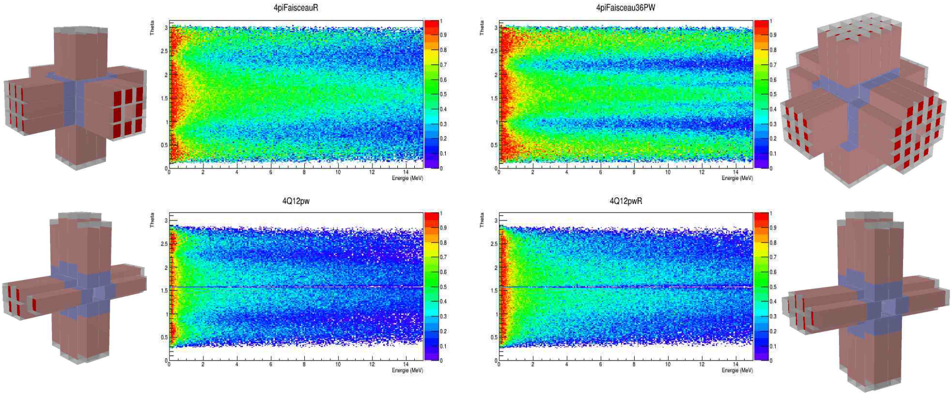


PARIS configurations: Edge effects



- No events detected at the edges
- Will affect efficiency of detecting E2 γ-transitions

PARIS configurations: Edge effects



- Modified configurations allow for better uniform detection.
- With reasonable number of detectors, multipolarity of the transition might not be a huge problem.

Concluding remarks

- (p, γ) or (α, γ) measurements can be done with intense proton or alpha beams using low-energy accelerators.
- PARIS is promising candidate to apply the 4π γ -summing technique
- Efficiency comparable to monolithic detectors
- Efficiency well balanced for low as well as high energy gammas
- High granularity of the clusters will allow to determine multipolarity of the transition
- Position of detectors along beam axis important
  - modified configurations could be an answer