Nuclear astrophysics in the era of multi-messenger observations at INFN-LNS

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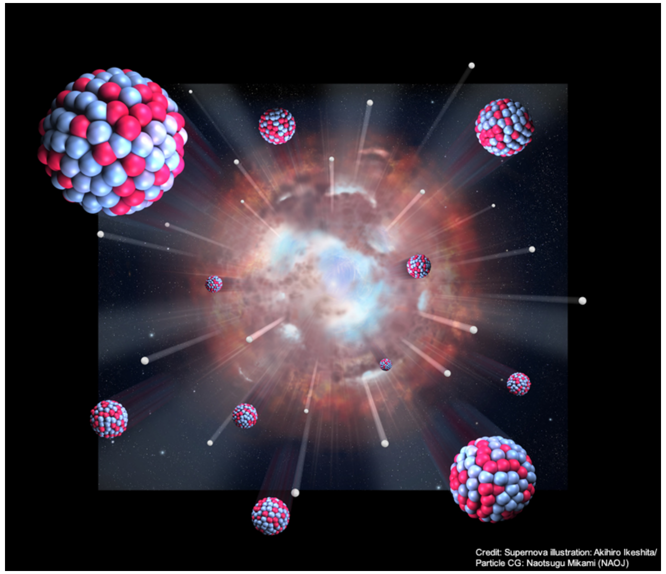
Outline

1. Very few words about the r-process

2. Constraining the r-process through a better understanding of the s-process

3. Study of nuclear reactions involved in the r-process

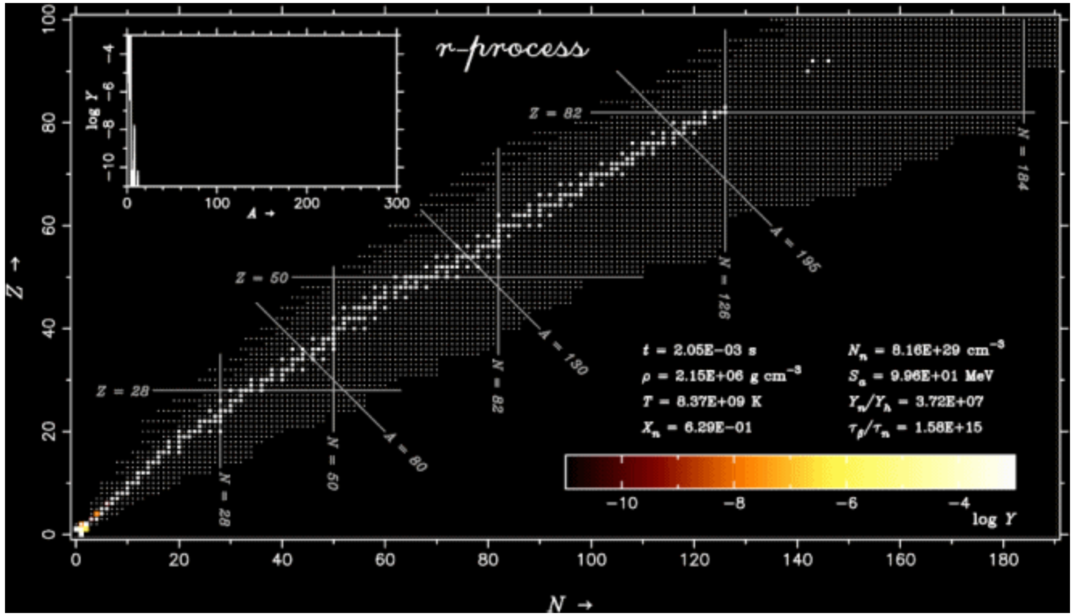
4. Studying the opacity of a plasma made up of lanthanides (nuclear methods and atomic physics)



r process nucleosynthesis

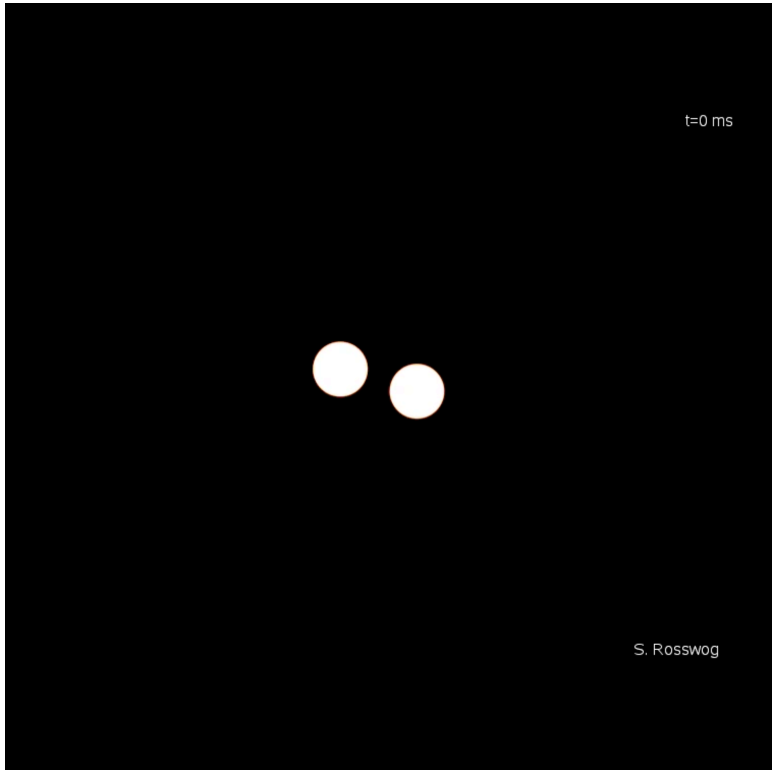
- It produces **~50%** of the stable isotopes heavier than Fe
- Candidate site: **neutron star mergers (cold r-process)**
- Nuclear physics input:

Masses, shell structure, half lives, fission parameter, P_n values (probability of neutron emission following β-decay)

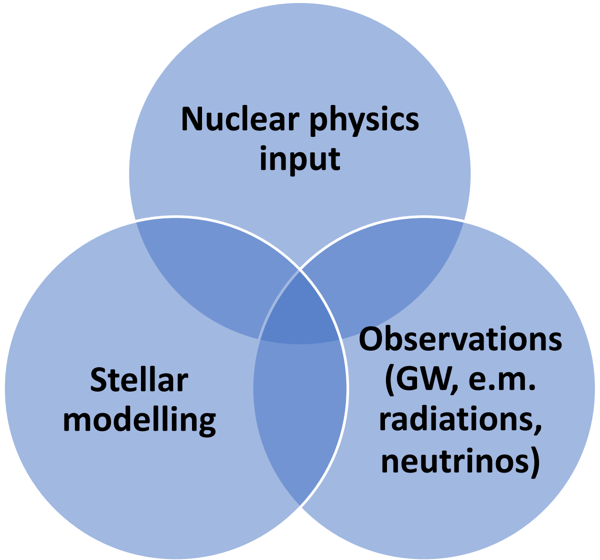


https://fr.cdn.v5.futura-sciences.com/sources/images/dossier/rte/18FuturaSciences.gif

Example: animation of the coalescence of two neutron stars with masses 1.4 and 1.5 $M_\odot$



http://compact-merger.astro.su.se/Movies1/ns14_ns15_6mio_3D_density_v5.mov



→ **Multimessenger astronomy**

Some review papers:
Annu. Rev. Nucl. Part. Sci. 67 (2017) 253
Prog. Part. Nucl. Phys. 86 (2016) 86
Prog. Part. Nucl. Phys. 66 (2011) 346

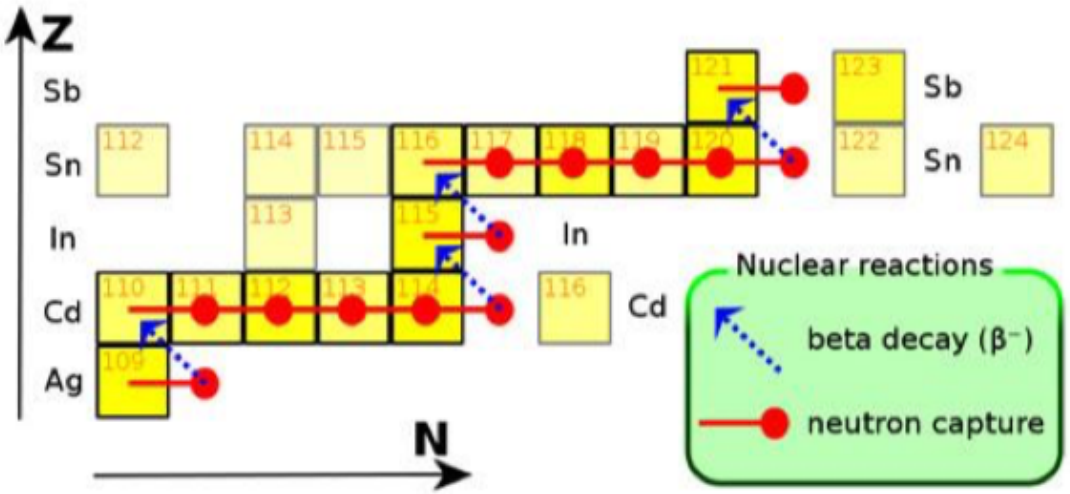
r process nucleosynthesis

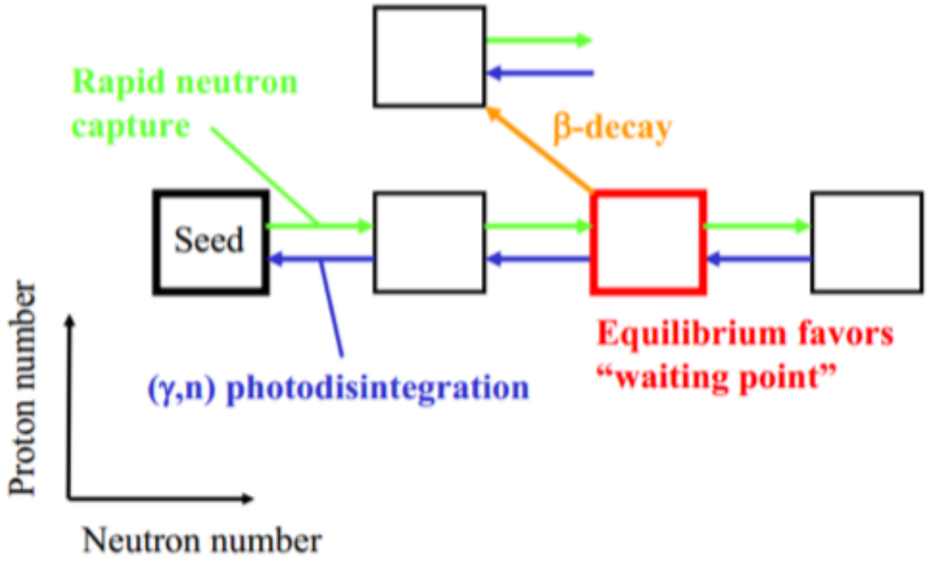
Temperatures 10^9 K (cold r-process → NS mergers)
(hot r-rpocess → CC supernova)

Neutron densities 10^{22} n/cm^3

Timescale < ms

Neutrons can be absorbed until the neutron separation energy is less than or equal to zero (drip line)
→ β-decay and new sequence of neutron captures





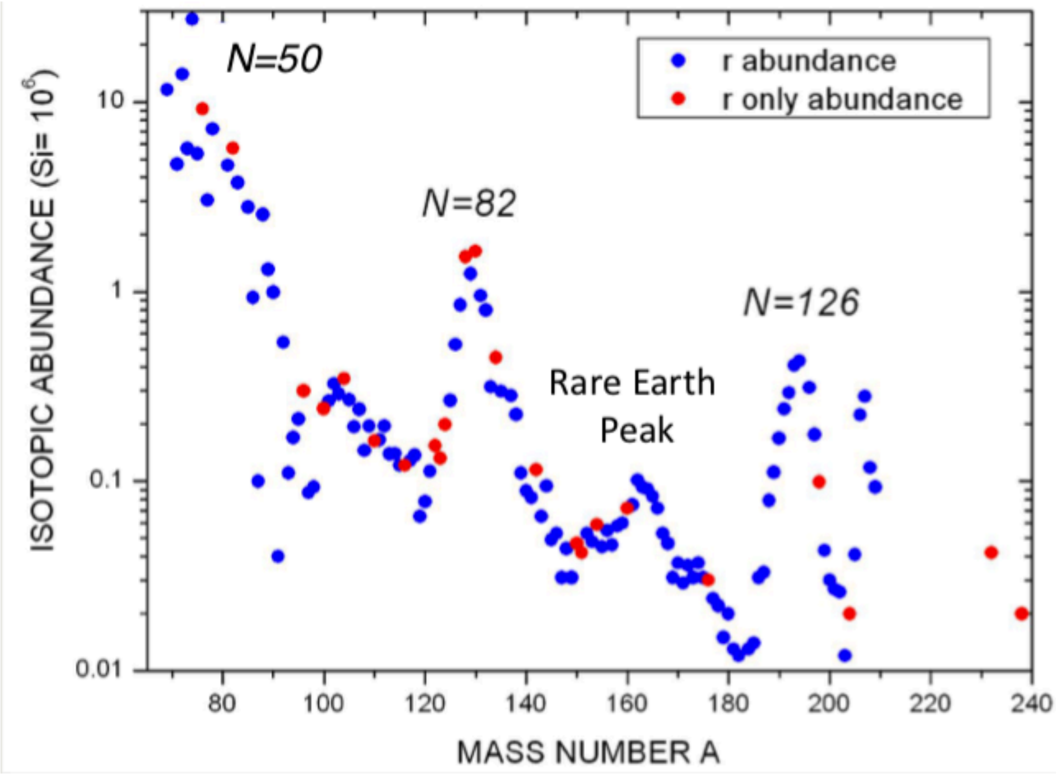
Photodisintegration can play an important role in the r-process path owing to the high temperatures
→ **(n,γ) - (γ,n) equilibrium (less important for NS mergers)**

At shell closure (n,γ) rates decrease and right beyond (γ,n) rates are very large.
→ As a result of the r process path waiting at shell closures the abundance of nuclei in the corresponding mass range is increased

2. Constraining the r-process through a better understanding of the s-process

Constraining r-process abundances

$$N_r = \underbrace{N_\odot}_{\text{measured}} - \underbrace{N_s}_{\text{well-known}} - \underbrace{N_p}_{\text{negligible}}$$



We have seen in the previous slide that individual abundances of r-process nuclei *cannot* be deduced from the observational data of kilonovae expanding shells.

Key role of the s-process… *hopefully* well known
Few r-process only nuclei to test the models

s-process: slow neutron capture, moving along the stability valley

→ **Need of continuous/pulsed neutron source & complicated stellar structure to keep s-process on**

Candidate neutron sources:
$^{13}C(\alpha,n)^{16}O$ → low neutron densities 10^6 n/cm^3

$^{22}Ne(\alpha,n)^{25}Mg$ → high neutron densities 10^9 n/cm^3

This is especially critical since comparatively high neutron fluxes might produces abundance pattern *close* to the one of the r-process (at least close to the branching points)

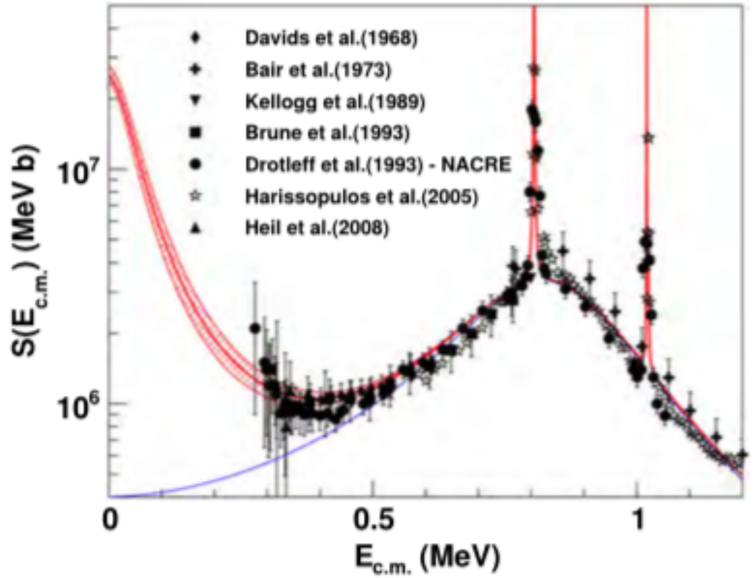
Constraining r-process abundances

The r-process pattern is extracted from the solar system abundances by subtracting the s-process (and p-process) contributions through models, the elemental yield is used to get information of r-process sites (entropy, Y_e, explosion mechanism, role of hydrodynamics)

s-process nucleosynthesis plays a crucial to constrain the r-process. At LNS, an intense activity on the s-process is ongoing focusing on:

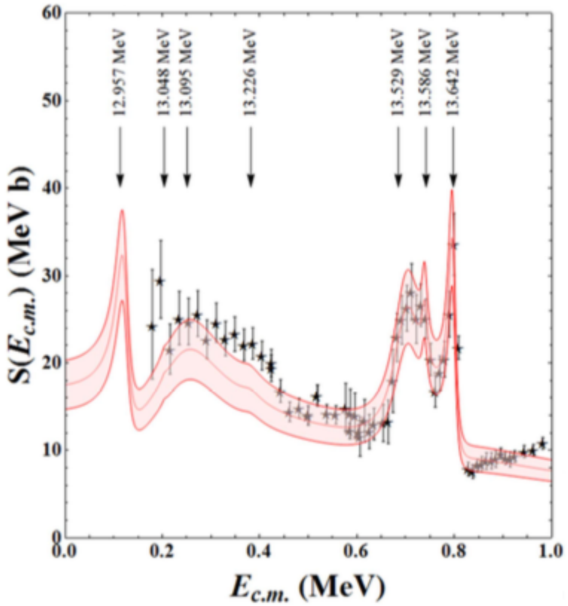
1. Investigating the neutron sources of the s-process: **$^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$**

2. Constraining astrophysical models of s-process by studying production and destruction of probe nuclei (mainly ^{19}F)
Fluorine is very sensitive on the stellar physical conditions, so its abundance allows us to see "inside" the s-process site



Red band:
$^{13}C(\alpha,n)^{16}O$ S-factor measured at LNS down to astrophysical energies

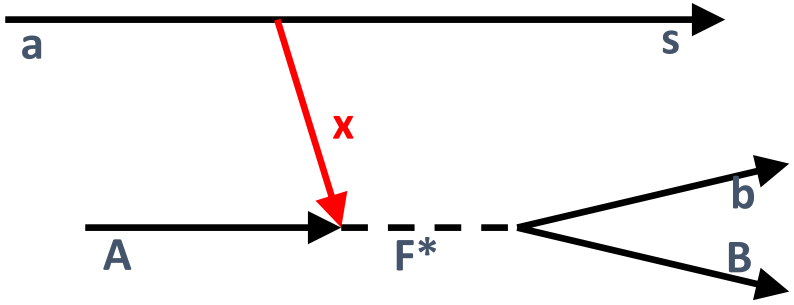
Astrophysical Journal 777 (2013) 143



Red band:
$^{19}F(p,\alpha)^{16}O$ S-factor measured at LNS down to astrophysical energies

Astrophysical Journal 845 (2017) 19

The Trojan Horse Method (for resonant reactions)



R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

In the latest years, large efforts were made to give a quantitative justification of THM, to estimate the uncertainties and improve the description of the 2→3 cross section

$$
\begin{aligned}
M^{\mathrm{PWA(prior)}}(P, \mathbf{k}_{aA}) = {} & (2\pi)^2 \sqrt{\frac{1}{\mu_{bB}k_{bB}}}\,\varphi_a(\mathbf{p}_{sx}) \\
& \times \sum_{J_F M_F j' l l' m_{j'} m_l m_{l'} M_n} i^{l+l'} \langle j m_j l m_l | J_F M_F\rangle \langle j' m_{j'} l' m_{l'} | J_F M_F\rangle \\
& \times \langle J_x M_x J_A M_A | j' m_{j'}\rangle \langle J_s M_s J_x M_x | J_a M_a\rangle\, \mathrm{e}^{-\mathrm{i}\delta^{hs}_{bBl}}\, Y_{lm_l}(-\hat{\mathbf{k}}_{bB}) \\
& \times \sum_{\nu,\tau=1}^{N} [\Gamma_{\nu bBjlJ_F}(E_{bB})]^{1/2}[\mathbf{A}^{-1}]_{\nu\tau}\, Y^*_{l'm_{l'}}(\hat{\mathbf{p}}_{xA}) \\
& \times \sqrt{\frac{R_{xA}}{\mu_{xA}}}\,[\Gamma_{\nu xAl'j'J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA}, R_{xA}) \big(j_{l'}(p_{xA}R_{xA}) \\
& \times [(B_{xAl'}(k_{xA}, R_{xA}) - 1) - D_{xAl'}(p_{xA}, R_{xA})] \\
& + 2Z_xZ_Ae^2\mu_{xA} \int_{R_{xA}}^{\infty} \mathrm{d}r_{xA}\, \frac{O_{l'}(k_{xA}, r_{xA})}{O_{l'}(k_{xA}, R_{xA})}\, j_{l'}(p_{xA}r_{xA})\big).
\end{aligned}
$$

Amplitude of the TH reaction

Same R-matrix term as in OES cross section but for the appearence of the inverse penetration factor making it possible to observe suppressed resonances at low energies

negligigle at usual experimental precisions

Fourier transform of the s-x relative motion wave function

solid sphere scattering phase shift

Inverse penetration

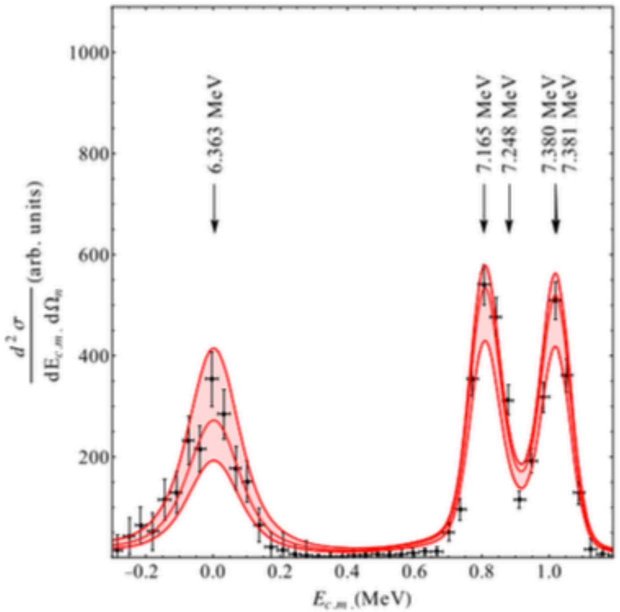
R-matrix-like boundary condition

Using THM to better constrain the $^{13}C(\alpha,n)^{16}O$

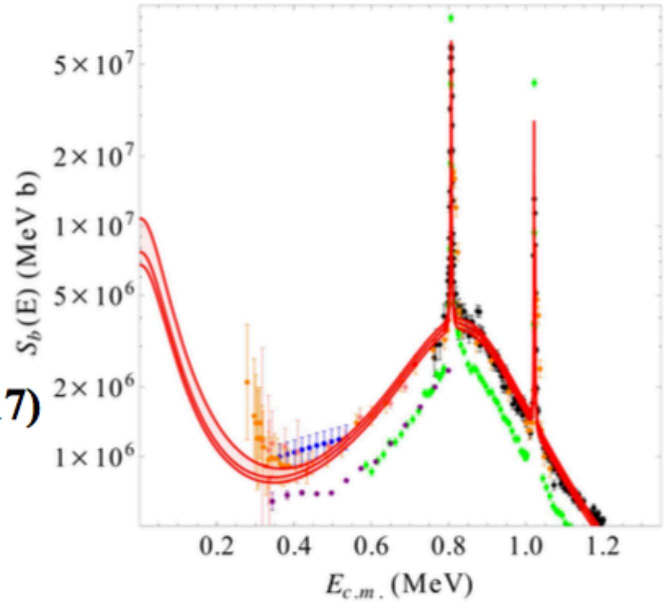
The $1/2^+$ excited state of ^{17}O was recently shown to be centered at positive $E_{c.m.}$ values (at about 4.7 keV) by Faestermann et al. (2015) → $\mathbf{\Gamma_n = 0.135}$ **MeV**

Avila et al. (2015) calculated with high accuracy the asymptotic normalization coefficient of the threshold resonance **ANC($1/2^+$ state of ^{17}O) ~ 3.6 ± 0.7 fm^{-1}** → so we can derive the corresponding γ_α

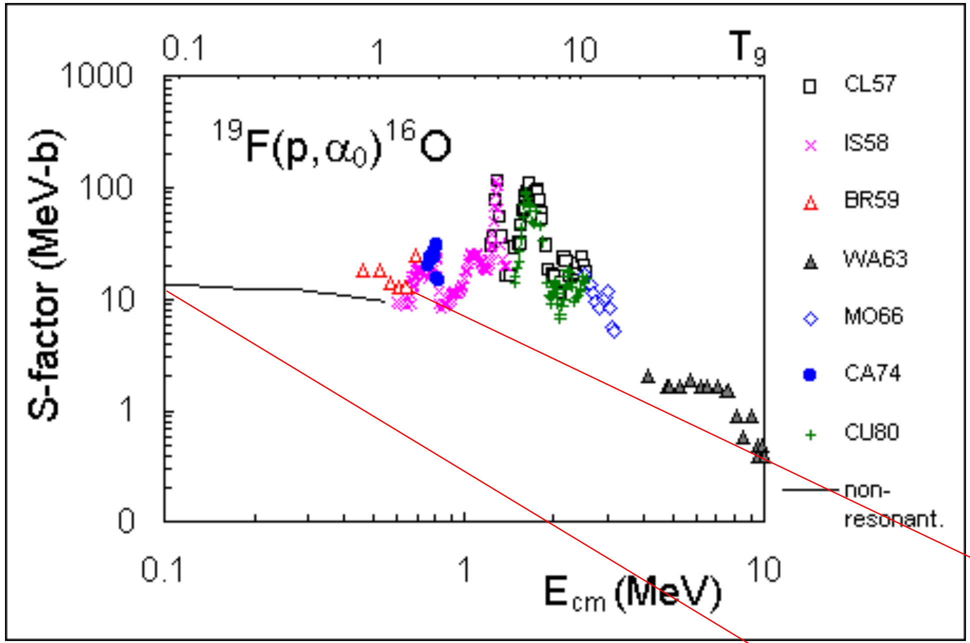
We fitted THM HOES indirect data to obtained the **γ values of the other two peaks** (not taken from literature) at higher energies discriminating among the different direct datasets to unambiguously define the absolute value od *S*-factor



Trippella & La Cognata (2017)

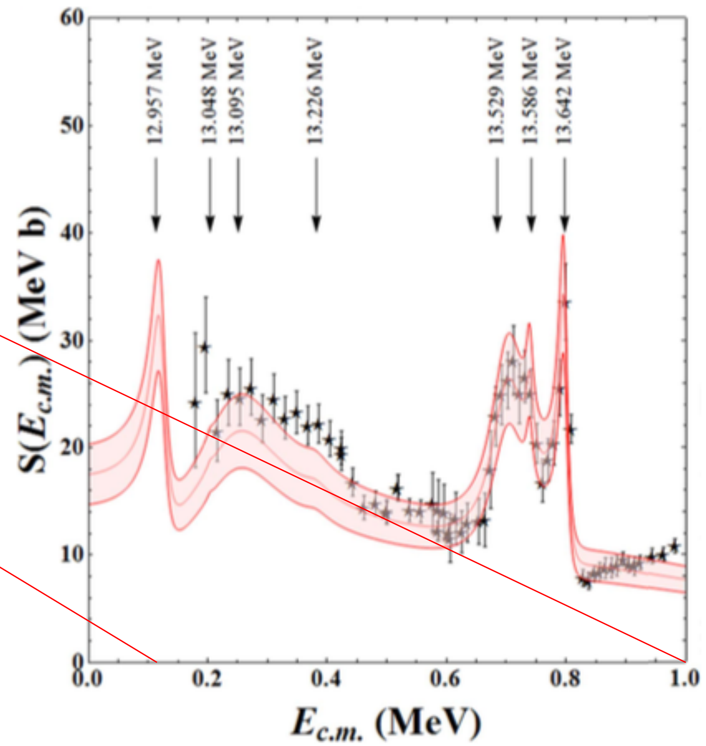


Exploring the astrophysical energy region of the $^{19}F(p,\alpha)^{16}O$



Red band: new THM S-factor
Solid stars: I. Lombardo et al., Phys. Lett. B 748 (2015) 178

I. Indelicato et al., ApJ 845 (2017) 19



The THM measurement has made it possible to explore the whole energy region of astrophysical interest, showing the occurrence of a 113 keV resonance

^{19}F → probe of AGB stars interiors

Astrophysical consequences under investigation

Also: the ^{19}F+alpha destruction channel also studied using the THM

→ D'Agata et al. APJ 860 (2018) 61

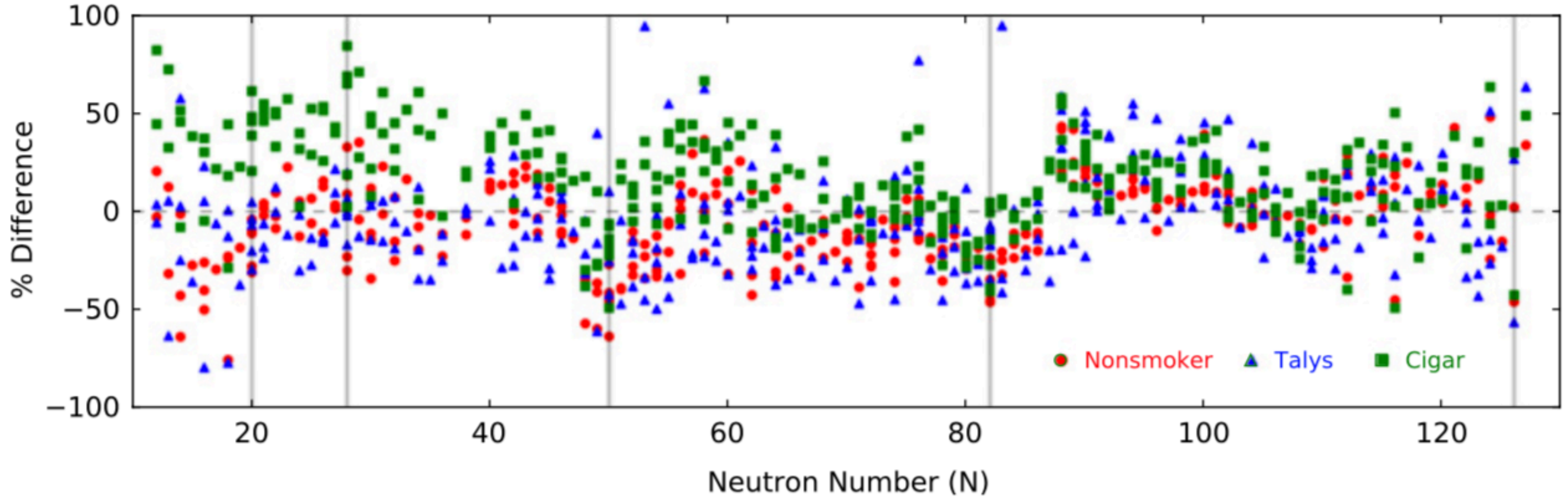
What next? Exploring the role of ^{16}O excited states → high resolution necessary

New experiment performed at the 2000 mm chamber @ LNS

3. Study of nuclear reactions involved in the r-process

Nuclear physics input: n-capture reactions

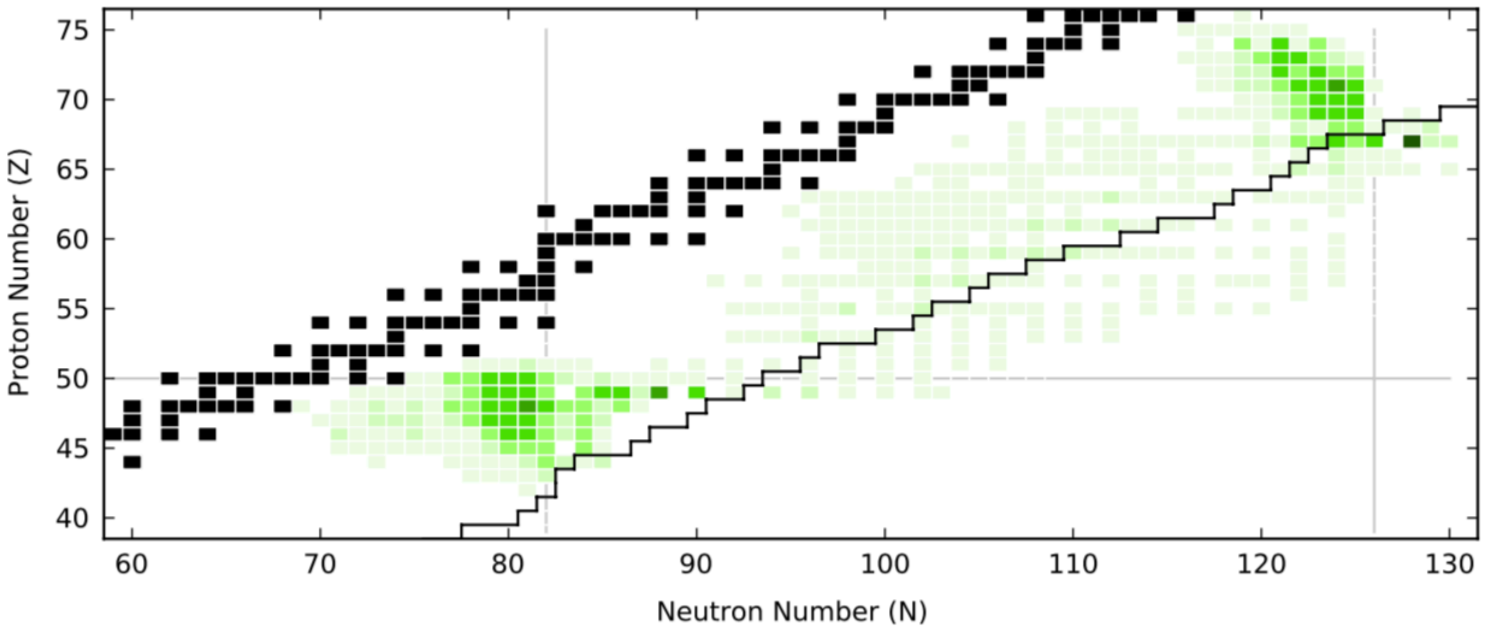
Little or no data on n-capture cross sections available → too short $T_{1/2}$
Cross section calculations necessary.
How reliable?
Often, worse than 1 order of magnitude



How to perform measurements?
→ **Indirect methods**
e.g. Trojan Horse Method, Surrogate reactions

Important <u>neutron capture rates</u> in neutron star mergers

- Along the hot r-process path no sensitivity on cross sections owing to (n,γ)⇔(γ,n) equilibrium
- **Enhanced sensitivity for neutron star mergers** since neutrons are available when (γ,n) reactions become negligible

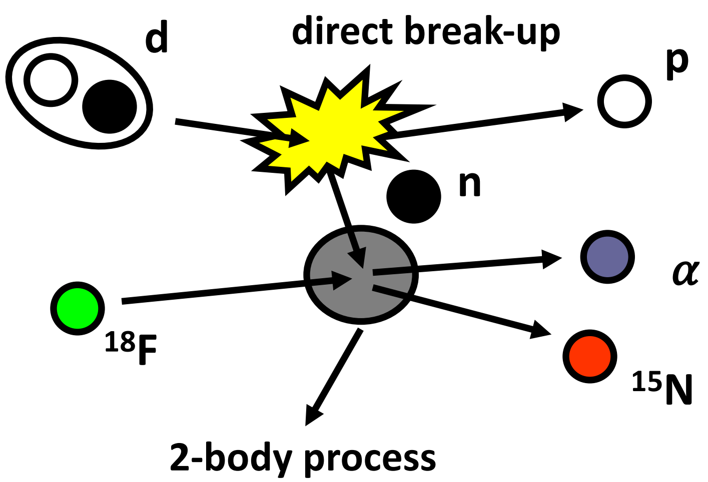


Prog. Part. Nucl. Phys. 86 (2016) 86

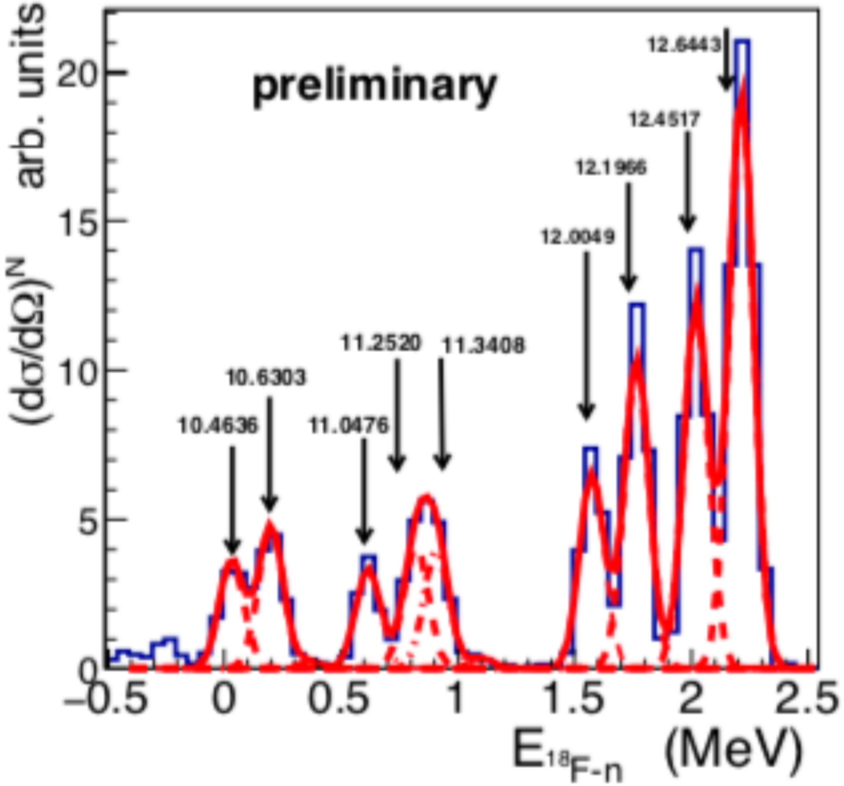
The THM for n+radioactive nucleus reactions

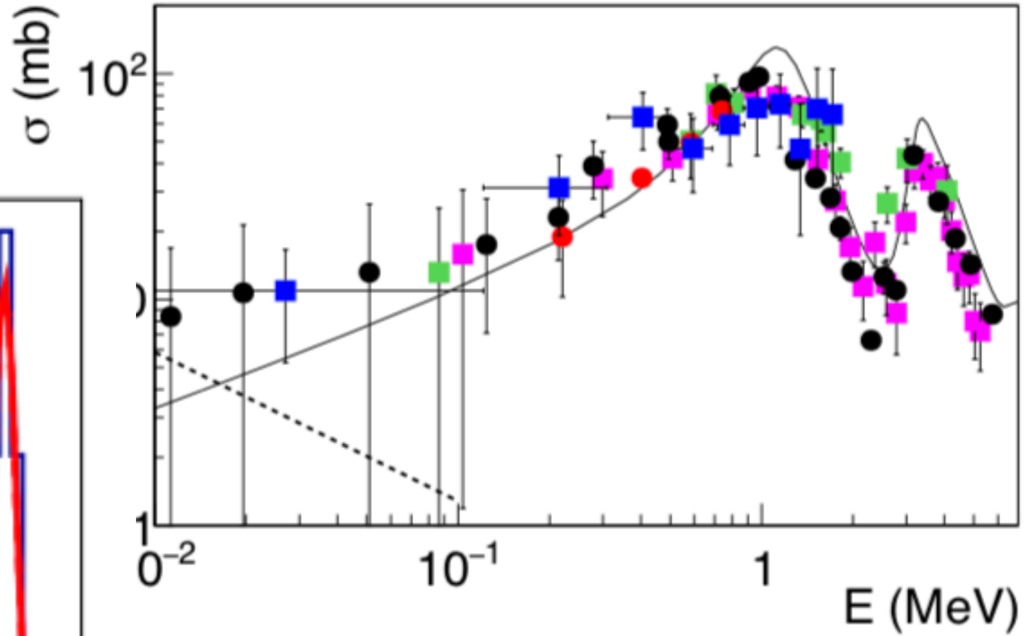
Benchmarks (stable nuclei or "almost stable"): **$^{17}O(n,\alpha)^{14}C$** PRC 95 (2017) 025807, PRC 87 (2013) 012801
$^{6}Li(n,\alpha)^{3}H$ JPG 37 (2010) 125105, EPJA 25 (2005) 649
$^{7}Be(n,\alpha)^{4}He$ submitted to APJ

First measurement of RIB(short lived!!!!!)+neutron: analysis ongoing



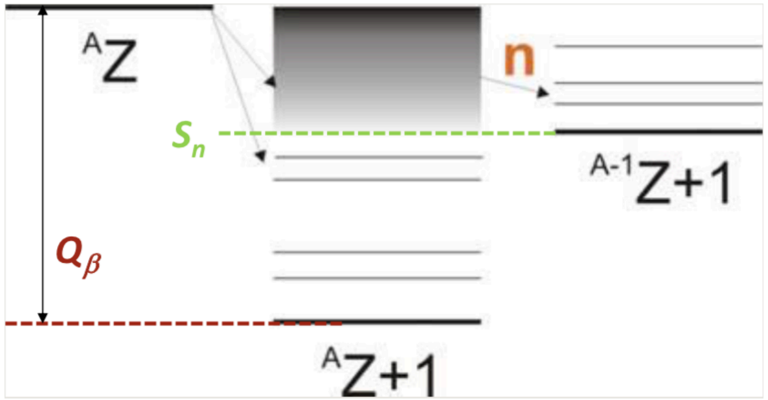
JPS Conf. Proc. 14, 021104 (2017)





$^{7}Be(n,\alpha)^{4}He$ cross section measured with the THM using *d* to transfer a neutron. Courtesy of L. Lamia

Nuclear physics input: β-delayed n-emission

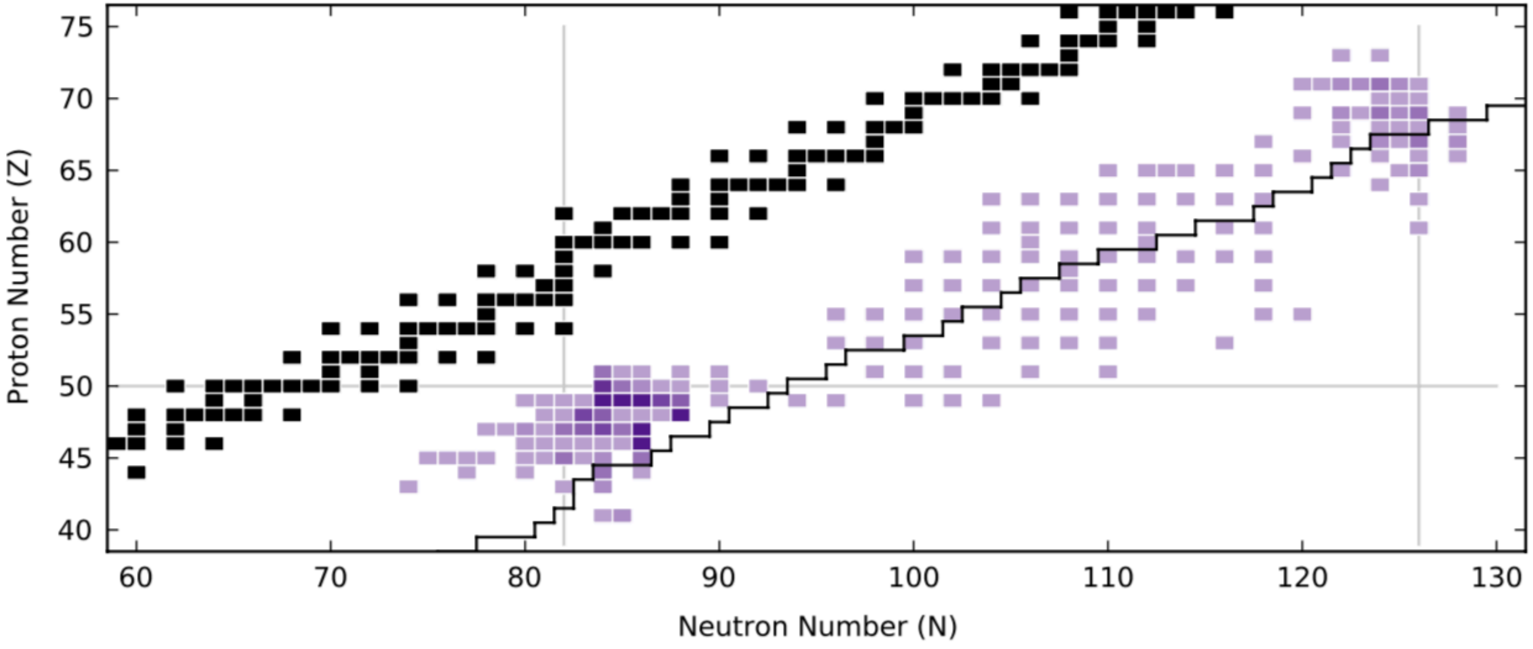


S_n (neutron separation energy) < Q_β (Q-value β-decay)

"Delayed": emission with β-decay half-life of the precursor nucleus ^{A}Z

Important nuclear structure information:

- Time-dependence of n-emission → $\mathbf{T_{1/2}(^{A}Z)}$ ≈ few ms – tens of s
- **Emission probability $\mathbf{P_n}$** and neutron spectrum: β-strength above S_n



Important <u>β-delayed neutron emitters</u> in neutron star mergers

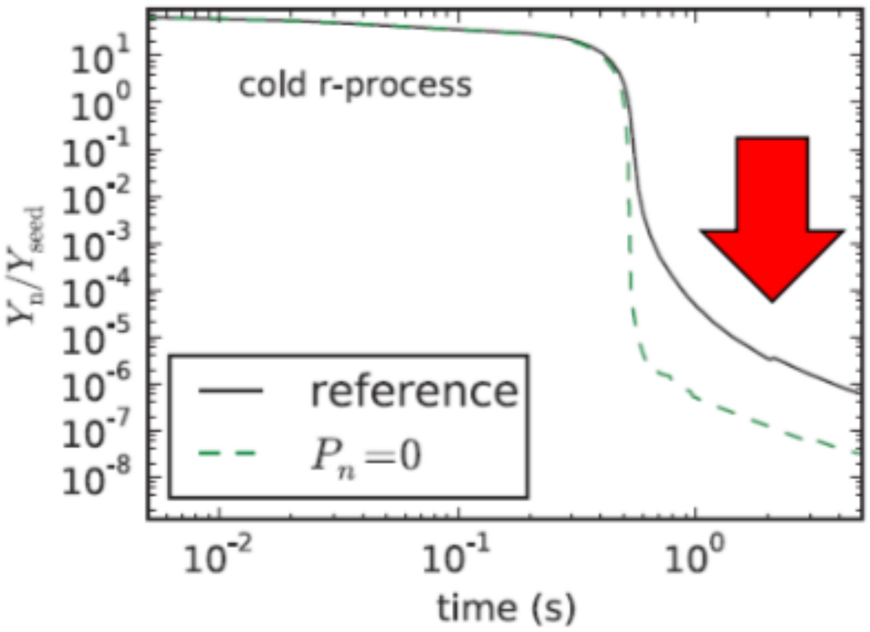
Influence on nucleosynthesis:

- Injection of neutrons during freezeout
- Production of less-neutron-rich nuclei

Reshuffle of r-process yields

Prog. Part. Nucl. Phys. 86 (2016) 86

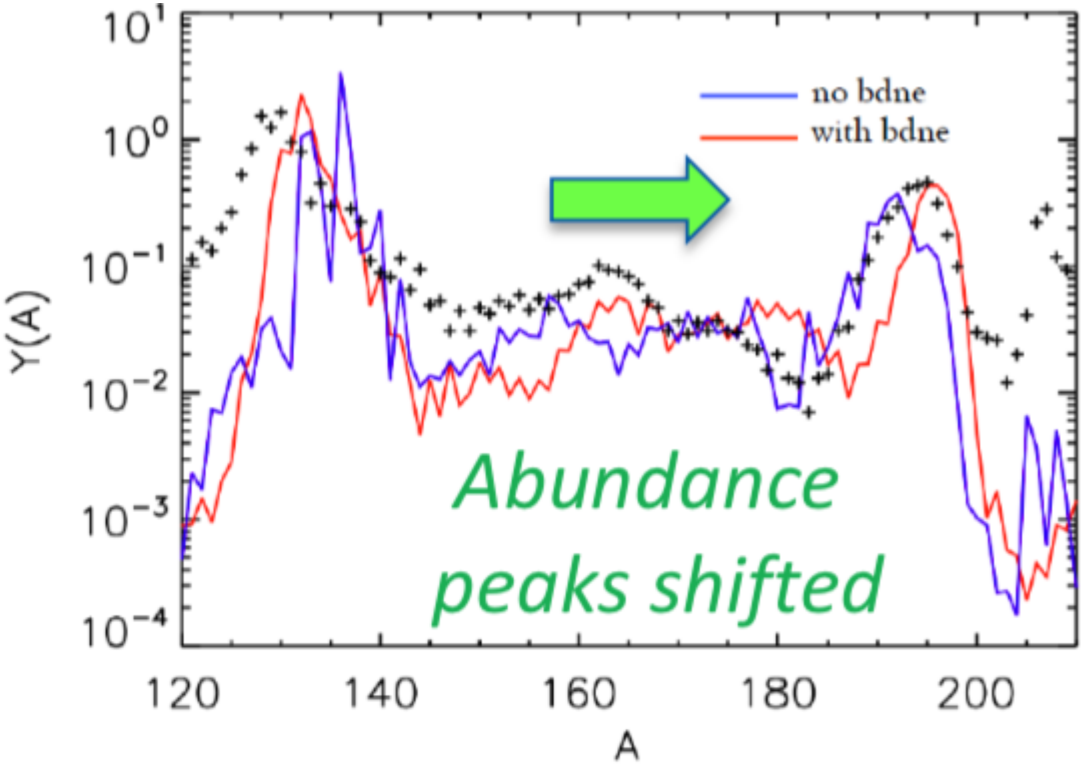
Nuclear physics input: β-delayed n-emission



PRC83, 045809 (2011)

Cold scenario: the case of neutron star mergers

Production of additional neutrons vs. depletion of neutron rich nuclei

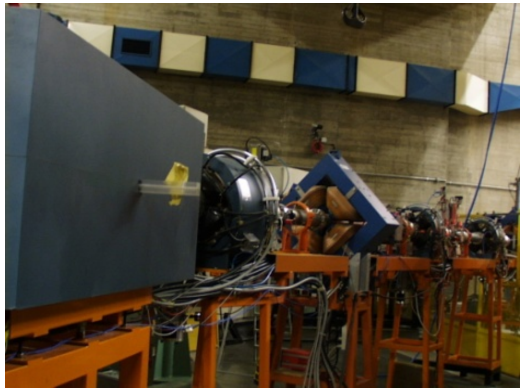


Cold evolutions have a greater availability of neutrons at late times than hot scenarios, from fission and/or from the extra β-delayed neutron emission

Thus we find the most favored solutions tend to initially populate a rare earth peak at lower A, and **late-time neutron captures shift the peak to the correct placement**.

JPG44, 034003 (2017)

POLYFEMO @ LNS



FRIBs: in-flight fragment separator

Cocktail beams
→ Possibility to measure many βn emitters at the same time.

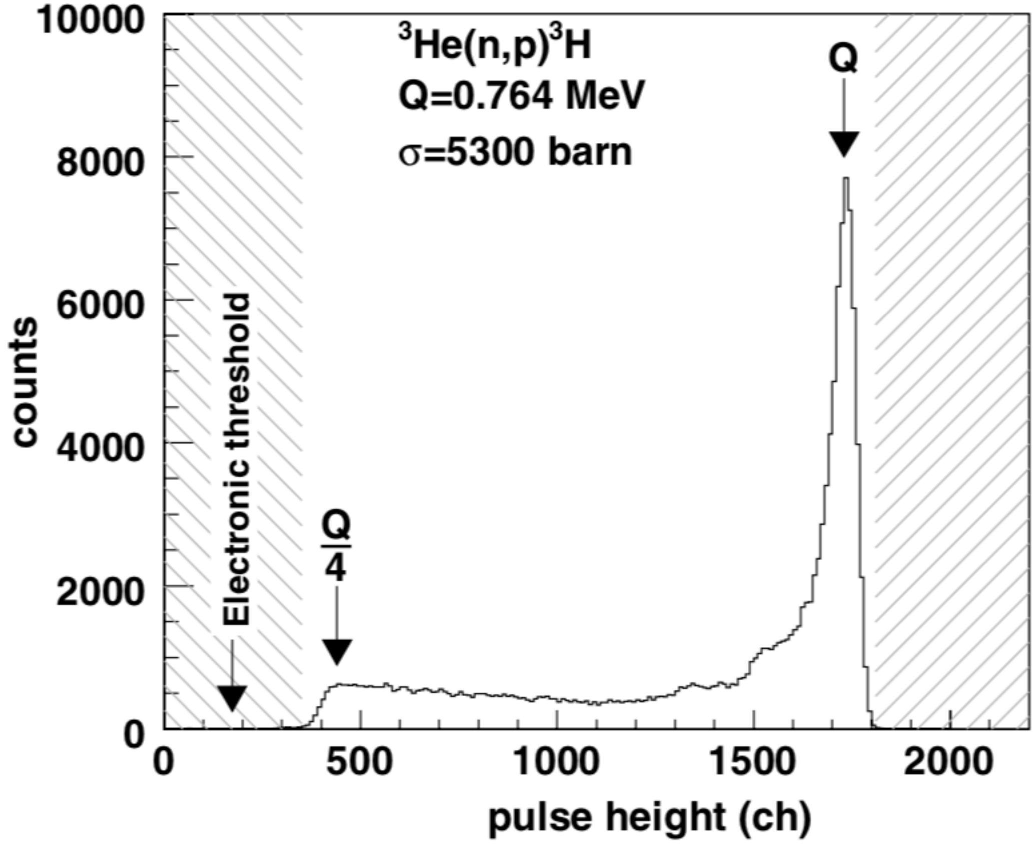
Candidate nuclei to test the approach:
^{66}Co ($T_{1/2}$ ~ 0.2 s) and ^{72}Ni ($T_{1/2}$ ~ 1.6 s)

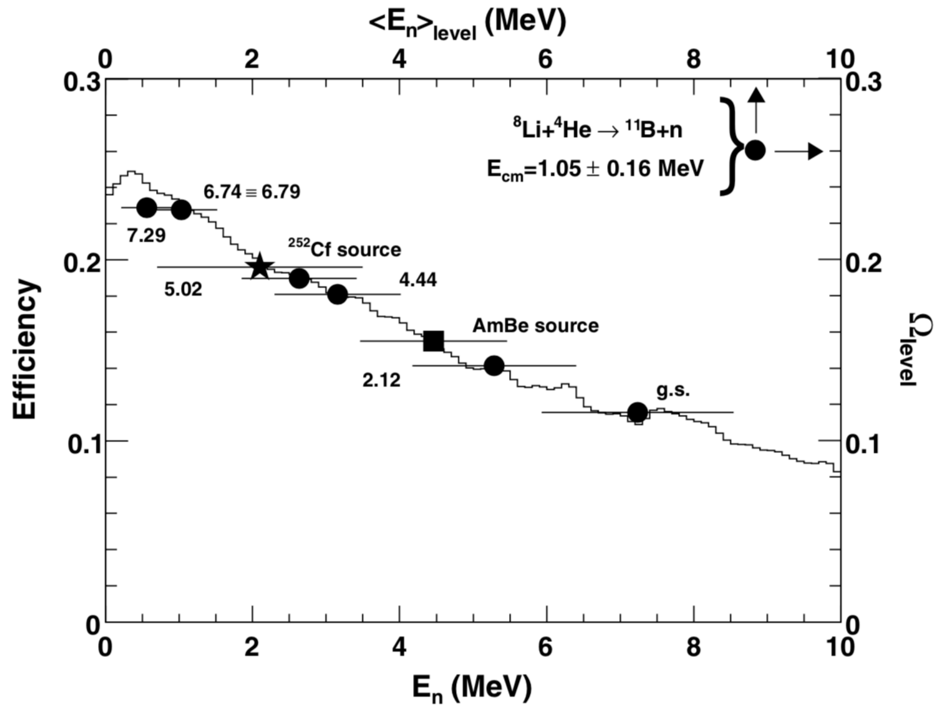
Journal of Physics: Conf. Series 1014 (2018) 012016

FRIBs will be coupled with the Polycube neutron detector for P_n measurements

In the next future, improvements in the ECR sources, Cyclotron and FRIBS (FRAISE) upgrade will extend the range of the measured nuclei

Neutron detection with POLYFEMO





Efficiency measured with sources and reactions, as well as simulated with GEANT4

Implantation chamber under construction, including beta and gamma counters

Simulation of the whole system under development using GROOT

^{3}He counters → no neutron energy measurement

large detection efficiency

4. Studying the opacity of a plasma made up of lanthanides.

Atomic physics: measurement of opacities

Neutron star merger

Kilonova

Powered by radioactive nuclei decays

- Peak luminosity: proportional to their quantity
- **When is it reached?**

Gravitational waves

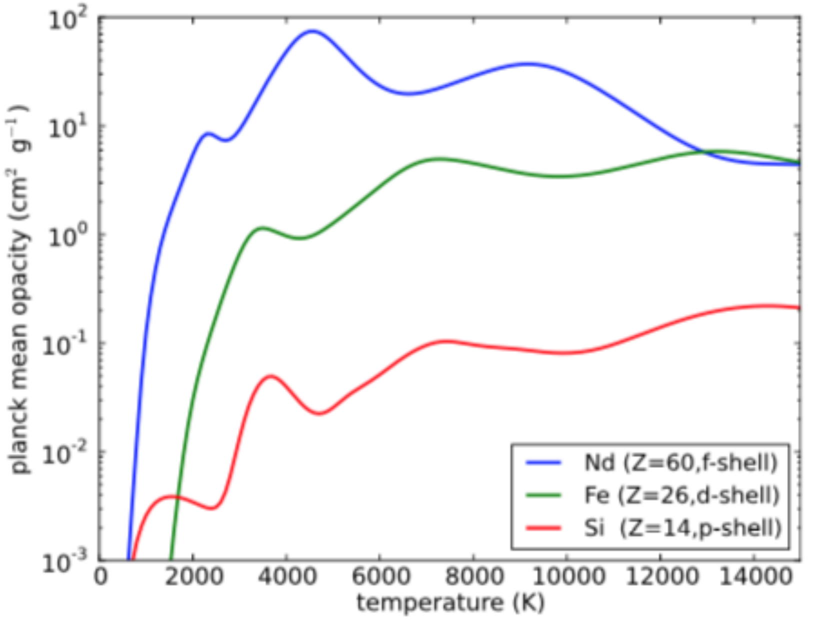
Observed using LIGO/VIRGO

What is opacity? Photon cross section per unit mass of absorbing material

→ ∝ to the number of atomic transition in the heated matter

→ ∝ to the square of number of atomic levels

The opacity of matter containing a small fraction of lanthanides is orders of magnitude larger than one containing iron peak elements



The Astrophysical Journal 774 (2013) 25

$$\kappa_{\mathrm{Fe}} \sim 0.1\, cm^2\, g^{-1};\ \kappa_{\mathrm{light-r}} \sim 1\, cm^2\, g^{-1};\ \kappa_{\mathrm{heavy-r}} \sim 10\, cm^2\, g^{-1}$$

$$2.7\ \mathrm{days} \left(\frac{\kappa}{1\,\mathrm{cm^2\,g^{-1}}}\right)^{1/2} \left(\frac{M_{\mathrm{ej}}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v_{\mathrm{ej}}}{0.1\,c}\right)^{-1/2}$$

Where:

κ → opacity

M_{ej}, v_{ej} → mass and speed of the ejected matter

Summary

1. Increasingly accurate observations call for more accurate nuclear data on the r-process

2. Constraining the r-process through a better understanding of the s-process:
    a. study of the neutron sources
    b. study of production/destruction of critical elements

3. Study of nuclear reactions involved in the r-process
    a. indirect study of n+RIB reactions
    b. Investigation of the beta-delayed neutron emission

4. Studying the opacity of a plasma made up of lanthanides in a controlled enviroments, where physical conditions similar to the ones in the ejecta can be produced.

THANKS for your attention!