Nuclear astrophysics at LNS in the multimessenger era

Marco La Cognata

Summary

1. What is multimessenger astronomy? What is the connection with nuclear physics?

2. What is the nuclear physics input affecting astrophysical observables? (light curves, abundances, luminosity, etc.)

3. What are the measurements that can be performed at LNS?

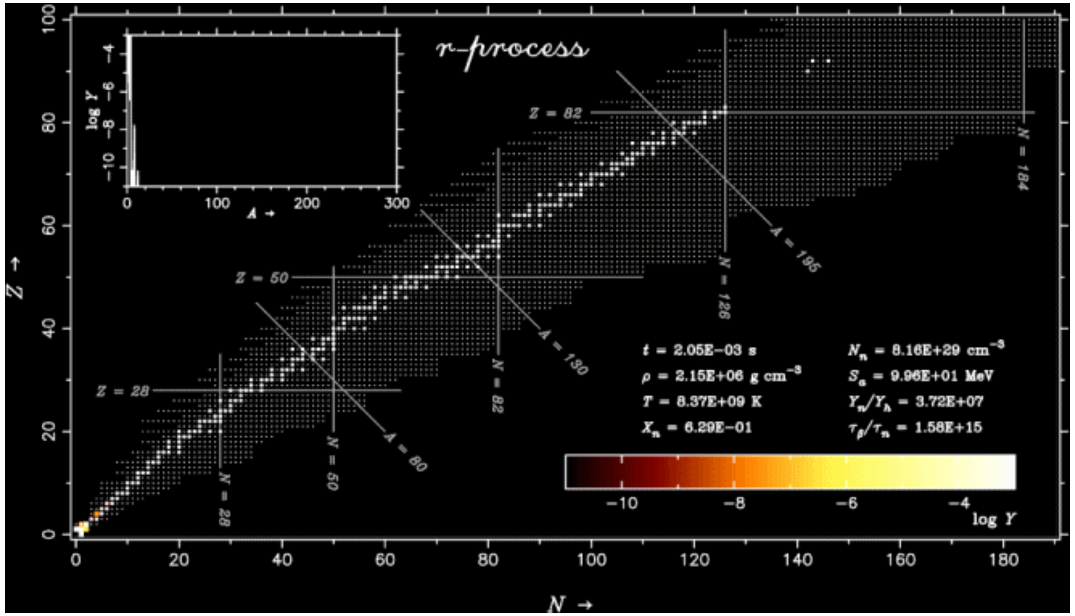
4. What are the apparatuses to be used?

5. Additional explosive scenarios

6. Measurements and papers in nuclear astrophysics in 2017 @LNS

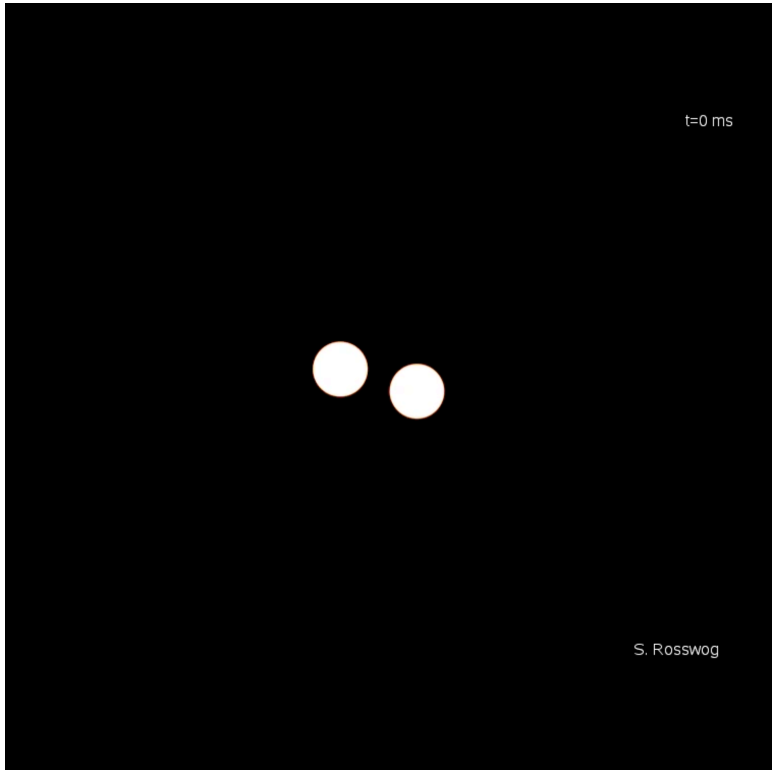
r process nucleosynthesis

- It produces **~50%** of the stable isotopes heavier than Fe
- Candidate site: **neutron star mergers**
- Nuclear physics input:
Masses, shell structure, half lives, fission parameter, P_n values (probability of neutron emission following β decay)

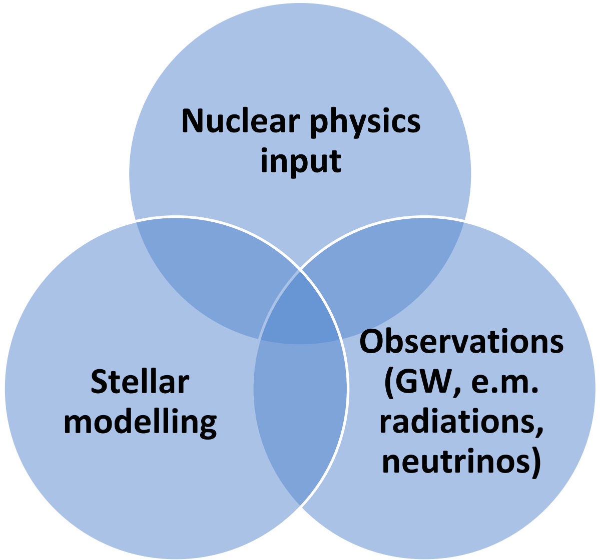


https://fr.cdn.v5.futura-sciences.com/sources/images/dossier/rte/18FuturaSciences.gif

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



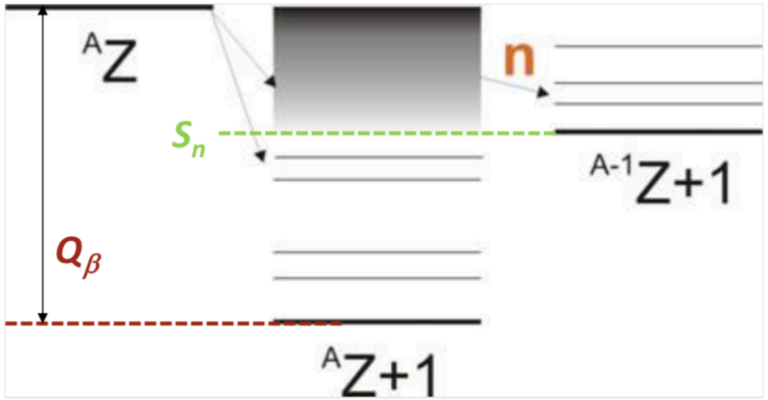
http://compact-merger.astro.su.se/Movies1/ns14_ns15_6mio_3D_density_v5.mov



→ **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

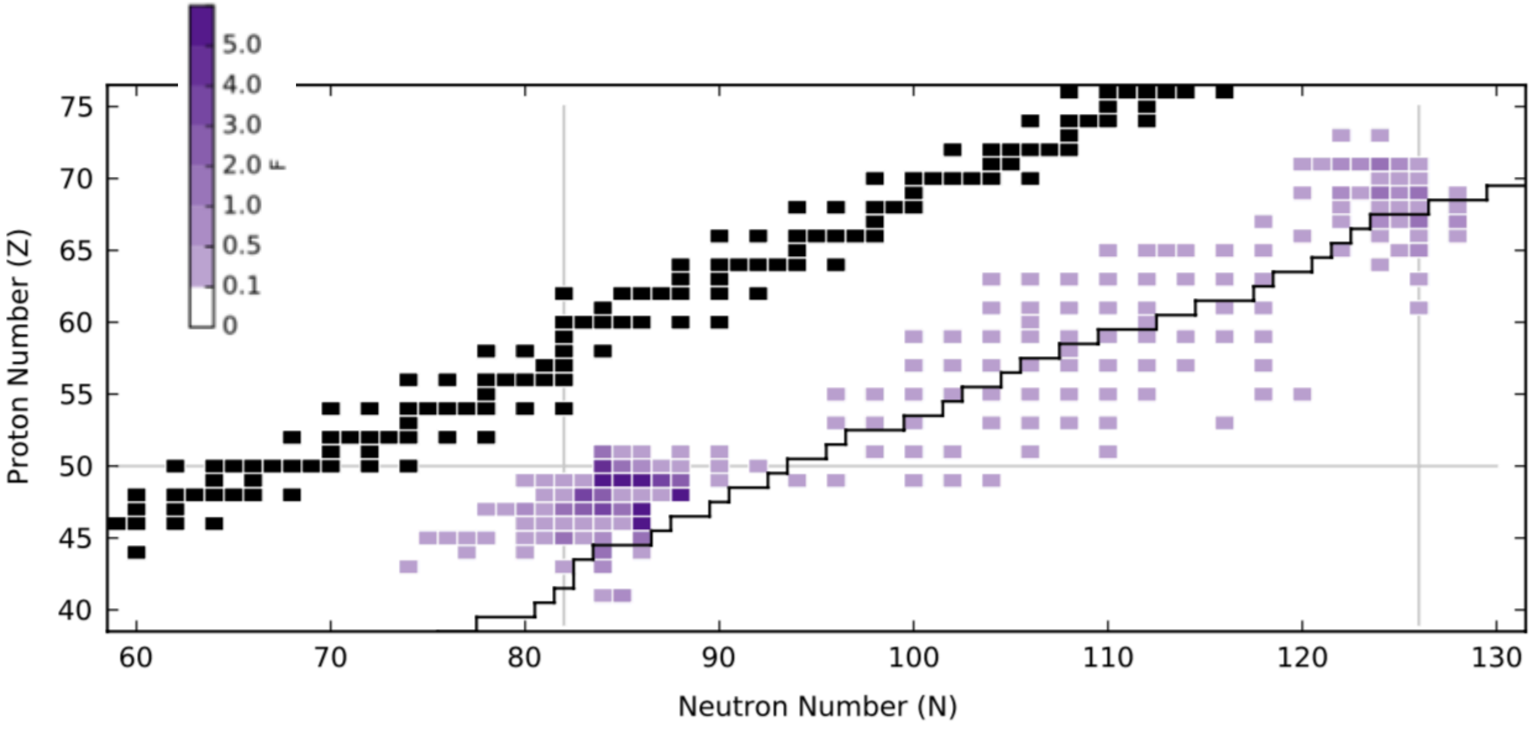
Nuclear physics input: β-delayed n-emission



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 β-delayed neutron emitters 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

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

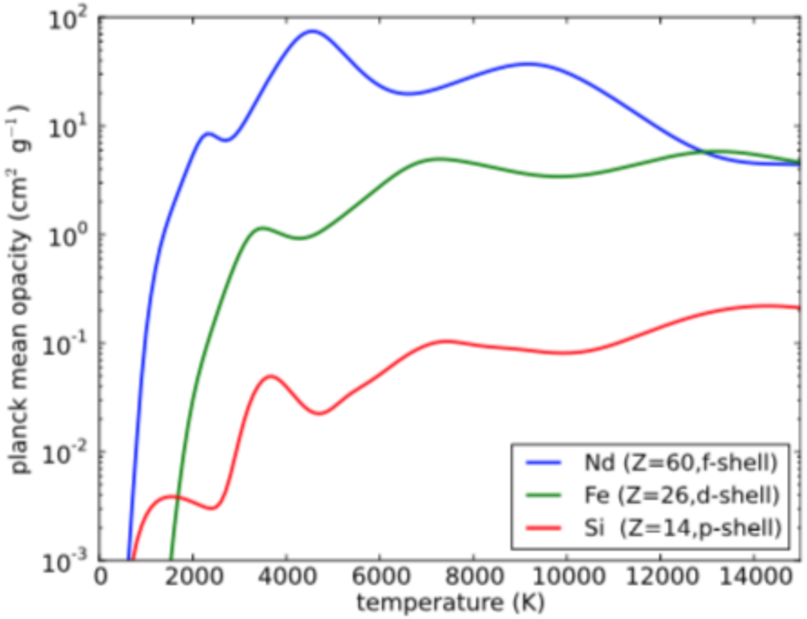
Observed using LIGO/VIRGO

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

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

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

Where:

κ → opacity

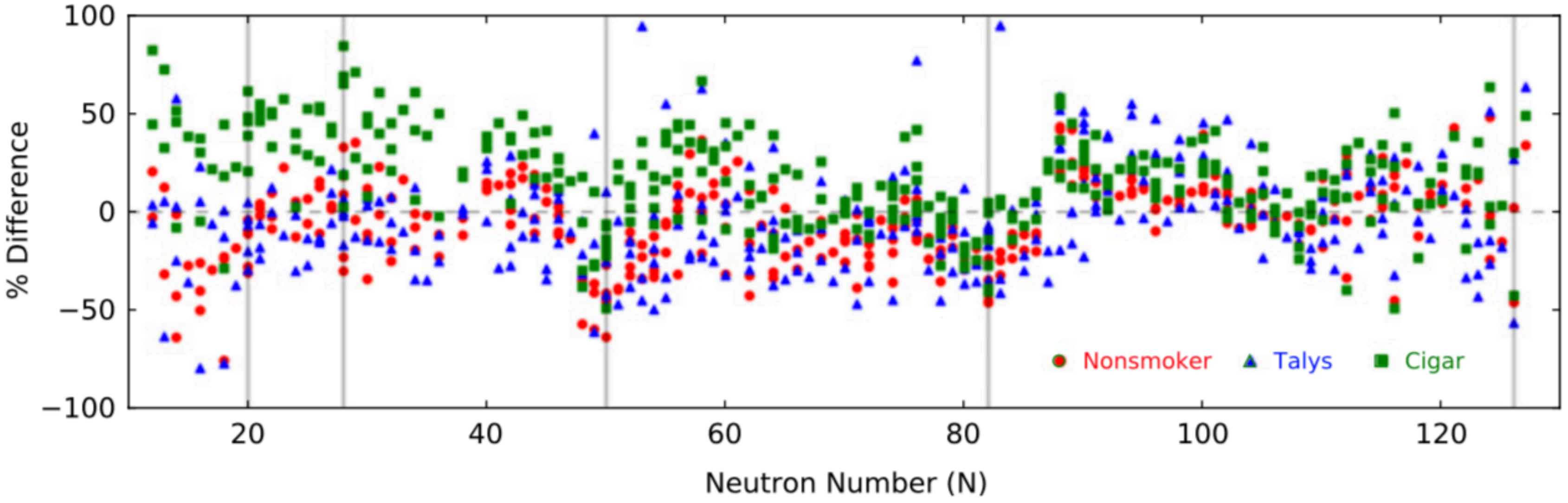
M_{ej}, v_{ej} → mass and speed of the ejected matter

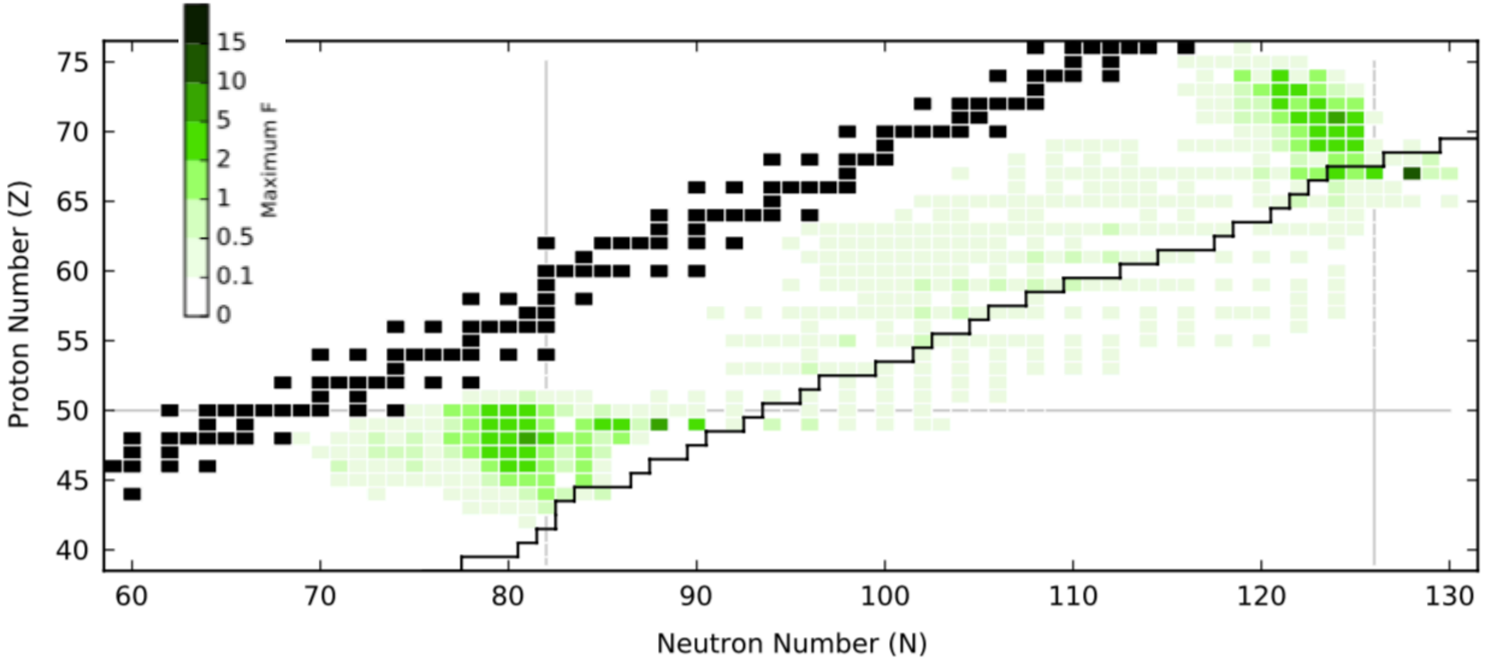
Nuclear physics input: n-capture reactions

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

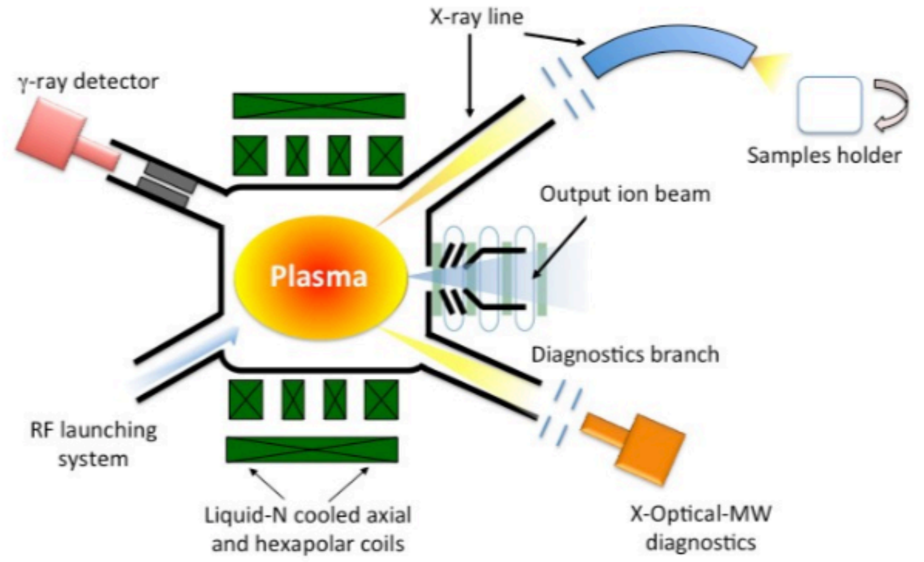
- Along the hot r-process path no sensitivity on cross sections owing to $(n,\gamma) \Leftrightarrow (\gamma,n)$ equilibrium
- **Enhanced sensitivity for neutron star mergers** since neutrons are available when (γ,n) reactions become negligible





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

LNS and multimessenger astronomy



Eur. Phys. J. A 53 (2017) 145

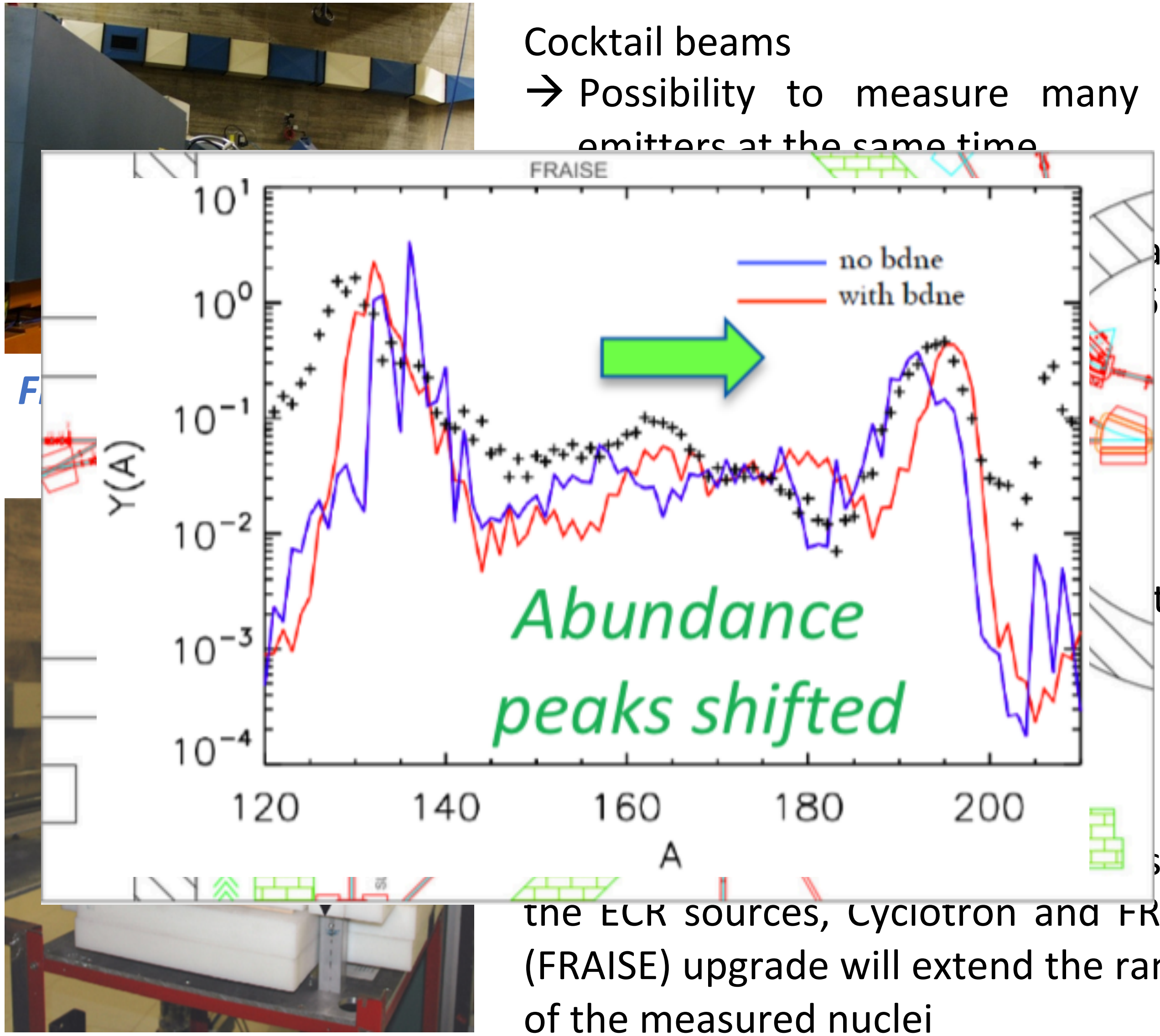
Pandora @ LNS

Production of controlled plasma at the same densities of kilonovae ejecta at peak luminosity

→ Measurement of opacities of different mixtures of atomic species

→ Accurate predictions of kilonovae light curves

→ Constraining r-process yields and kilonovae energetics



Polycube neutron detector

Cocktail beams

→ Possibility to measure many βn emitters at the same time

ach:

s)

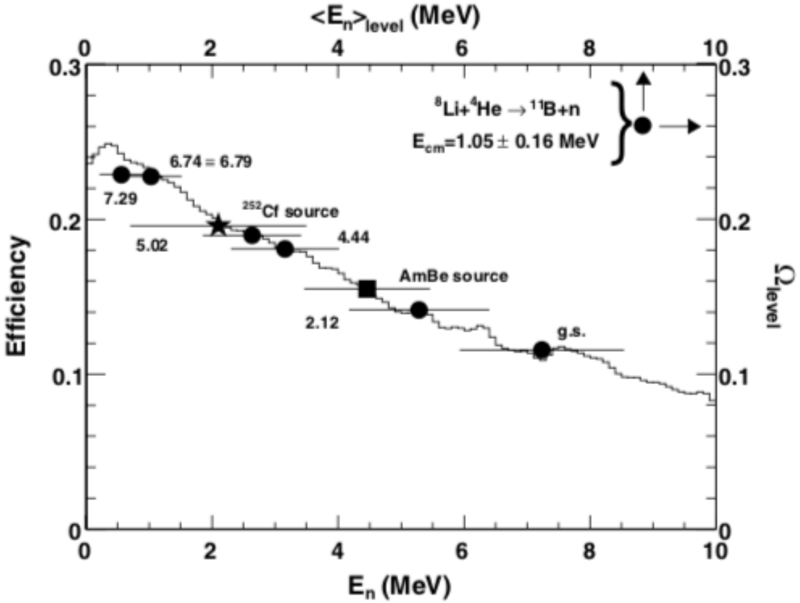
the

P_n

in

the ECR sources, Cyclotron and FRIBS (FRAISE) upgrade will extend the range of the measured nuclei

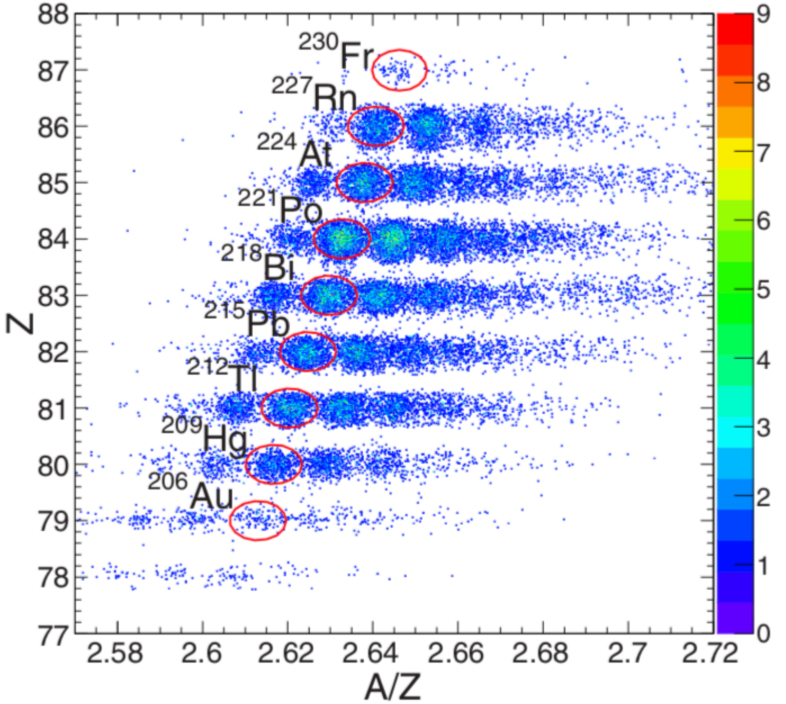
More on β-delayed n-emission



Efficiency of the Polycube → well known, many measurements of n-emitting reactions already performed

J. Phys. G: Nucl. Part. Phys. 37 (2010) 105105

Beta detector still to be developed



Opportunities of cocktail beams→ In previous experiments, an opportunity for parallel studies by means of time correlation and half-life measurements

PHYSICAL REVIEW C 95, 064322 (2017)

FRIBS/FRAISE complementary to other facilities (mostly using U fragmentation)

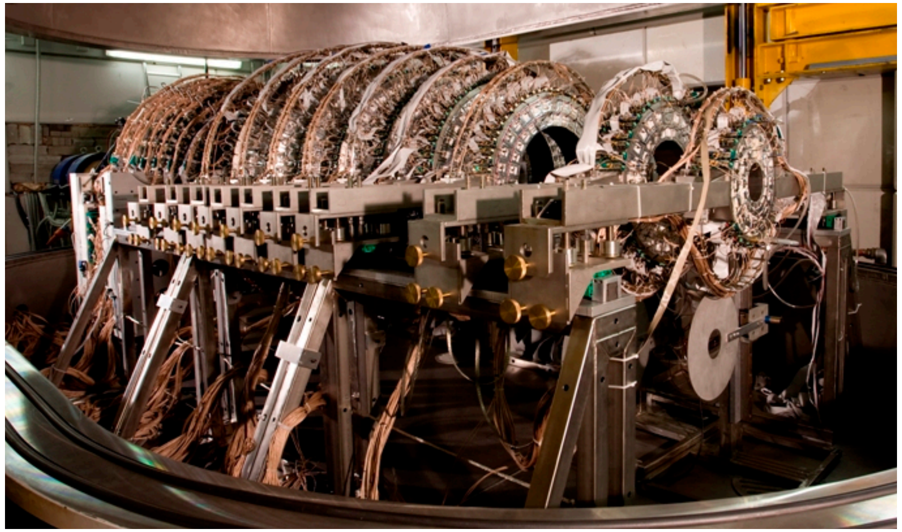
Target measurements (IF POSSIBLE!) → reaching A=150, where few measurements are present

- Study of contaminants: which would represent a removable background?
- Effect of daughter nuclei: adding up to the time correlation spectra

Neutron-capture reactions

Direct measurements of neutron-induced reactions on radioactive nuclei are impossible unless lifetimes are large enough to allow for target preparation.

→ *Need for indirect techniques*

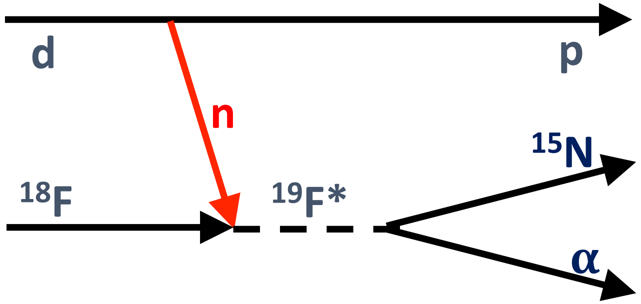


- **(n,γ) reactions**

1. Spectroscopy of neutron rich nuclei → possible use of CHIMERA
2. Use of the surrogate reaction approach PHYSICAL REVIEW LETTERS 121, 052501 (2018)

- **(n,α) or (n,p) reactions**

1. Application of the Trojan Horse Method Rep. Prog. Phys. 77 (2014) 106901



Test measurements: ^{6}Li(n,α)^{3}H, ^{10}B(n,α)^{7}Li, ^{17}O(n,α)^{14}C
(using stable nuclei)

Ongoing analysis: ^{18}F(n,α)^{15}N
(short-lived radioactive nucleus + neutron)

Constraining r-process abundances

The r-process pattern is extracted from the solar system abundances by subtracting the s-process (and p-process) contributions

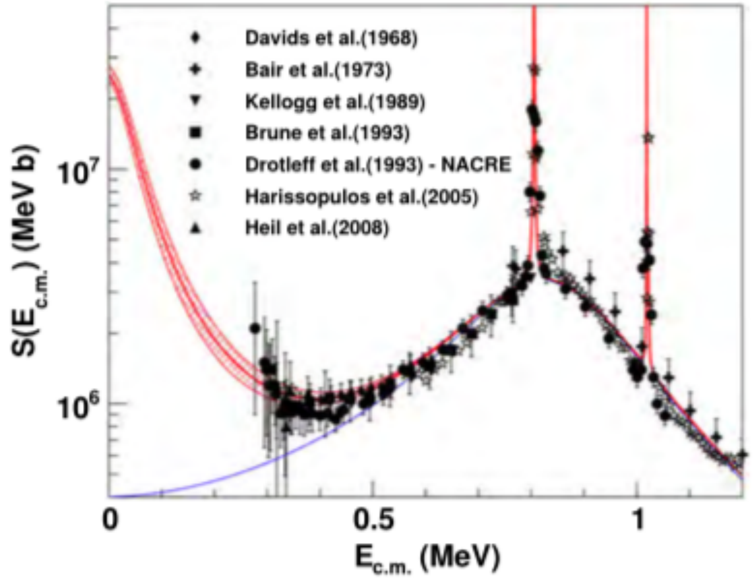
through models, the elemental yield is used to get information of r-process sites (entropy, Y_e, explosion mechanism, role of hydrodynamics)

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 $^{22}Ne(\alpha,n)^{25}Mg$**

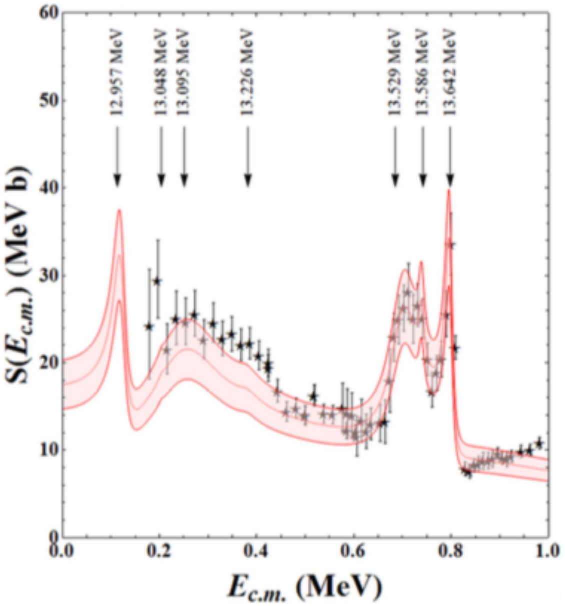
2. Constraining astrophysical models of s-process by studying production and destruction of probe nuclei (mainly ^{19}F)

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

Other multimessenger astronomy cases

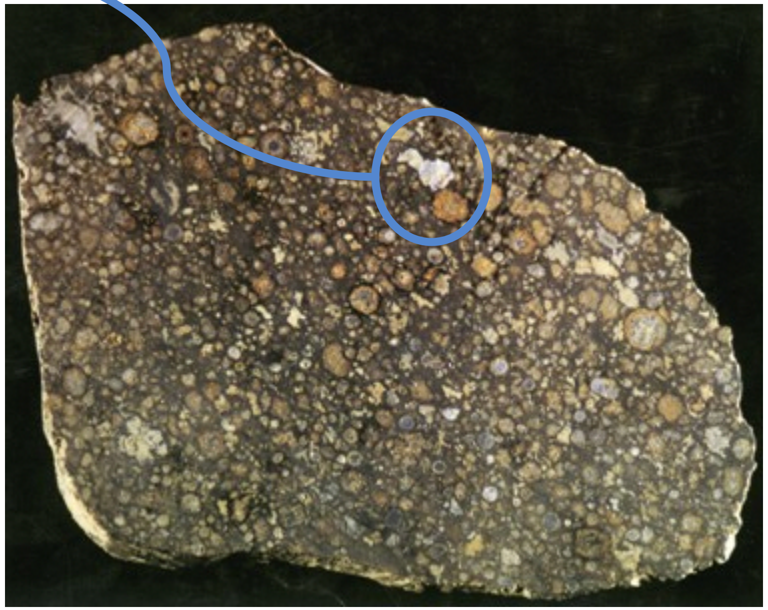
In CAIs (the oldest solid of the Solar System):
the inferred 6.5 x 10^{-5} < $(^{26}Al/^{27}Al)_0$ <2 x 10^{-6}.
There is no correlation between O- and Mg-isotope compositions.
→^{26}Al was injected into the ^{26}Al-poor protosolar nebula, possibly b
from a neighboring massive star.

Presolar grains
Corundum, hibonite and carbonaceous chondrites formed before t
the solar system show excesses in ^{26}Mg. The highest ratios are fou
originated in supernova ejecta, but the largest number of grains wi
>3 x 10^{-3} (at least 100 times larger than the solar value) are of the t
come from low mass stars.

Observation of 1808.65 keV γ-rays from the decay of ^{26}Al to ^{26}Mg in the interstellar medium demonstrated that ^{26}Al nucleosynthesis does occur in the **present Galaxy**. The present-day equilibrium mass of ^{26}Al was found to be 2.8±0.8 $M_\odot$.

The irregular distribution of ^{26}Al emission seen along the plane of the Galaxy provided the main argument for the idea that **massive stars** dominate the production of ^{26}Al. (Diehl et al 2006)

In CAIs (the oldest solid of the Solar System):
the inferred 6.5 x 10^{-5} < $(^{26}Al/^{27}Al)_0$ <2 x 10^{-6}.
→^{26}Al was injected into the ^{26}Al-poor protosolar nebula, possibly by a wind from a neighboring massive star.



Presolar grains:
Corundum, hibonite and carbonaceous chondrites formed before the birth of the solar system show excesses in ^{26}Mg. The highest ratios are found in grains originated in supernova ejecta, but the largest number of grains with $^{26}Al/^{27}Al$ >3 x 10^{-3} (at least 100 times larger than the solar value) are of the type that come from **low mass stars**.

STATUS OF THE ART

PHYSICAL REVIEW C **76**, 045804 (2007)

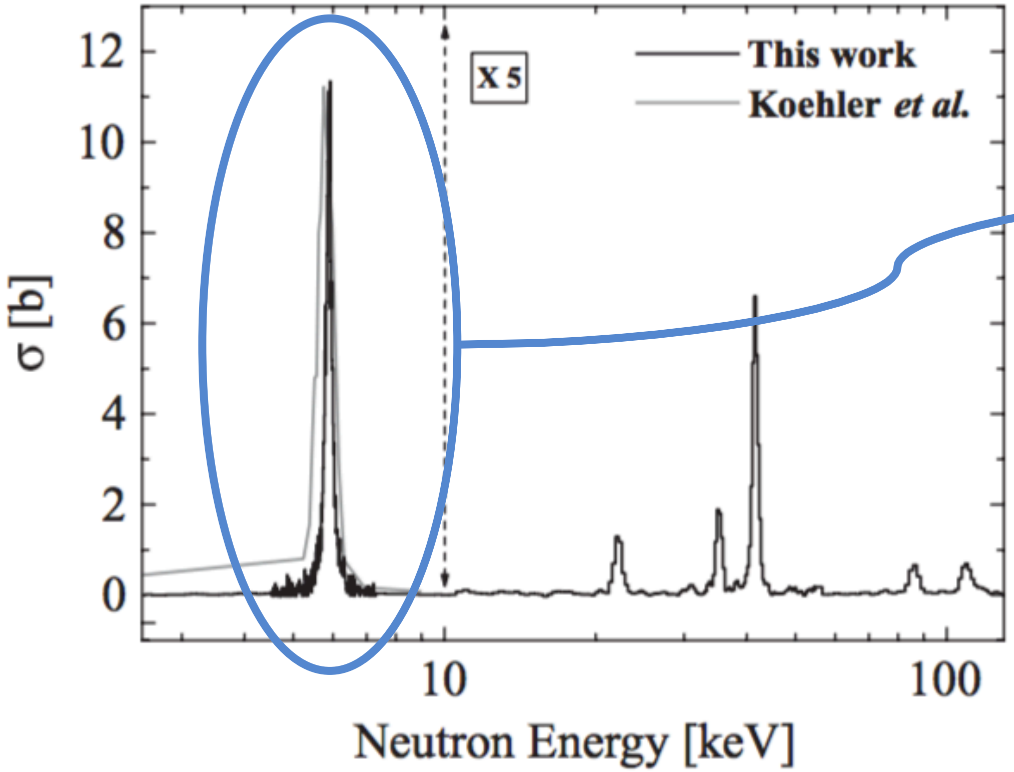
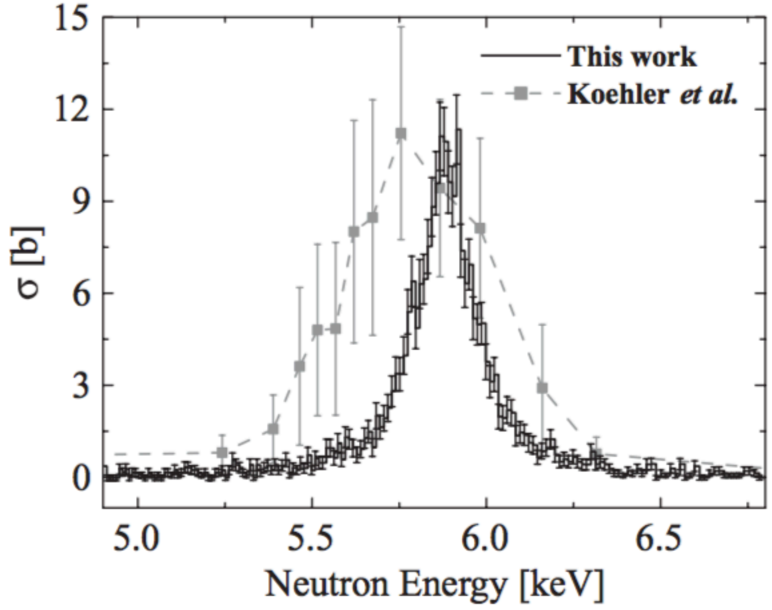


FIG. 5. ^{26}Al$(n, \alpha_0 + \alpha_1)^{23}$Na cross section determined in this work (black line) compared with the ^{26}Al$(n, \alpha_0)^{23}$Na cross section obtained by Koehler *et al.* [11] (gray line).



Two data sets available at low energies, showing large discrepancy.

- Koehler *et al.* (1993)
- De Smet *et al.* (2007)

The MACS from the latter work s have to be considered as lower limits for kT above 22 keV

STATUS OF THE ART

The Astrophysical Journal Supplement Series, 193:16 (23pp), 2011 March

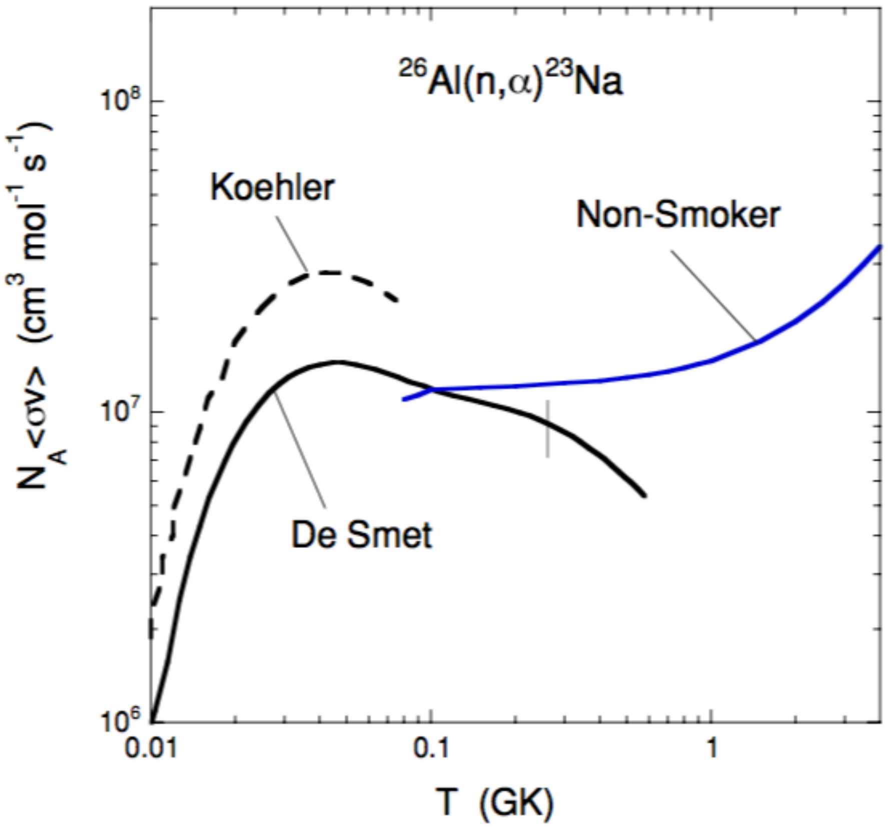


Figure 15. Reaction rates for ^{26}Al(n,α)^{23}Na: black solid line, De Smet et al. (2007); dashed line, Koehler et al. (1997); and blue solid line, Rauscher & Thielemann (2000). The first two rates are based on experimental results, while the latter rate is estimated using the Hauser–Feshbach model. Beyond the vertical line, near $T \approx 0.26$ GK, the experimental rate of De Smet et al. (2007) represents a lower limit. Note that for this comparison only, the rates represent "laboratory rates," i.e., they do not account for thermal target excitations.

Temperatures of interest → No experimental data available

- 1.1 GK (convective shell C/Ne burning)

Reaction[b]	Rate Multiplied By					
	100	10	2	0.5	0.1	0.01
^{26}Al^g(n,p)^{26}Mg	0.017	0.16	0.63	1.3	1.9	2.0
^{26}Al^g(n,α)^{23}Na	0.12	0.54	...	...	...	...
^{26}Al^m(n,p)^{26}Mg	0.58	...	...	...	...	...

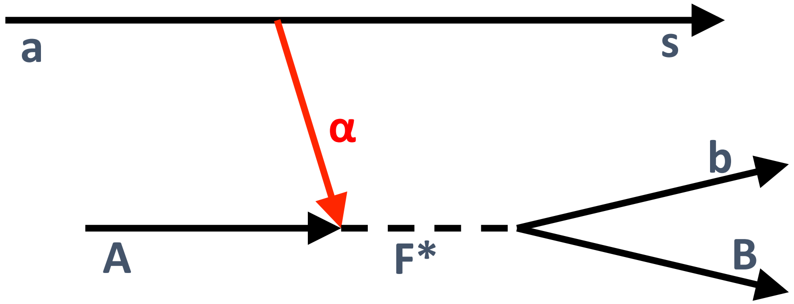
- 2.3 GK (explosive Ne/C burning)

Reaction[b]	Rate Multiplied By					
	100	10	2	0.5	0.1	0.01
^{26}Al^g(n,p)^{26}Mg	0.017	0.14	0.57	1.6	2.9	3.8
^{26}Al^g(n,α)^{23}Na	0.21	0.54	...	...	...	...
^{26}Al^m(n,p)^{26}Mg	0.36	...	...	...	...	...
^{26}Al^m(n,α)^{23}Na	0.79	...	...	...	...	...

- 0.05 – 0.5 GK (AGB stars)

→ Large discrepancy between available data sets

Nuclear astrophysics @ FRIBS/FRAISE



Using ^{6}**Li** or ^{20}**Ne** we can transfer a α particle and induce the reaction of astrophysical importance at the relevant energies

^{14}O(α,p)^{17}F → **breakout from the hot CNO cycle**: in explosive hydrogen burning, this reaction determined the permanent loss of catalysts leading to the production of heavy (A>100) proton-rich nuclei

^{13}N(α,p)^{16}O → In **asymptotic giant branch (AGB) stars**, the ^{13}C(α,n)^{16}O reaction is the n-source for heavy element production. However, the ^{13}C supply might be reduced if ^{13}N is burnt to ^{16}O before it decays → **influence on the s-process** in massive AGB stars

^{34}Ar(α,p)^{37}K → ^{34}Ar is a waiting point in **x-ray bursts**: if the (α,p) reaction rate is weak OR if the temperature is too low to overcome the Coulomb barrier, nuclear flow must await β decay before continuing on → **influence on nucleosynthesis and luminosity**

^{18}Ne(α,p)^{21}Na → it influences X-ray burst light curves as well as nucleosynthesis, in particular the abundance of ^{15}N, ^{18}F, ^{21}Ne and ^{33}S in the ashes of the thermonuclear runaway

Complementary to SPES
https://web.infn.it/spes/images/NEW_SITE/PDF/SPES_Beam_Tables/4_beam_spes_all.pdf

Nuclear astrophysics @ LNS: recent studies

THM has been successfully applied by the LNS nuclear astrophysics group over the past 25 years to many reactions of astrophysical interests. Here are a few examples of works published in 2018

nature
International journal of science

Letter | Published: 23 May 2018

An increase in the $^{12}C + {}^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino, C. Spitaleri, M. La Cognata, S. Cherubini, G. L. Guardo, M. Gulino, S. Hayakawa, I. Indelicato, L. Lamia, H. Petrascu, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, R. Spartá & L. Trache

Nature **557**, 687–690 (2018) | Download Citation

The Astrophysical Journal, 860:61 (11pp), 2018 June 10 https://doi.org/10.3847/1538-4357/aac207

The $^{19}F(\alpha, p)^{22}Ne$ Reaction at Energies of Astrophysical Relevance by Means of the Trojan Horse Method and Its Implications in AGB Stars

G. D'Agata[1,2], R. G. Pizzone[1], M. La Cognata[1], I. Indelicato[1], C. Spitaleri[1,2], S. Palmerini[3,4], O. Trippella[3,4], D. Vescovi[3,4], S. Blagus[5], S. Cherubini[1,2], P. Figuera[1], L. Grassi[5], G. L. Guardo[1], M. Gulino[1,6], S. Hayakawa[1,7], R. Kshetri[1,8], L. Lamia[1,2], M. Lattuada[1,2], T. Mijatović[5], M. Milin[9], Đ. Miljanić[5,10], L. Prepolec[5], G. G. Rapisarda[1], S. Romano[1,2], M. L. Sergi[1,2], N. Skukan[5], N. Soić[5], V. Tokić[5], A. Tumino[1,6], and M. Uroić[5]
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Received 2018 January 16; revised 2018 March 27; accepted 2018 April 27; published 2018 June 12

PHYSICAL REVIEW C **97**, 065801 (2018)

Trojan horse measurement of the $^{10}B(p,\alpha_0)^7Be$ cross section in the energy range from 3 keV to 2.2 MeV

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(Received 7 November 2017; revised manuscript received 12 February 2018; published 1 June 2018)

The European Physical Journal A
November 2018, 54:189 | Cite as

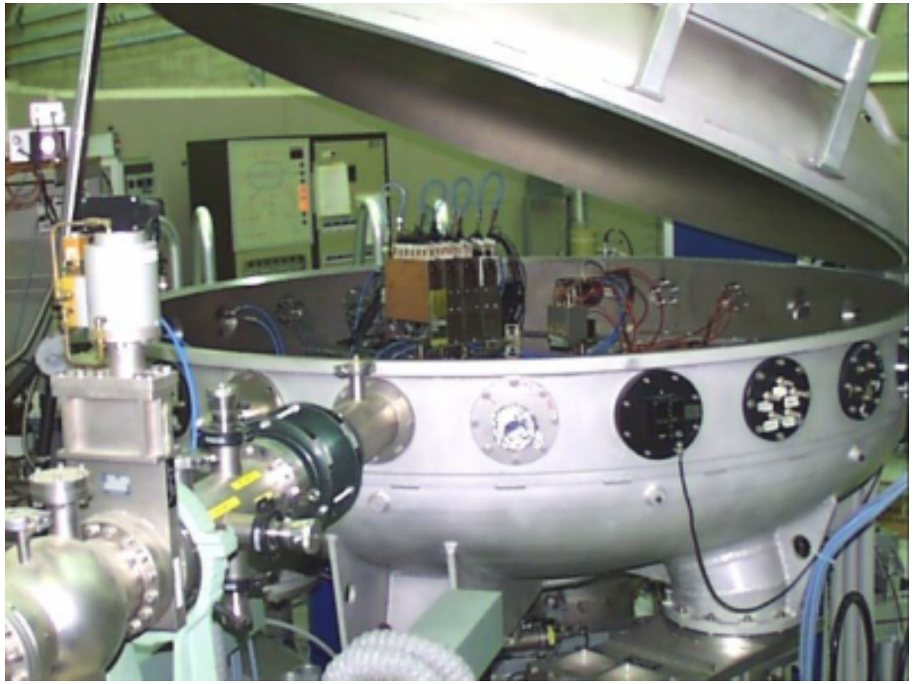
Study of the $^{10}B(p,\alpha_1)^7Be$ reaction by means of the Trojan Horse Method

Authors | Authors and affiliations

G. G. Rapisarda, C. Spitaleri, A. Cvetinović, R. Spartà, S. Cherubini, G. L. Guardo, M. Gulino, M. La Cognata, L. Lamia, R. G. Pizzone, S. Romano, M. L. Sergi, A. Tumino

Regular Article - Experimental Physics
First Online: 08 November 2018

Nuclear astrophysics with LNS tandem in 2017



LNS TANDEM and CT2000 scattering chamber plays a very important role for nuclear astrophysics measurements

List of experiments performed in 2017:

1. 25Mg(n,a)22Ne with THM to study the 22Ne(a,n)25Mg reaction
2. 27Al(p,a)24Mg with the THM: study of the 26Al problem and of the NeNa cycle
3. 10Be-9Be reactions to investigate cluster structures of astrophysical interest
4. 17O-a scattering measured with the TTIK approach for AGB nucleosynthesis
5. 10Be-a scattering with TTIK for studying 14C cluster states
6. 19F(p,a)16O cross section measurement to study fluorine nucleosynthesis

Final remarks

Multimessenger astronomy ushered us into a high-precision astrophysical era, calling for increasingly accurate measurements of nuclear properties well outside the stability valley

Facilities and know-how present at LNS make it possible to tackle the questions raised by observations (with SC and TANDEM)

The physical problems to be investigated are mostly complementary to the one addressed by many laboratories worldwide

Future upgrades of LNS facilities will make it possible to extend the fields to be explored and the corresponding precision

Thanks for your attention

The ASFIN Nuclear Astrophysics Collaborations

C.Spitaleri, R. Alba, S. Cherubini, A. Di Pietro, P. Figuera, M.La Cognata, L.Lamia, M. Lattuada, C. Maiolino, G. Manicò, R.G. Pizzone, M.L. Pumo, G.G. Rapisarda, S.Romano, D. Santonocito, R. Spartà,

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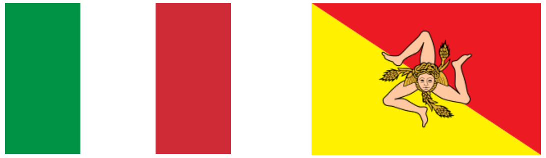

International Collaborations

Texas A&M, USA: C. Bertulani, V. Goldberg, G. Rogachev, A.M. Mukhamedzhanov
C.N.S. Riken, Wako, Japan: S. Kubono, H. Yamaguchi, S. Hayakawa
CIAE, Beijing, China: S. Zhou, C. Li, Q. Wen
Institute for nuclear research, Rez, Czech rep.: V. Kroha, V. Burjan, G.D'Agata , J. Mrazek
UNAM, Mexico: E. Chavez, L. Acosta
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IFIN & ELI-NP, Bucharest, Romania: L. Trache, G.L. Guardo, D. Lattuada, C. Matei, D. Balabanski
Atomki, Debrecen, Hungary: G.G. Kiss
CSNSM, Orsay, France: A. Coc , F. Hammache, N. De Sereville
Florida State University USA: I. Wiedenhover
Notre Dame University USA: M. Wiescher, M. Couder
University of Pisa: S. Degl'Innoccenti, P. Prada Moroni
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GSI, Darmstadt, Germany: S. Typel
Tashkent State University, Uzbekistan: R. Yarmukhamedov, S. Artemov