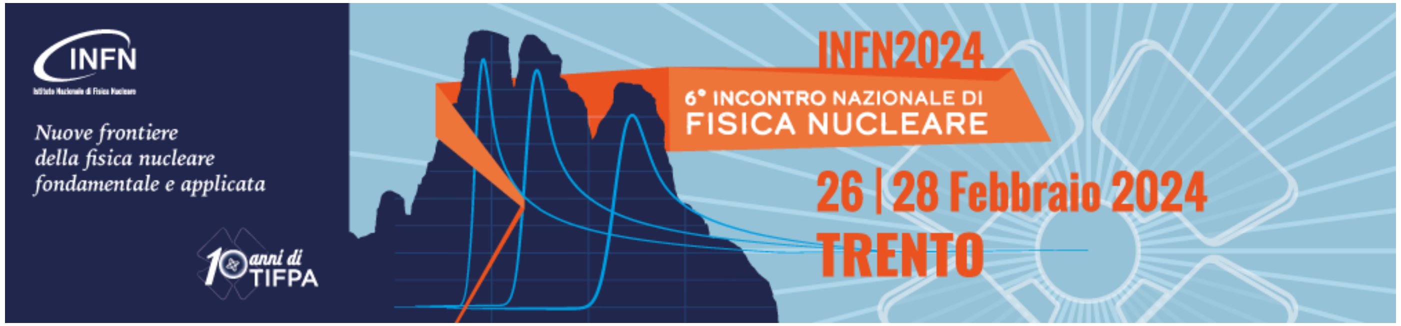


Study of reactions of astrophysical interest with indirect methods

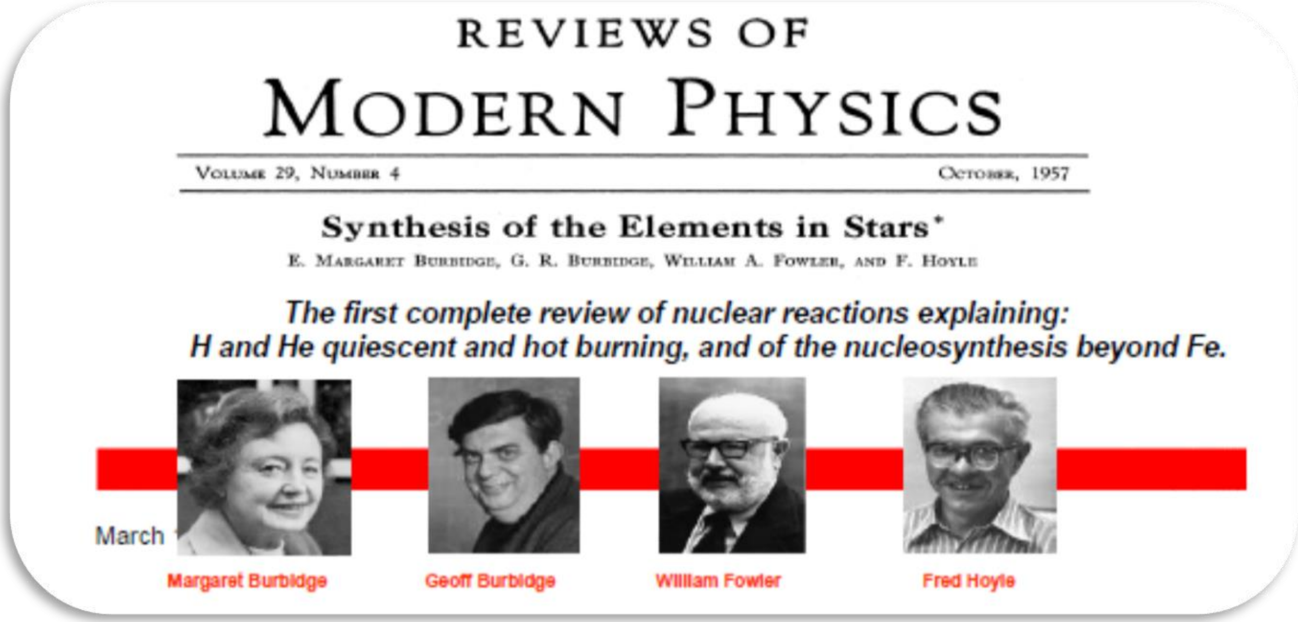
G.L. GUARDO

Experimental nuclear astrophysics

... Everything starts from the B²FH review paper of 1957,

the basis of the modern nuclear astrophysics

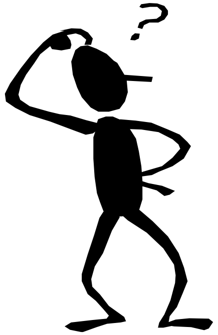
this work has been considered as the greatest gift of astrophysics to modern civilization

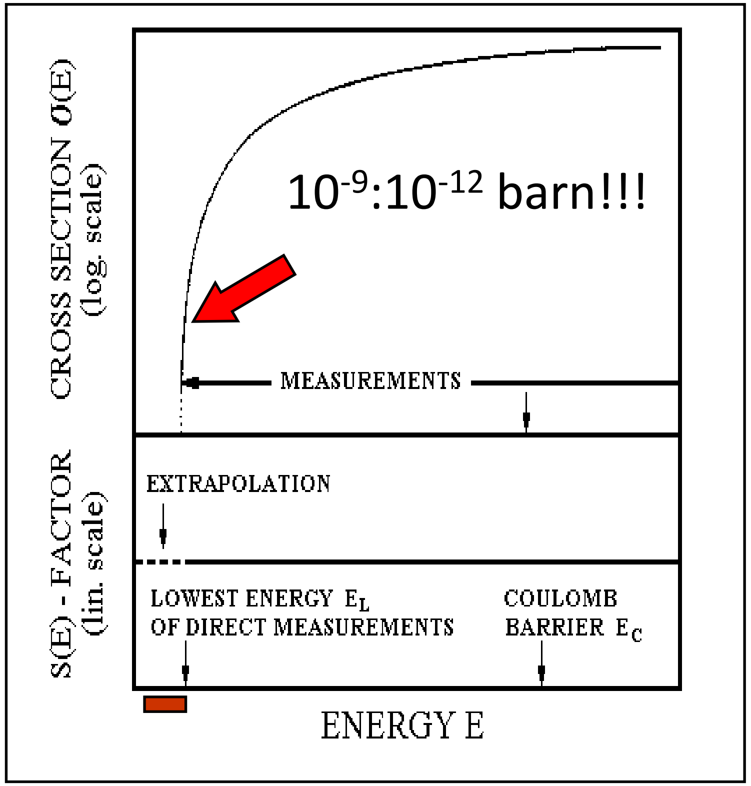


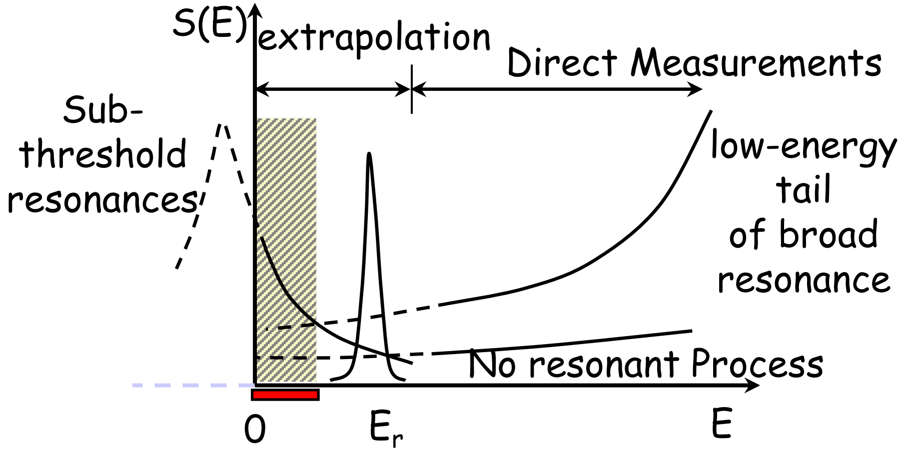
The elements composing everything from planets to life were forged inside earlier generations of stars!
Nuclear reactions responsible for both ENERGY PRODUCTION and CREATION OF ELEMENTS

Direct measurements

- Very small cross section values reflect in a faint statistic;
- Very low signal-to-noise ratio makes hard the investigation at astrophysical energies;
- Instead of the cross section, the S(E)-factor is introduced





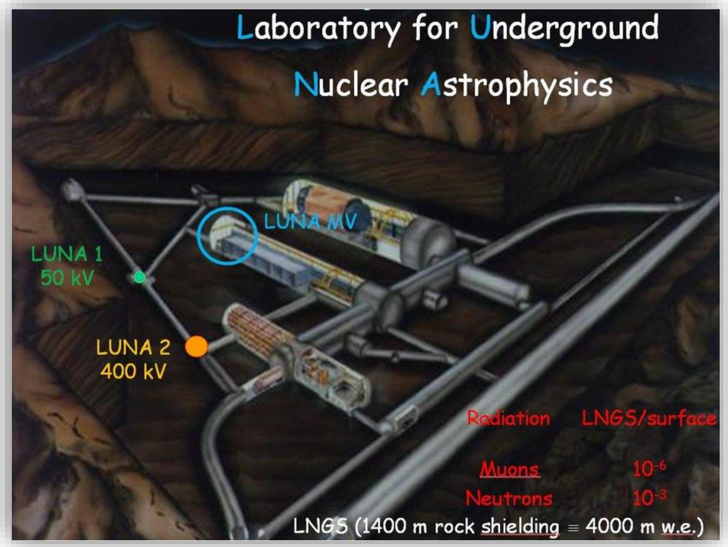


$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

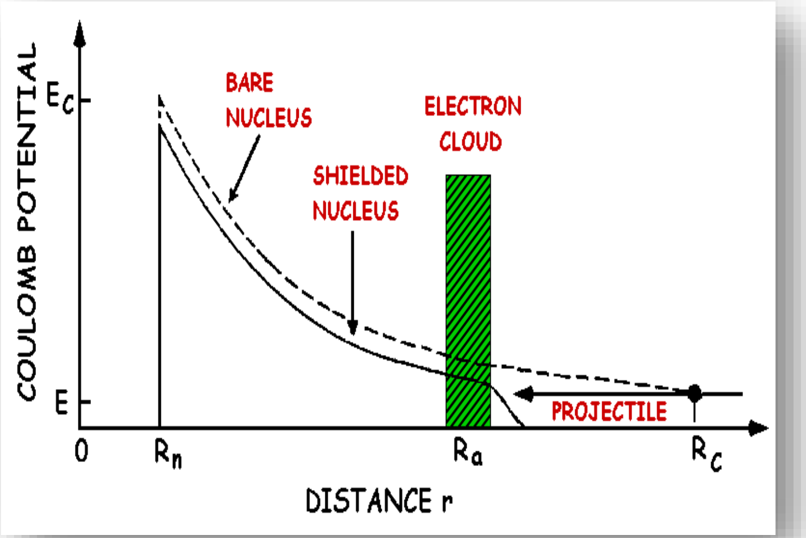
Direct measurements

Several efforts have been made in the last years in order to **improve the signal-to-noise ratio** for low-energy cross section measurement.

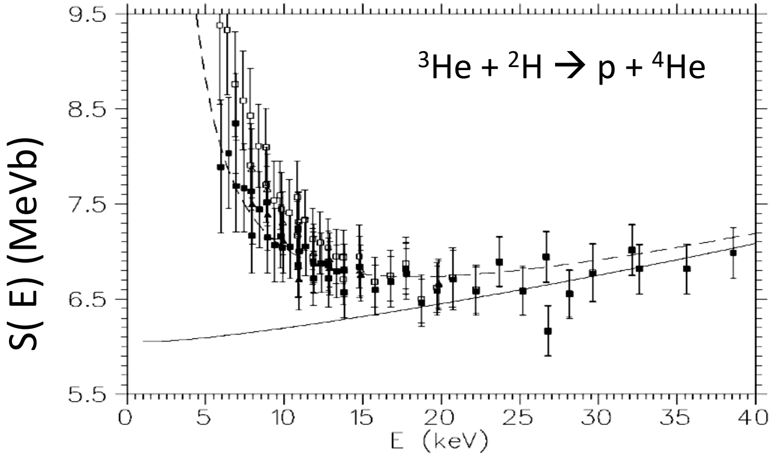
- ➢ **Longer measurements**
- ➢ **Higher beam currents**
- ➢ **4π detectors**
- ➢ **Pure targets**
- ➢ **Underground laboratories**



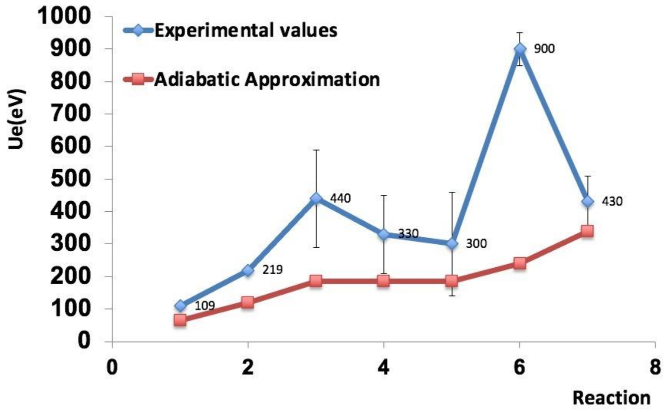
Electron screening



Due to the electron cloud surrounding the interacting ions the projectile feels a reduced barrier



Reaction	U_{ad} (eV)	U_{exp} (eV)	Reference
$^6Li(p,\alpha)^3He$	186	440±150	[Engstler et al.(1992)]
$^6Li(d,\alpha)^4He$	186	330±120	[Engstler et al.(1992)]
$H(^7Li,\alpha)^4He$	186	300±160	[Engstler et al.(1992)]
$^2H(^3He,p)^4He$	65	109±9	[Aliotta et al.(2004)]
$^3He(^2H,p)^4He$	120	219±7	[Aliotta et al.(2004)]
$H(^9Be,\alpha)^6Li$	240	900±50	[Zahnow et al.(1997)]
$H(^{11}B,\alpha)^8Be$	340	430±80	[Angulo et al. (1993)]



Theory.vs.Experiment→

Far to be understood…

Stellar Plasma

Indirect methods

Beyond the extrapolation procedure, indirect and innovative experimental methods are highly demanded to address missing or incomplete aspects led by the complexity of nuclear reactions in stars.

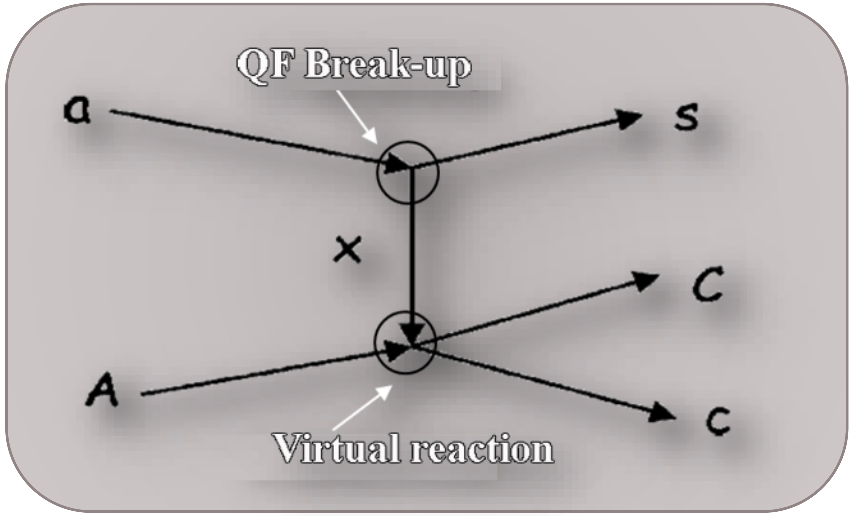
The basic idea of using an indirect method in order to measure a cross section of interest for nuclear astrophysics is to overcome the experimental problems related to the low-energy regime typical of an astrophysical scenario using peculiar nuclear properties or dynamics that can provide information about the nuclear reaction of interest.

Among the others, the main indirect methods developed in the last decades are:

- **Trojan Horse Method**
- **Asymptotic Normalization Coefficient**
- **Coulomb Dissociation**
- **Surrogate Reaction Method**
- **Life-time measurements**
- **Nuclear structure and spectroscopy measurements**

The Trojan Horse Method

*The idea of the **THM** is to extract the cross section of an astrophysically relevant two-body reaction **A+x→c+C** at low energies from a suitable three-body reaction **a+A→c+C+s***



Quasi free kinematics is selected

- ✓ **only *x* - A interaction**
- ✓ ***s* = spectator (p_s~0)**

$E_A > E_{Coul}$ →

- **NO coulomb suppression**
- **NO electron screening**
- **NO centrifugal barrier**

- *THM Review paper→ Spitaleri C. et al., Prob. of Fund. Mod. Phys., 1991*
  Tumino A. et al., An. Rev. Nuc. and Part. Sci. 2021

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Theoretical Approach

The TH-nucleus is chosen because of:

- **its large amplitude in the *a*=*x*⨁*s* cluster configuration;**
- **its relatively low-binding energy;**
- **Its known *x-s* momentum distribution $|\Phi(p_S)|^2$ in *a*.**

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - B_{xs}$$

$B_{x\text{-}s}$ plays a key role in compensating for the beam energy thanks to the *x-s intercluster motion* inside a, it is possible to span an energy range of several hundreds of keV with only one beam energy

In the Plane Wave Impulse Approximation (PWIA) the cross section of the three body reaction can be factrorized as

$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c} \propto KF \cdot |\Phi(p_s)|^2 \cdot \frac{d\sigma_{Ax}}{d\Omega}$$

Three body measured cross section

Calculated kinematical factor

Fourier trasform for the x-s intercluster motion

Astrophysically relevant two body cross section

Measurement with THM

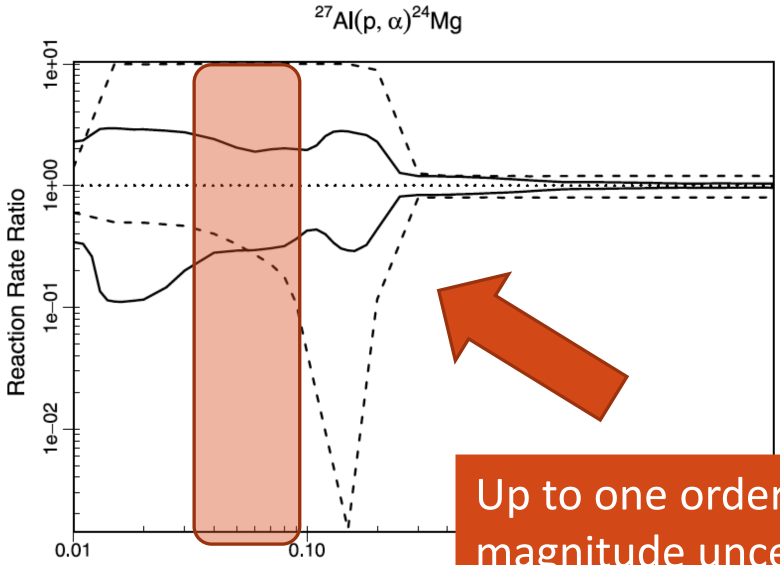
^{27}Al: an ingredient in multimessenger astronomy

MgAl cycle in massive stars

It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei

^{26}Al/^{27}Al abundance ratio

^{26}Al abundance is used to estimate the number of Galactic neutron stars and, therefore, of neutron star mergers (sources of GW). The ^{26}Al/^{27}Al is generally estimated, so it is influenced by ^{27}Al abundance predictions

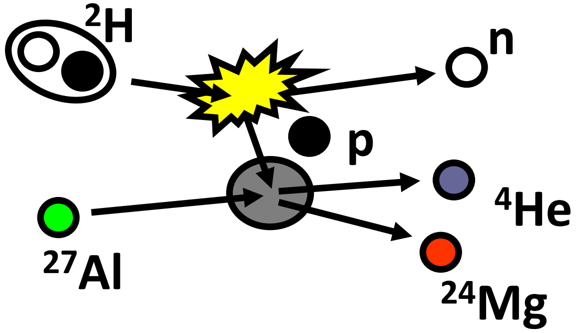


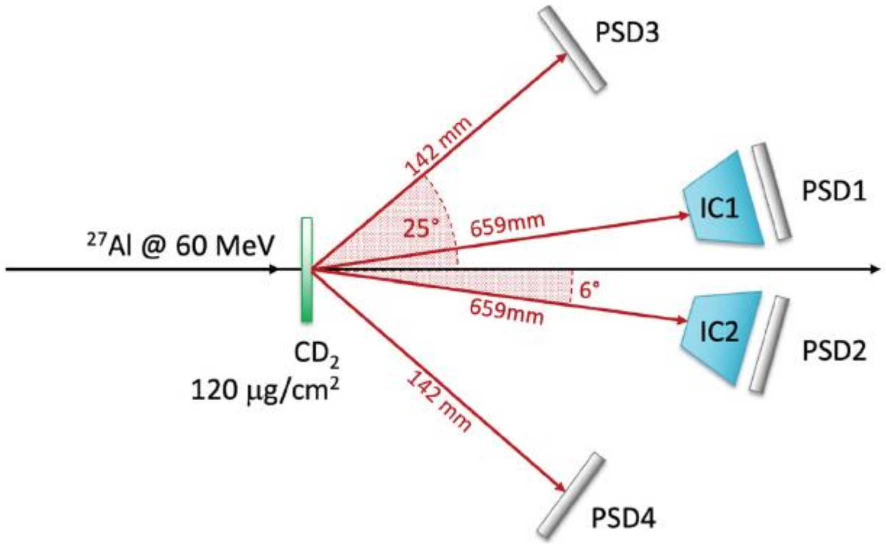
Up to one order of magnitude uncertainty

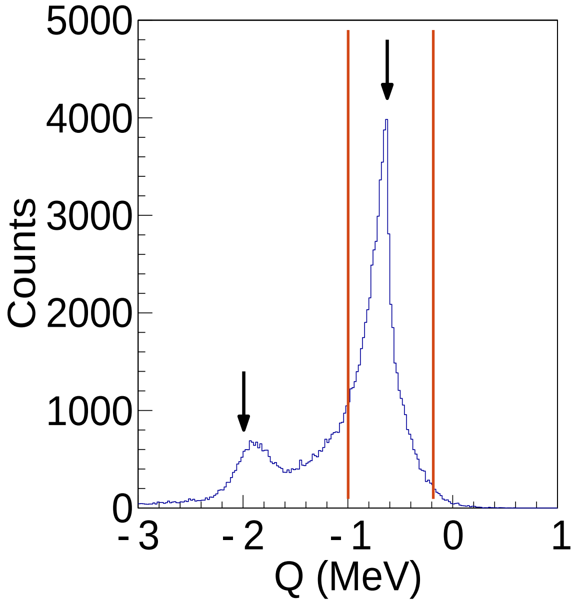
The most recent review [Iliadis et al. (2010)] shows that for most low-energy resonances only an upper limit is known

→ These resonances are the most influent for astrophysics

Measurement with THM

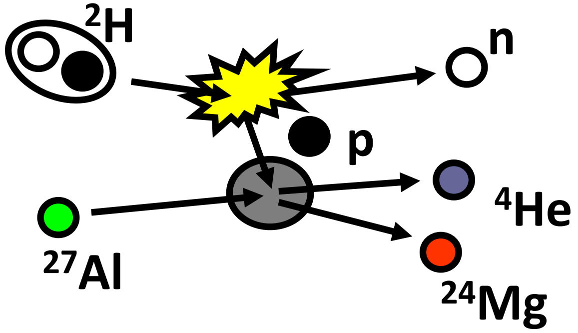


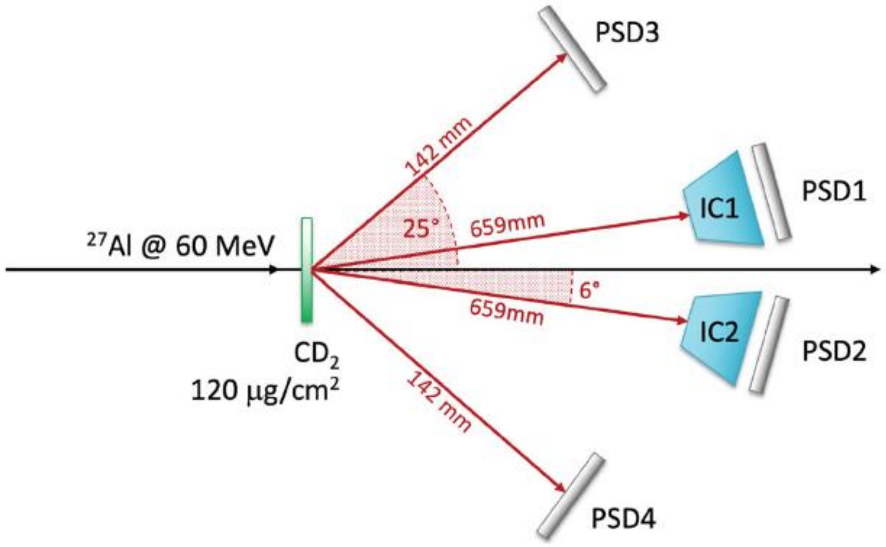


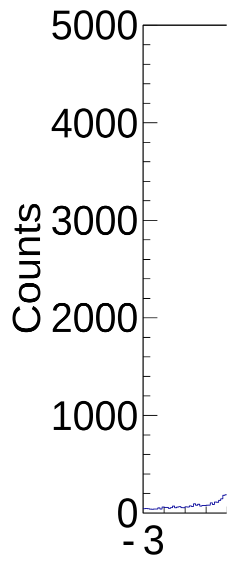


» ***Channel selection***

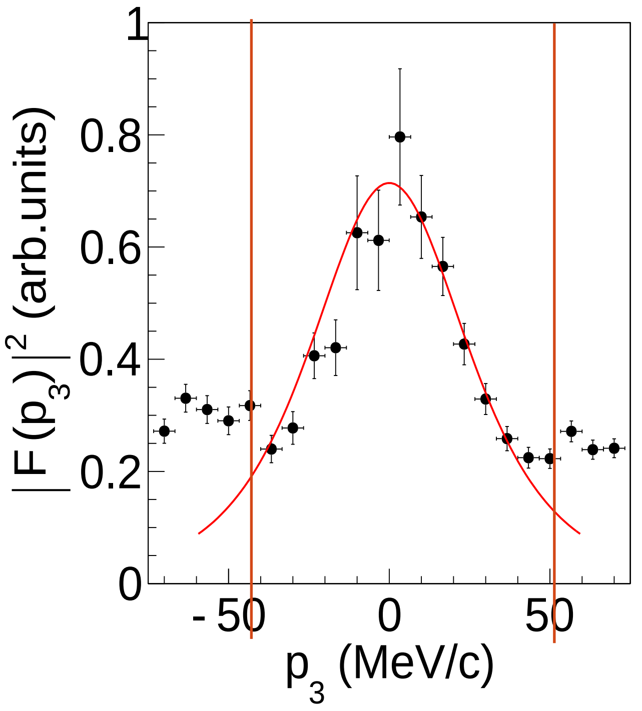
Measurement with THM





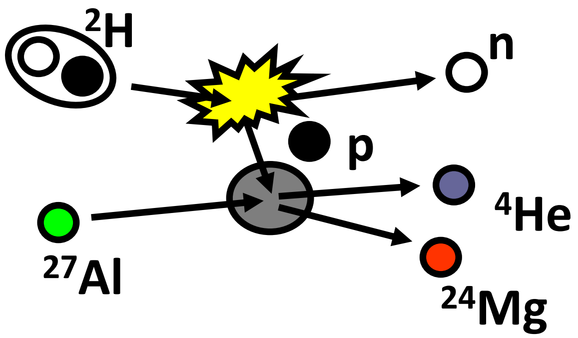


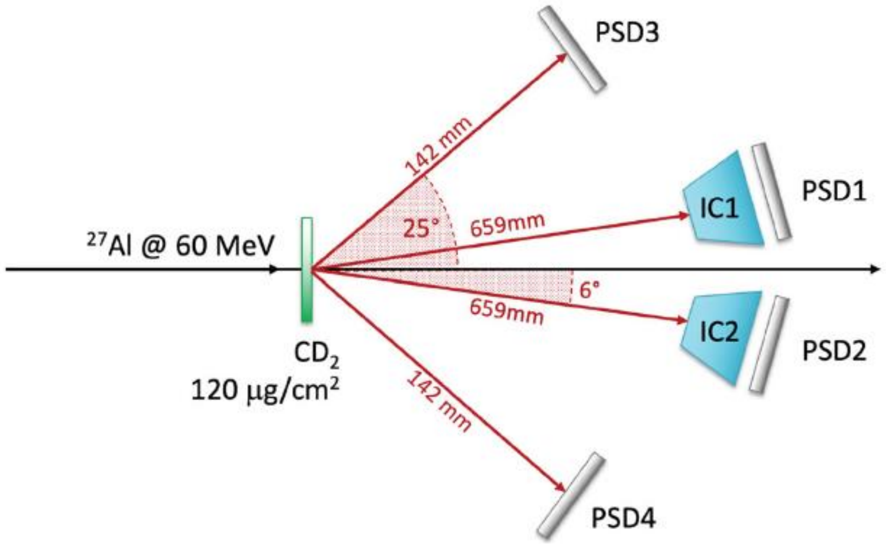
» *Char*

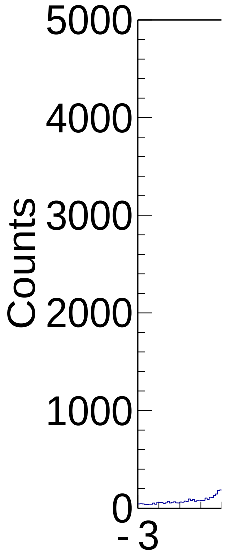


» ***QF mechanism selection***

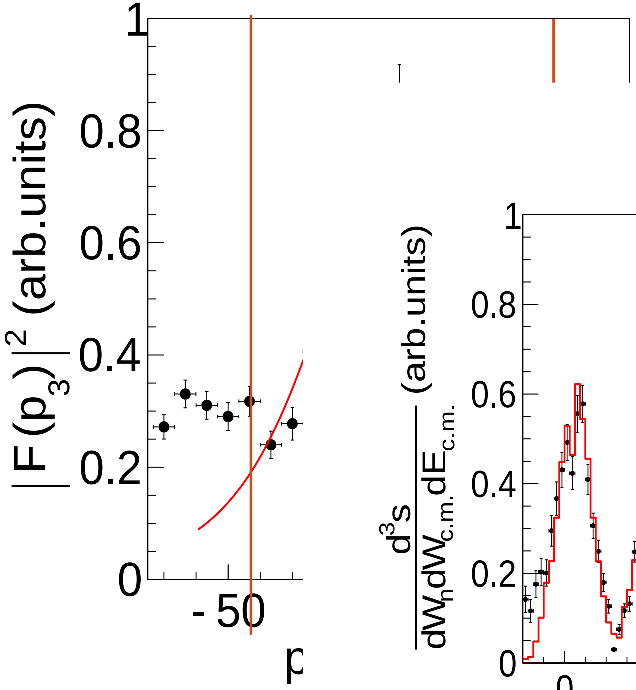
Measurement with THM



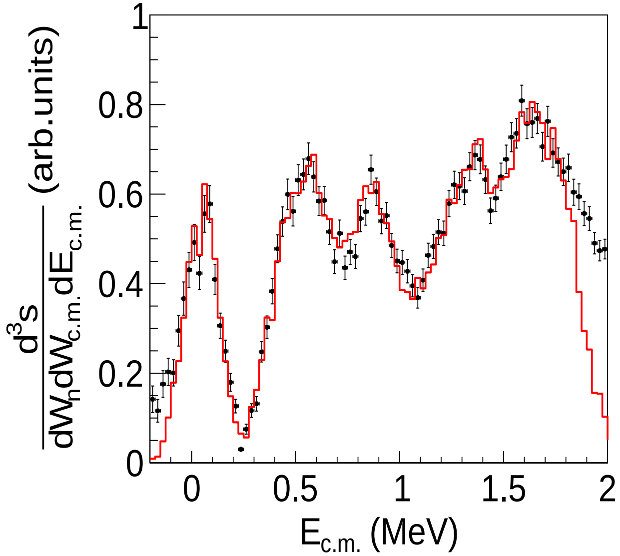




» *Char*



» *QF mec*



» *Three-body yield determination*

Measurement with THM

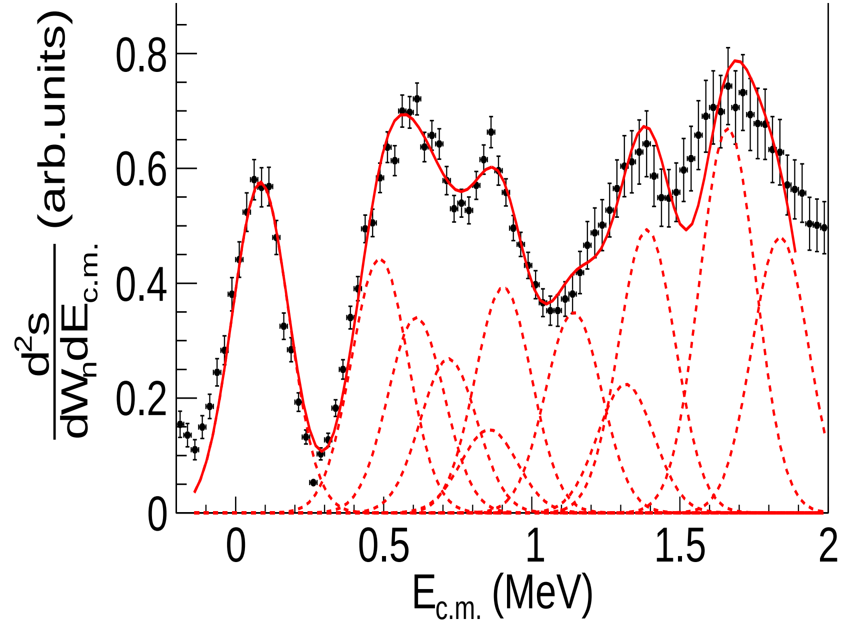
Contents lists available at ScienceDirect

Physics Letters B

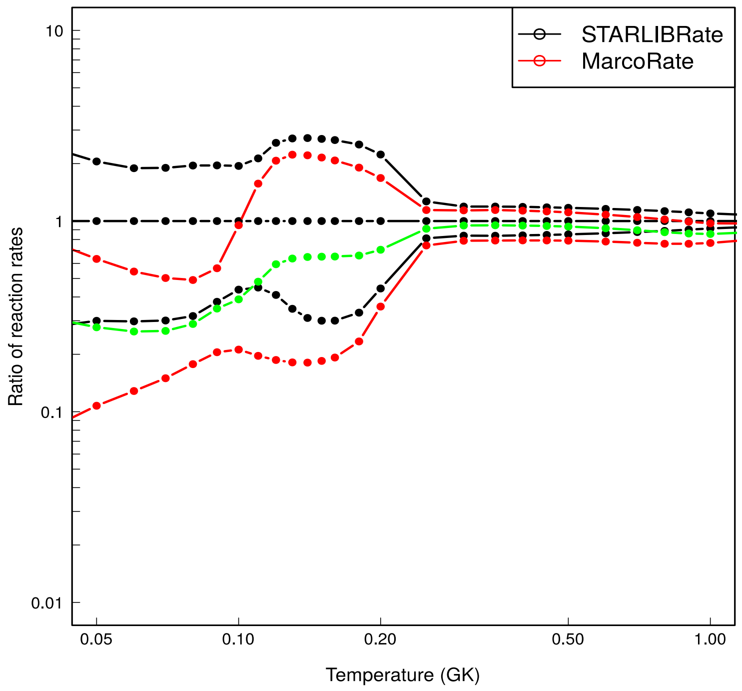
www.elsevier.com/locate/physletb

Exploring the astrophysical energy range of the $^{27}Al(p,\alpha)^{24}Mg$ reaction: A new recommended reaction rate

M. La Cognata [a,*], S. Palmerini [b,c], P. Adsley [d,e], F. Hammache [f], A. Di Pietro [a], P. Figuera [a], R. Alba [a], S. Cherubini [a,g], F. Dell'Agli [h], G.L. Guardo [a,g], M. Gulino [a,i], L. Lamia [a,g,j], D. Lattuada [a,i], C. Maiolino [a], A. Oliva [a,g], R.G. Pizzone [a], P.M. Prajapati [a], S. Romano [a,g,j], D. Santonocito [a], R. Spartá [a,g], M.L. Sergi [a,g], A. Tumino [a,i]



The green line is the THM recommended rate



Results of THM

In the last 30 years the THM has been applied to several reaction of astrophysical interest in different scenario, ranging from BBN to Novae Explosion.

Variuos TH nucleus has been used, such as:

d, ^{3}He, ^{6}Li, ^{9}Be, ^{14}N, ^{16}O, ^{20}Ne

In order to study proton-induced, alpha-induced, neutron-induced and heavy particle-induced reactions

Perfect method for study neutron-induced reaction cross sections with radioactive ion beams!!!!

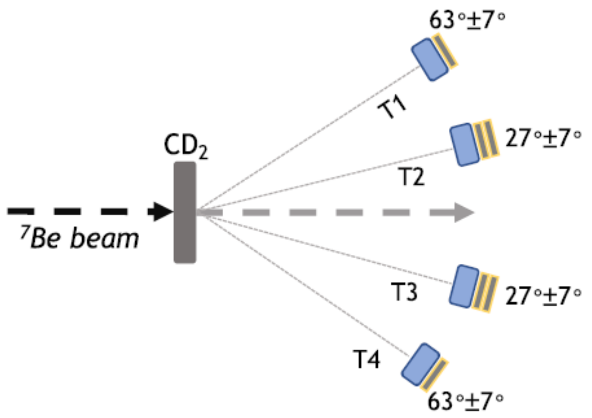
Recent results of THM

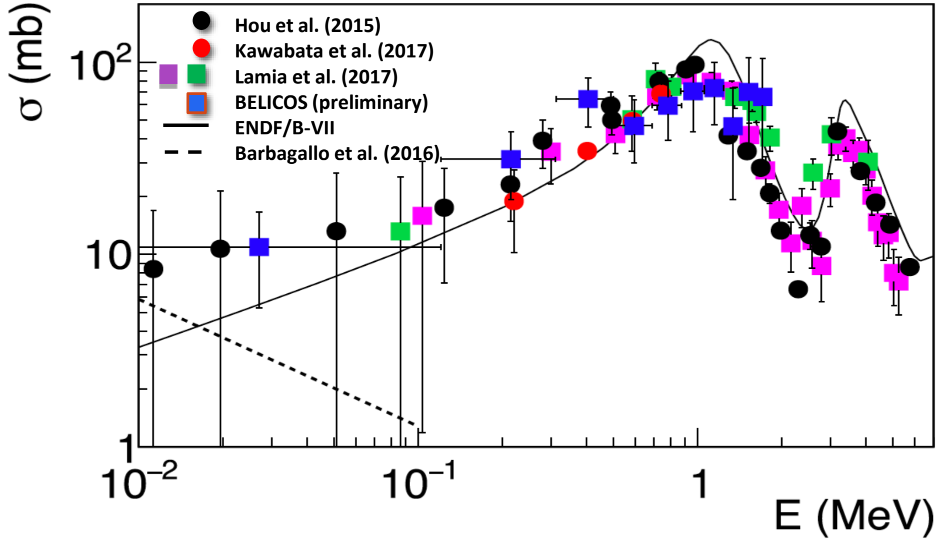
Application of THM with RIBs and neutron induced reactions

The Astrophysical Journal, 850:175 (5pp), 2017 December 1
https://doi.org/10.3847/1538-4357/aa965c

On the Determination of the ^{7}Be(n, α)^{4}He Reaction Cross Section at BBN Energies

L. Lamia[1,2], C. Spitaleri[1,2], C. A. Bertulani[3], S. Q. Hou[3,4], M. La Cognata[2], R. G. Pizzone[2], S. Romano[1,2], M. L. Sergi[2], and A. Tumino[2,5]
[1] Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Catania, Italy
[2] INFN—Laboratori Nazionali del Sud, Catania, Italy
[3] Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, TX 75428, USA
[4] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[5] Facoltà di Ingegneria e Architettura, Università degli Studi di Enna "Kore", Enna, Italy
Received 2017 September 12; revised 2017 October 20; accepted 2017 October 24; published 2017 November 30





The Astrophysical Journal, 879:23 (8pp), 2019 July 1
https://doi.org/10.3847/1538-4357/ab2234

Cross-section Measurement of the Cosmologically Relevant ^{7}Be(n, α)^{4}He Reaction over a Broad Energy Range in a Single Experiment

L. Lamia[1,2], M. Mazzocco[3,4], R. G. Pizzone[2], S. Hayakawa[5], M. La Cognata[2], C. Spitaleri[1,2], C. A. Bertulani[6], A. Boiano[7], C. Boiano[8], C. Broggini[4], A. Caciolli[3,4], S. Cherubini[1,2], G. D'Agata[1,2,13], H. da Silva[9], R. Depalo[3,4], F. Galtarossa[10], G. L. Guardo[1,2], M. Gulino[2,11], I. Indelicato[1,2], M. La Commara[7,12], G. La Rana[7,12], R. Menegazzo[4], J. Mrazek[13], A. Pakou[14], C. Parascandolo[7], D. Piatti[3,4], D. Pierroutsakou[7], S. M. R. Puglia[2], S. Romano[1,2], G. G. Rapisarda[2], A. M. Sánchez-Benítez[15], M. L. Sergi[2], O. Sgouros[2,14], F. Soramel[3,4], V. Soukeras[2,14], R. Spartá[1,2], E. Strano[3,4], D. Torresi[2], A. Tumino[2,11], H. Yamaguchi[5], and G. L. Zhang[16]

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Recent results of THM

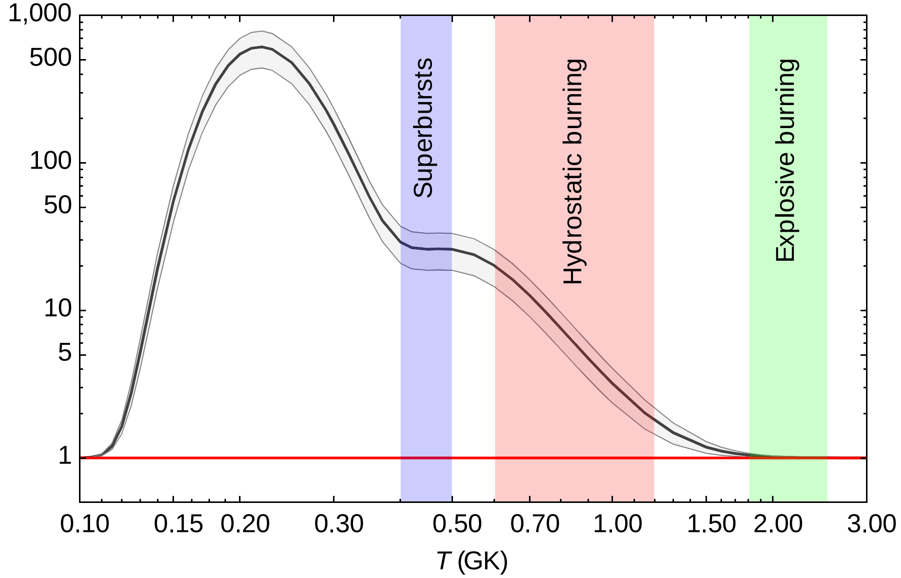
nature
International journal of science

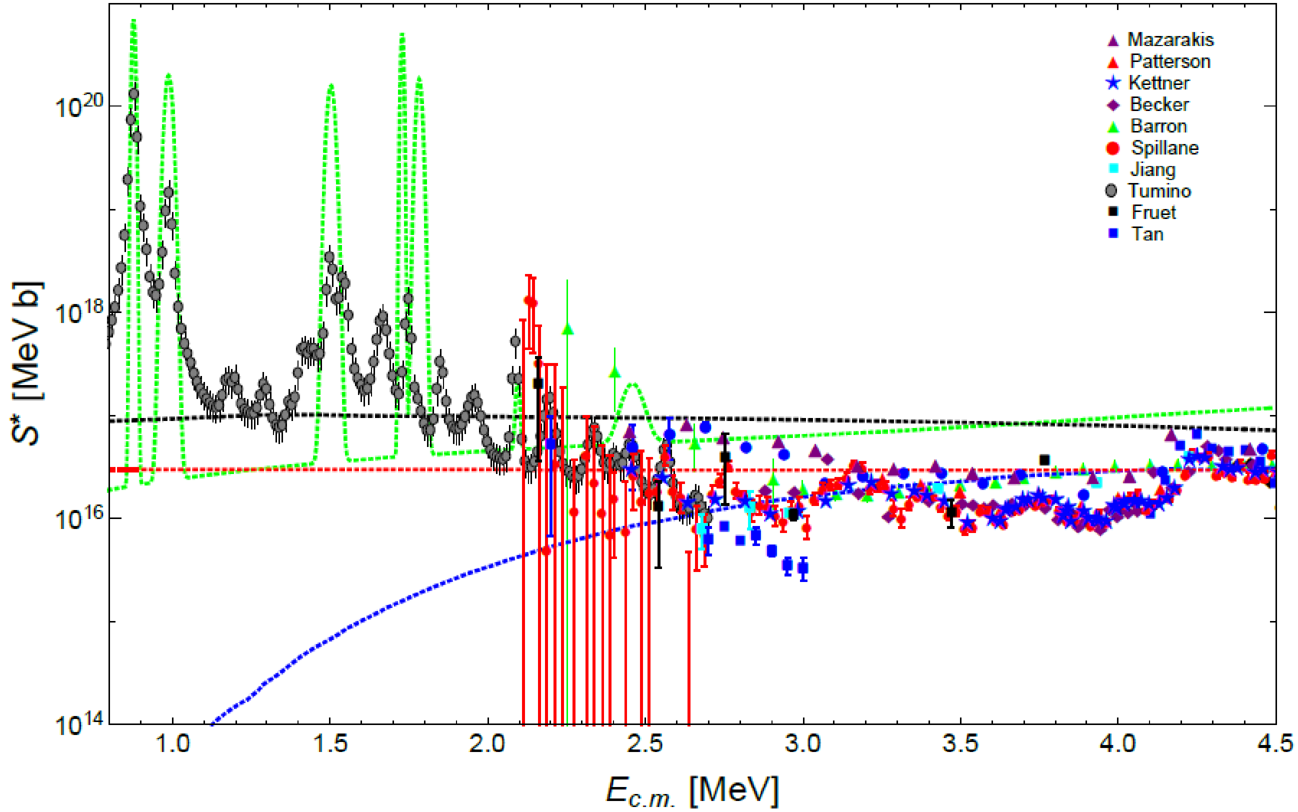
Letter | Published: 23 May 2018

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



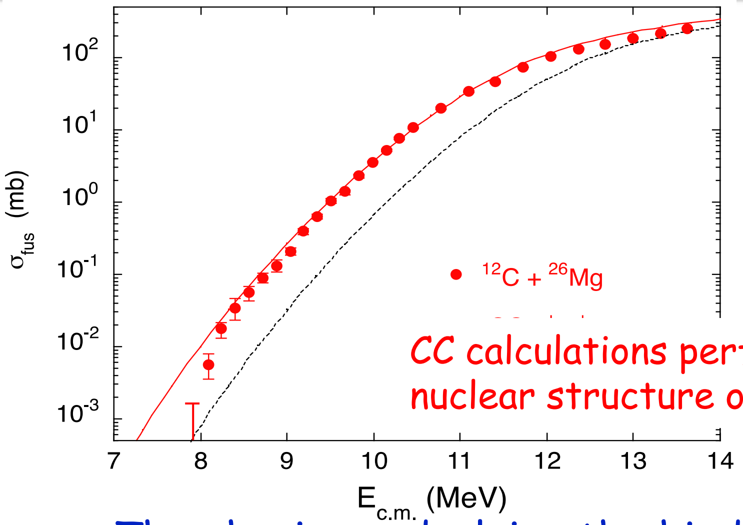


Blue => hindrance
Red => Caughland & Fowler 1988
Black => Godbey 2019

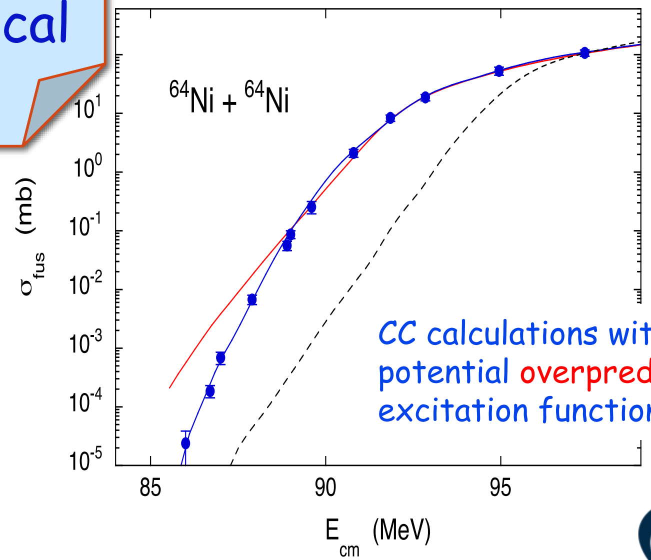
Fusion hindrance effect

- Heavy-ion sub-barrier fusion hindrance is one of the links between nuclear physics and astrophysics
- Fusion hindrance has been recently observed even in medium-light systems
- Consequences for the dynamics of stellar evolution have to be clarified by further experimental and theoretical work.

Fusion hindrance in the light heavy-ion systems of astrophysical interest is not well established nor understood



CC calculations performed with CCFULL, using the nuclear structure of the two colliding nuclei



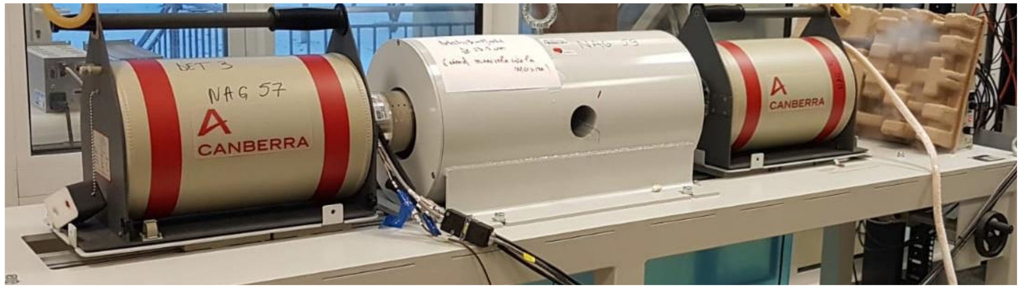
CC calculations with a WS potential overpredict the excitation function

The physics underlying the hindrance phenomenon is not yet clarified. Recent theoretical developments imply the influence of the Pauli exclusion principle, or an adiabatic approach where the ion-ion interaction evolves from a two-body to a one-body potential.
Q-value role cannot be neglect!!

A.M.Stefanini et al., EPJ Web of Conf. 279, 11013 (2023)

C.Simenel et al., PRC95, 031601(R) (2017)
T. Ichikawa, PRC92, 064604 (2015)

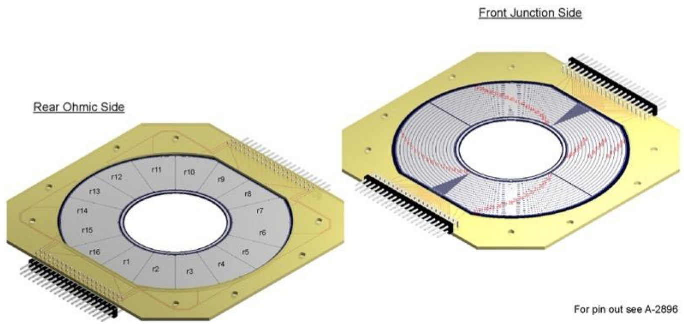
Fusion hindrance effect



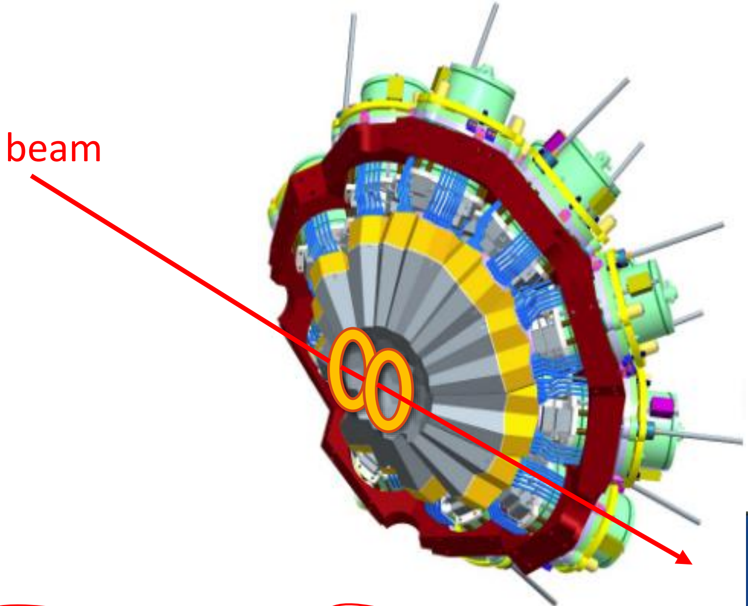
Fusion mechanism study for $^{13}C+^{16}O$, $^{12,13}C+^{19}F$, … using target activation method

In collaboration with IFIN-HH (A. Spiridon) @BeGa station

Measuring fusion cross sections at astrophysical energies using AGATA and Si detectors for γ-particle coincidences



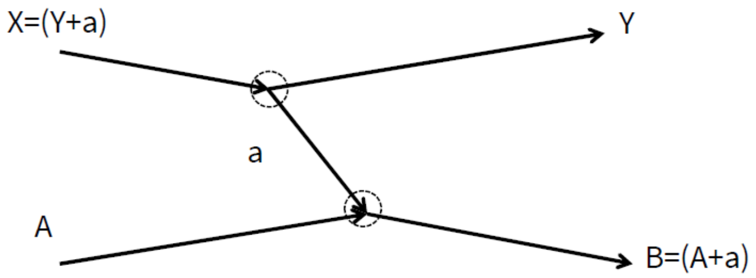
Sketch of the γ-array AGATA with two annular DSSD detectors upstream and downstream of the target



Next planned experiment: fusion of $^{16}O + ^{12}C$

Asymptotic Normalitation Coefficient

Studies performed by means of «simple» transfer reactions



The method involves comparing the bound state wave function of a two-body subsystem with the scattering wave function of a third particle interacting with the nucleus.
The bound state wave function describes the internal structure of the two-body system, while the scattering wave function characterizes the interaction between the third particle and the nucleus.

In Distorted Wave Born Approximation, the transition amplitude between the states before and after the reactions can be written as:

$$M(E_i, \vartheta_{c.m.}) = \sum_{M_a} \left\langle \chi_f^{(-)} \, \boldsymbol{I}_{Aa}^{B} \left| \Delta V \right| \boldsymbol{I}_{Ya}^{X} \, \chi_i^{(+)} \right\rangle$$

The ANC method relies on the asymptotic behavior of the nuclear wave function at large distances from the core, where the Coulomb and nuclear interactions become negligible.

Using DWBA we were able to find the ANC's coefficients from the spettroscopic factors. This gives us some advantages:

- For perihperal reactions, ANCs have small dependance from the potential
- R_{l_B, j_B, l_x, j_x} is nearly indipendent from b^2
- ANCs are defined in the nuclear «exterior», so are «observable»

$$\frac{d\sigma}{d\Omega} = \sum_{j_B, j_x} \left(C_{Aa, l_B, j_B}^{B}\right)^2 \left(C_{Ya, l_x, j_x}^{X}\right)^2 \frac{\sigma_{l_B, j_B, l_x, j_x}^{DWBA}}{b_{Aa, l_B, j_b}^{2} \, b_{Ya, j_x, j_x}^{2}} = \\ = \sum_{j_B, j_x} \left(C_{Aa, l_B, j_B}^{B}\right)^2 \left(C_{Ya, l_x, j_x}^{X}\right)^2 R_{l_B, j_B, l_x, j_x}$$

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Recent results of ANC

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Astrophysical S-factor for the ^{3}He(α, γ)^{7}Be reaction via the asymptotic normalization coefficient (ANC) method

G.G. Kiss[a], M. La Cognata[b,*], C. Spitaleri[b,c], R. Yarmukhamedov[d], I. Wiedenhöver[e], L.T. Baby[e], S. Cherubini[b,c], A. Cvetinović[b], G. D'Agata[b,c,f], P. Figuera[b], G.L. Guardo[b,c], M. Gulino[b,g], S. Hayakawa[b,h], I. Indelicato[b,c], L. Lamia[b,c,i], M. Lattuada[b,c], F. Mudò[b,c], S. Palmerini[j,k], R.G. Pizzone[b], G.G. Rapisarda[b,c], S. Romano[b,c,i], M.L. Sergi[b,c], R. Spartà[b,c], O. Trippella[j,k], A. Tumino[b,g], M. Anastasiou[e], S.A. Kuvin[e], N. Rijal[e], B. Schmidt[e], S.B. Igamov[d], S.B. Sakuta[l], K.I. Tursunmakhatov[d,m], Zs. Fülöp[a], Gy. Gyürky[a], T. Szücs[a], Z. Halász[a], E. Somorjai[a], Z. Hons[f], J. Mrázek[f], R.E. Tribble[n], A.M. Mukhamedzhanov[n]

PHYSICAL REVIEW C **104**, 015807 (2021)

Indirect determination of the astrophysical S factor for the ^{6}Li(p, γ)^{7}Be reaction using the asymptotic normalization coefficient method

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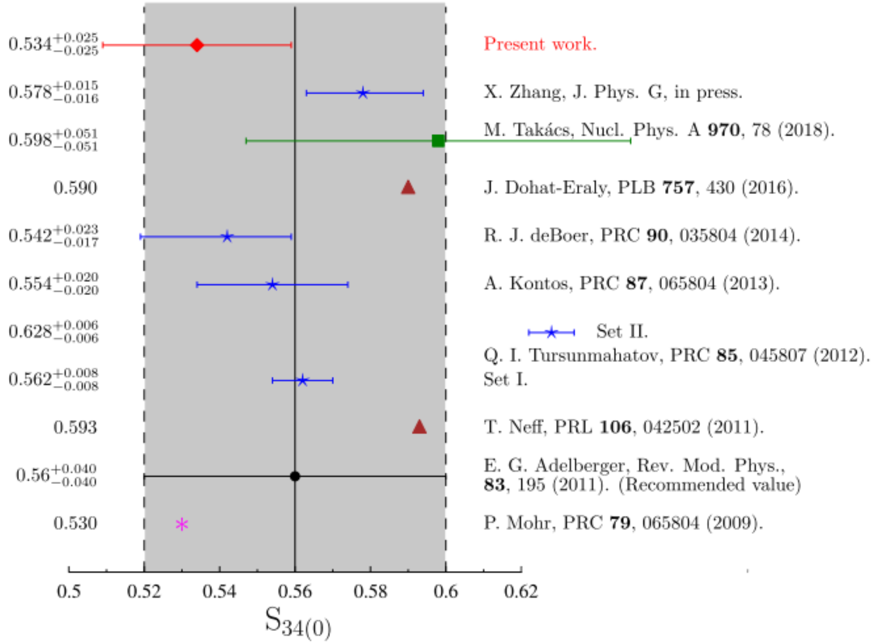
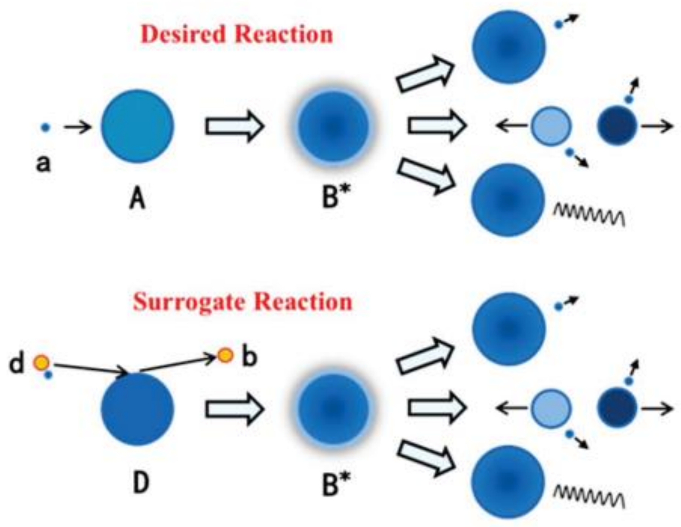


Astrophysical factor at Gamow energies for the Sun was extracted via the ANC method. For the ^{3}He(^{4}He,γ)^{7}Be case, in good agreement with previous experiments

Surrogate reaction method



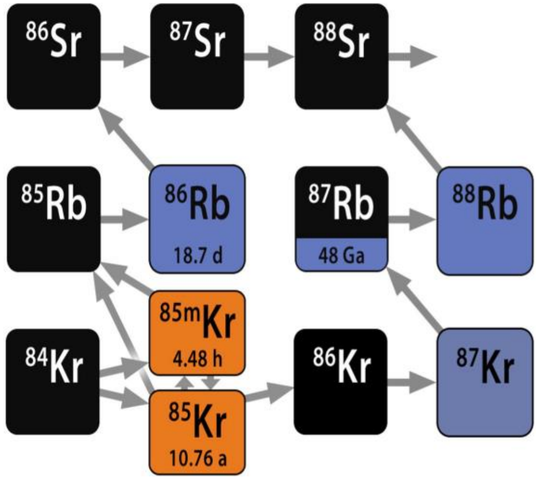
In the Surrogate Nuclear Reaction technique, a different reaction is used to populate the same compound nucleus (final-state nucleus) as the reaction of interest. This surrogate reaction is usually chosen because it has similar entrance channel properties as the reaction of interest.

In the surrogate reaction, the projectile interacts with the target nucleus to form a compound nucleus in an excited state.
Although the compound nucleus is formed via a different reaction pathway, it shares similar properties with the compound nucleus produced in the direct reaction.

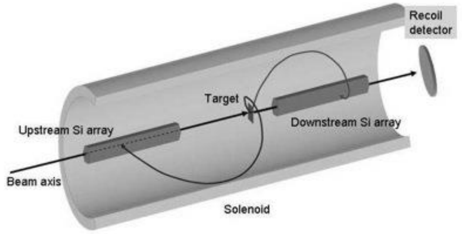
gamma

Surrogate reaction method

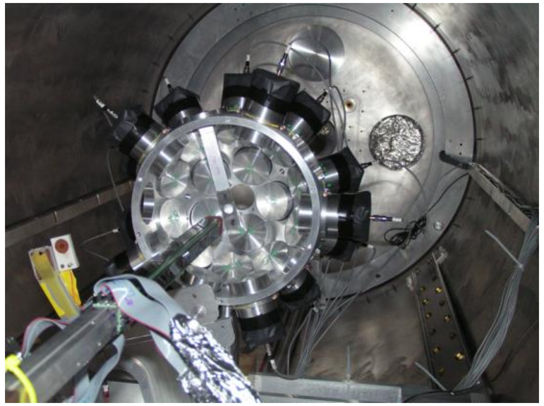
Nucleosynthesis s-process:
^{85}Kr branching



Only at ANL:
HELIOS solenoid
and high intensity radioactive beam ^{85}Kr
→ Surrogate reaction: (d,p) instead of (n,gamma)



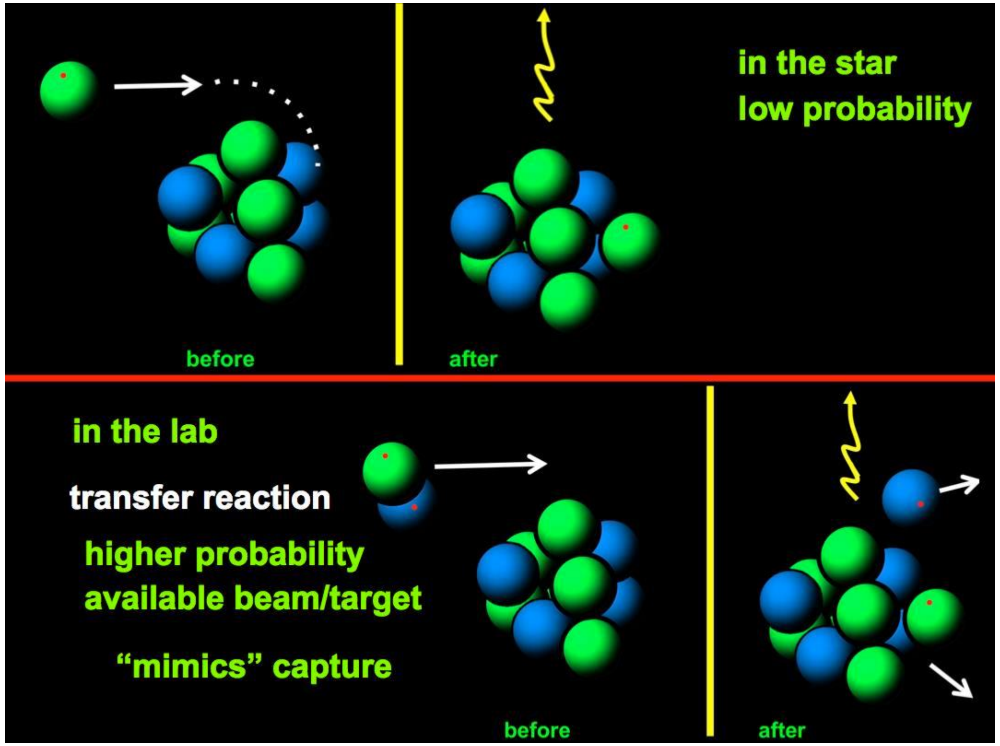
Contribution by the gamma group: gamma detection in the solenoid → **MoU in preparation**



NEW SOLENOID SOON @LNL

One-proton transfer reactions

(p,γ) reactions at deep sub-coulomb energies often play a role in several *astrophysics scenarios* → rp-process, novae synthesis, XRBs …



[ORNL website – Exp astrophysics, *Transfer Reactions*
https://www.phy.ornl.gov/groups/astro/measurements/transfer.html]

- If there are resonances very close to the S_p, the Gamow factor can hinder the cross section of several orders of magnitude → exp. difficulties!
- We can estimate the resonance strenght with an indirect technique based on the SF taken from (d,n) or (^{3}He,d) reactions:

$$\omega\gamma = \frac{2J_R + 1}{(2j_p + 1)(2j_t + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

But near the threshold $\Gamma_p << \Gamma_\gamma$, and therefore Γ_p determine the resonance strenght!

Γ_p and C^2S are *connected* one another!

$$\Gamma_p = \frac{2\hbar^2}{\mu R^2} \times P_l \times C^2\, S \times \theta_{sp}^2$$

AsFiN NUCLEX

SF → *reaction rate* estimate for several (p,γ) reactions

Recent results of proton transfer reaction

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Editors' Suggestion

Experimental study of the $^{30}Si(^{3}He, d)^{31}P$ reaction and thermonuclear reaction rate of $^{30}Si(p, \gamma)^{31}P$

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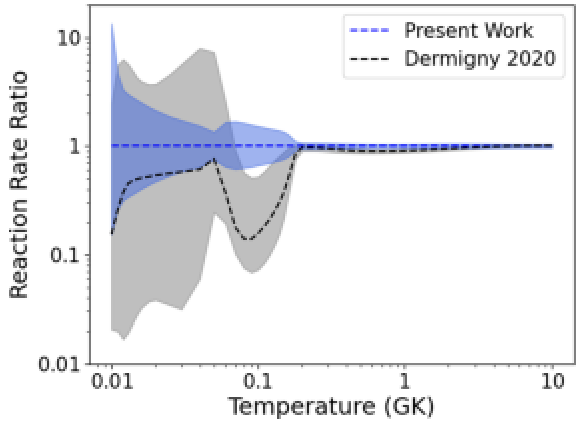


The $^{32}S(^{3}He,d)^{33}Cl$ transfer reaction

An example of transfer reaction useful both for nuclear structure and astrophysics is the $^{32}S(^{3}He,d)^{33}Cl$ reaction at *moderately-high bombarding* energies

→ we can determine the C^2S_p avoiding to detect neutrons as in the (d,n) case

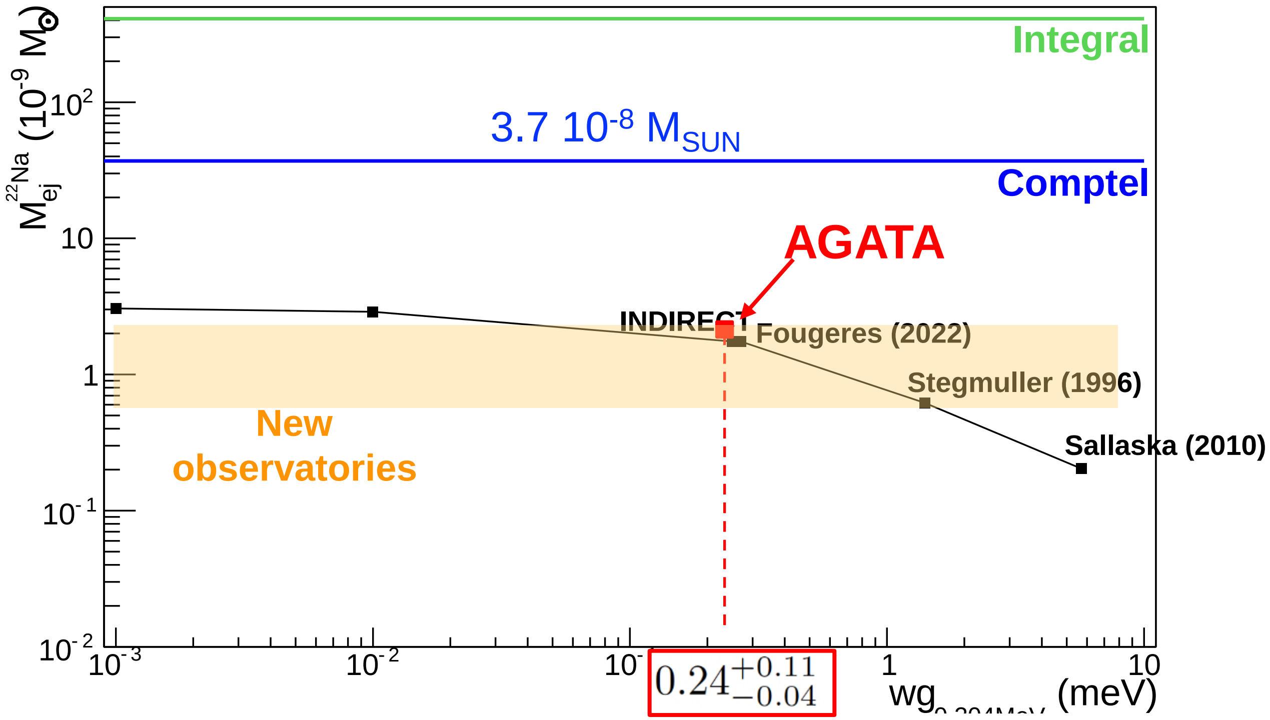
→ useful to understand the r.r. of the $^{32}S(p,\gamma)^{33}Cl$ reaction (rp-process)

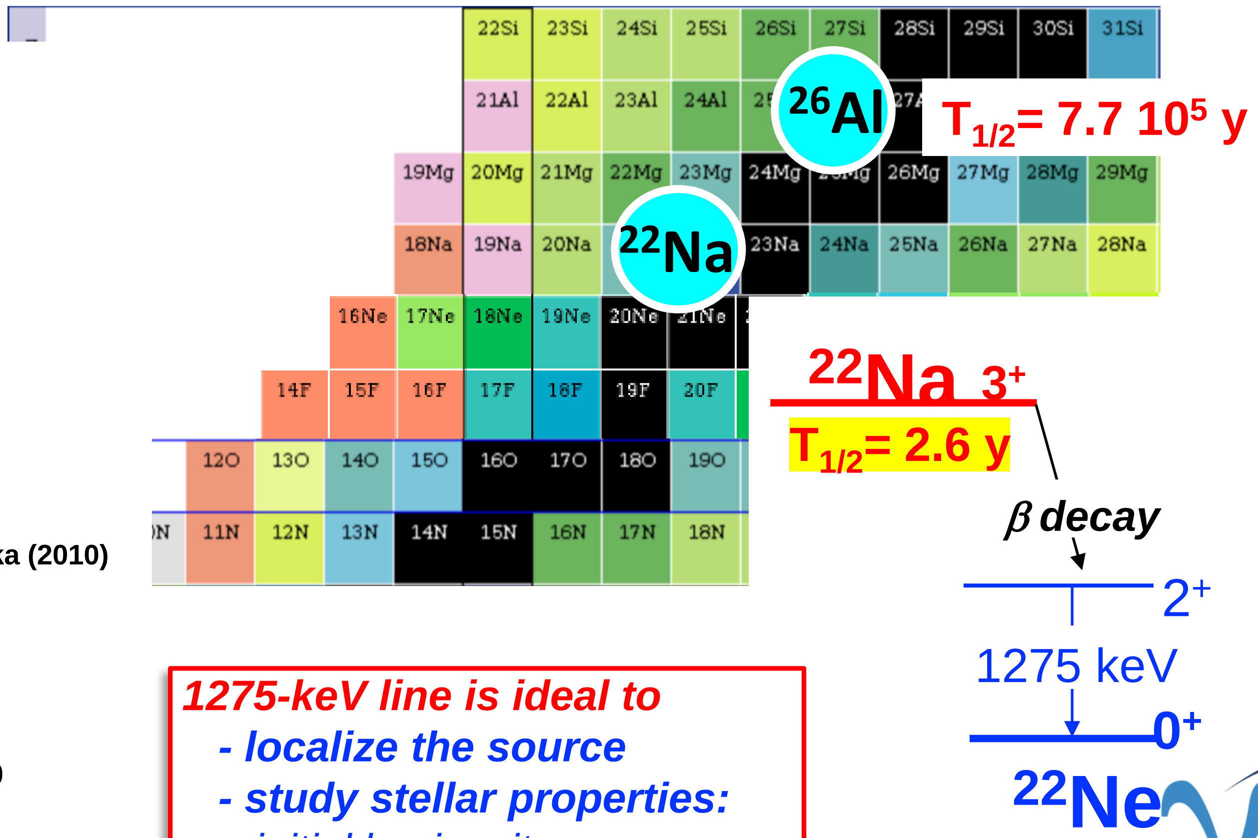
TAU-DEU experiment at LNL (CN accelerator) with the OSCAR hodoscope

Nuclear lifetime measurements

The lifetime of nuclear states directly affects the transition probabilities governing nuclear reactions, which in turn influence the reaction rates and the astrophysical processes they govern

^{26}Al and ^{22}Na are produced in largest amount *useful for identification & study novae outbursts as proposed by F. Hoyle and D. Clayton (1974)*





1275-keV line is ideal to
- ***localize the source***
- ***study stellar properties:***
  initial luminosity
  accretion rate, …

gamma

nature communications
5th September 2023
Article
https://doi.org/10.1038/s41467-023-40121-3

C. Fougères et al., AGATA experiment

Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes

Conclusions & perspectives

A - INFN has a long history on Indirect Methods for Astrophysics with different approach and several outstanding results over the years;

B - This expertise covered various astrophysics scenarios, giving new cross section values at Gamow energy;

C - Open the path to the application with radioactive beam measurements;

D – New detectors and approach are under development to face new quests in multimessenger era

Methods complementary to direct measurements
(Multi Diagnostic Experiments)


THANK YOU
FOR YOUR ATTENTION