**Open Quantum Systems:**
**From atomic nuclei to ultracold atoms and quantum optics**

Trento, *September* 30—*October* 4, 2019

# Nuclear astrophysics experiments with Trojan Horse Method


*Giovanni Luca Guardo*

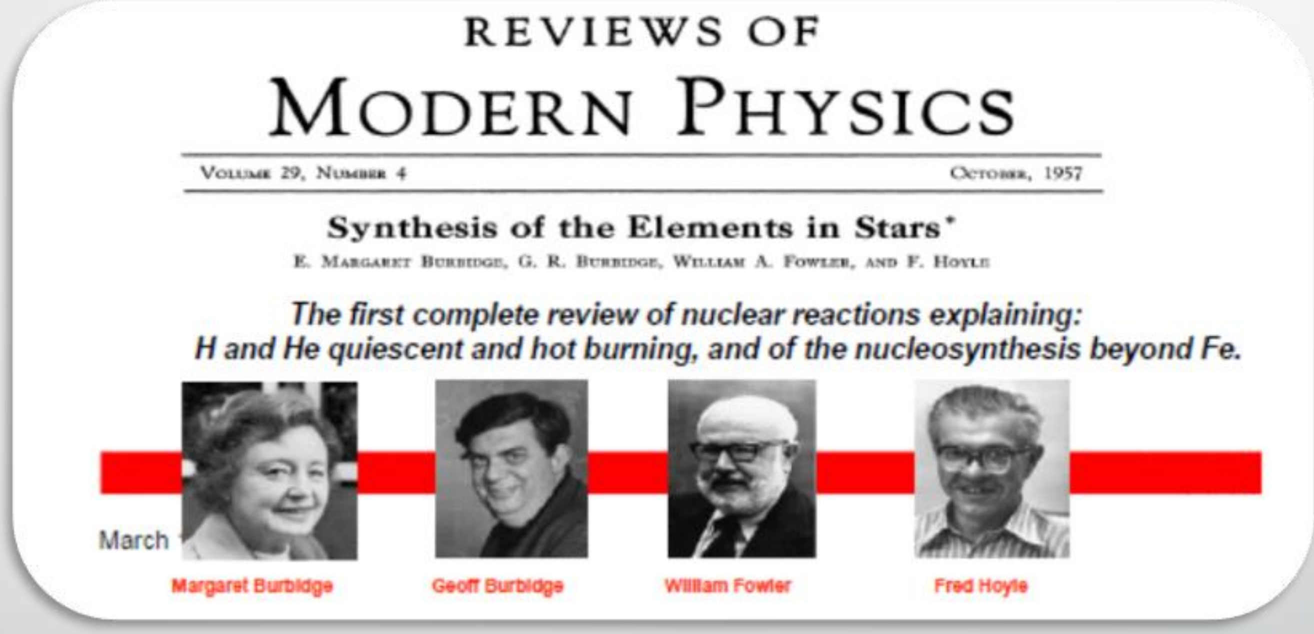
*on behalf of the AsFiN group*

# Experimental Nuclear Astrophysics

… Everything starts from the B$^2$FH review paper of 1957,

<u>the basis of the modern nuclear astrophysics</u>

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

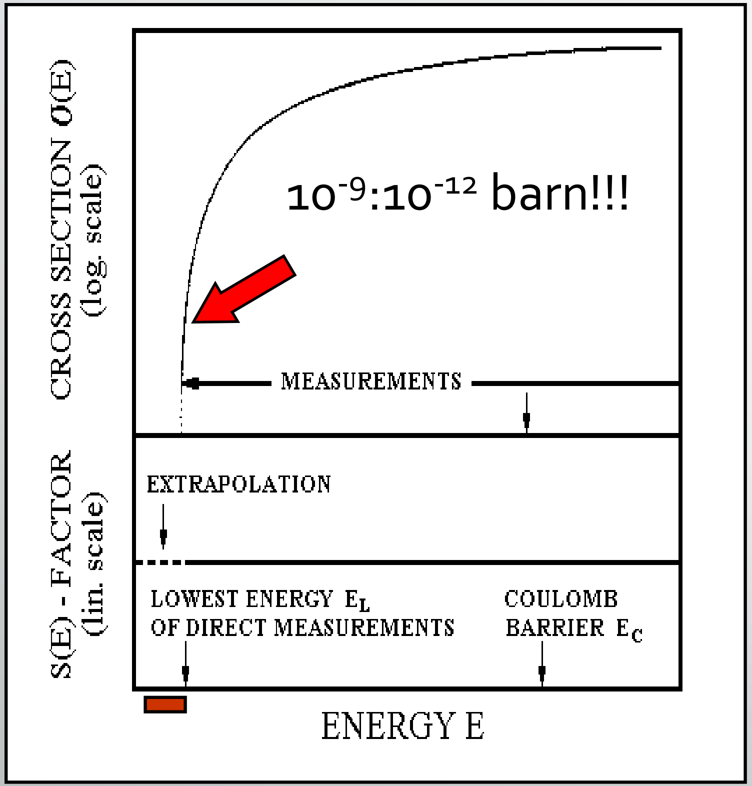


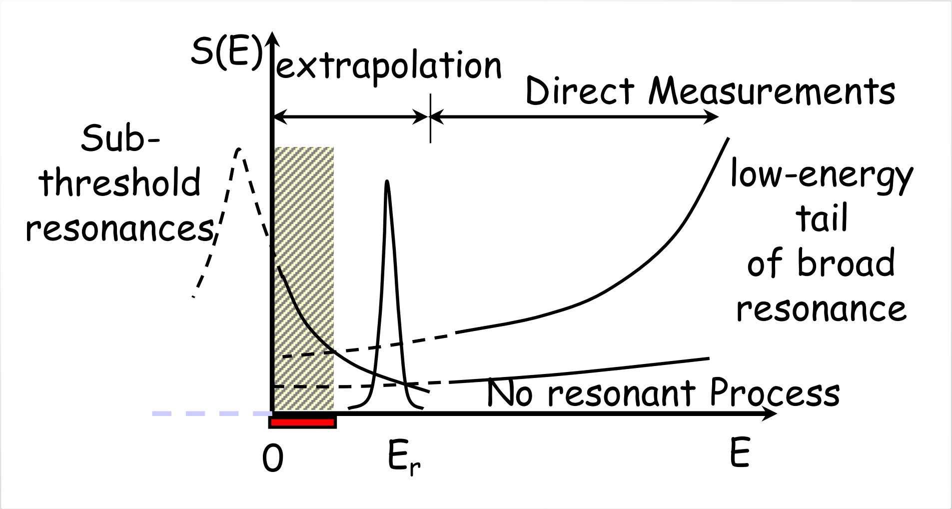

The elements composing everything from planets to life were forged inside earlier generations of stars!

Nuclear reactions responsible for both <u>ENERGY PRODUCTION</u> and <u>SYNYHESIS OF ELEMENTS</u>

# 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

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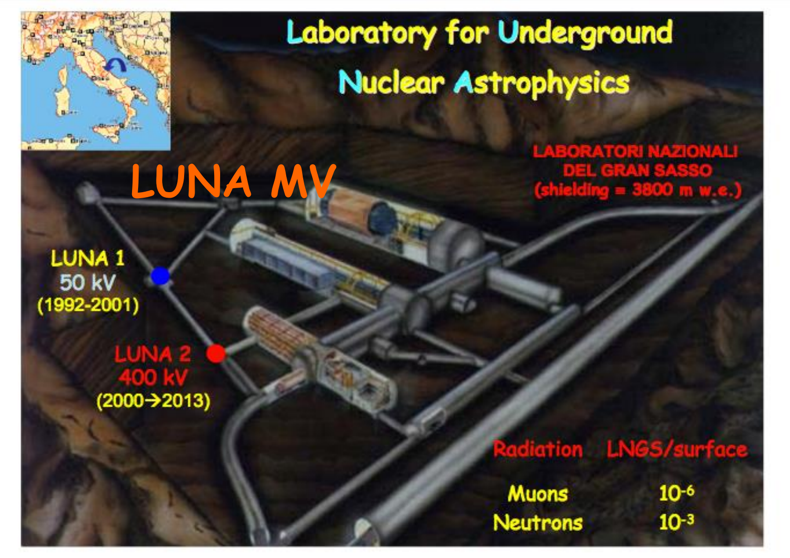
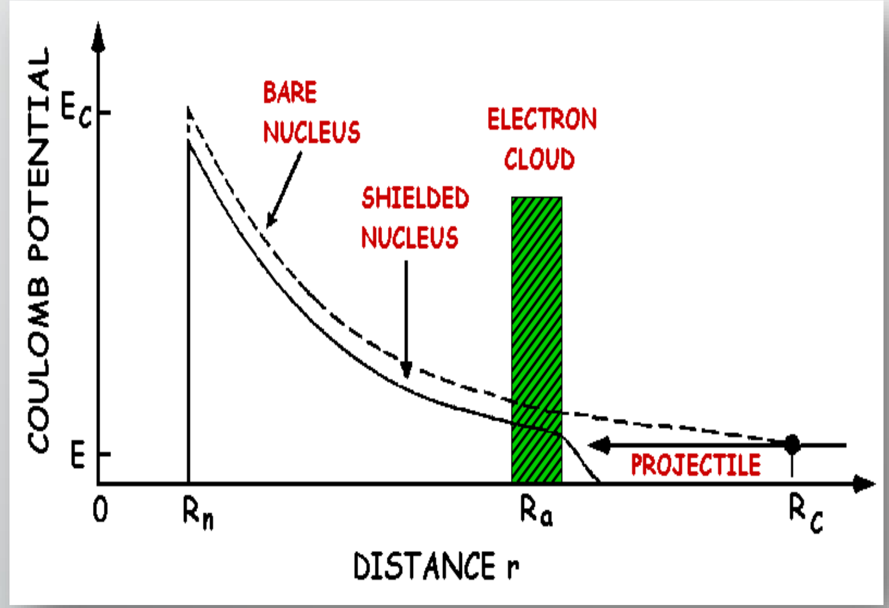
# Direct Measurements

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

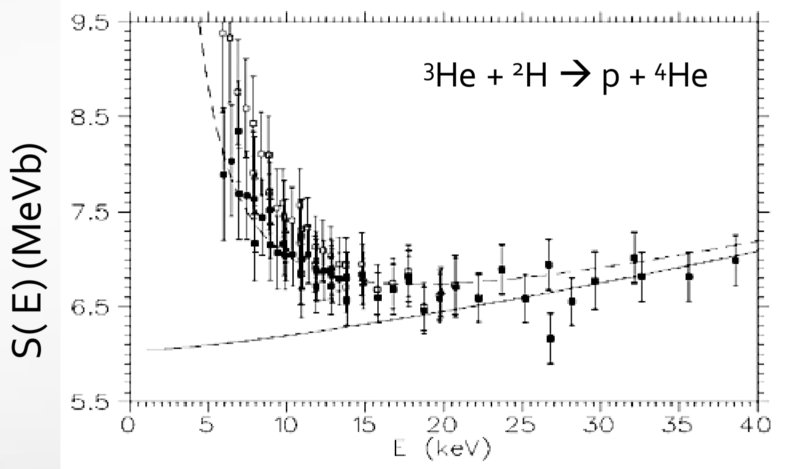
- ➢ Longer measurements
- ➢ Higher beam currents
- ➢ 4π detectors
- ➢ Pure targets
- ➢ Underground laboratories



# 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**

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# Indirect Methods

❖ **Coulomb dissociation**

G. Baur et al. Annu. Rev. Nucl. Part. Sci. 46,321,(1996)

to determine the absolute S(E) factor of a radiative capture reaction **A+x → B+γ** studying the reversing photodisintegration process **B+γ → A+x**

❖ **Asymptotic Normalization Coefficients (ANC)**

A.M. Mukhamedzhanov et al.: PRC 56,1302,(1997)

to determine the S(0) factor of the radiative capture reaction, **A+x → B+γ** studying a peripheral transfer reaction into a bound state of the **B** nucleus

❖ **Trojan Horse Method (THM)**

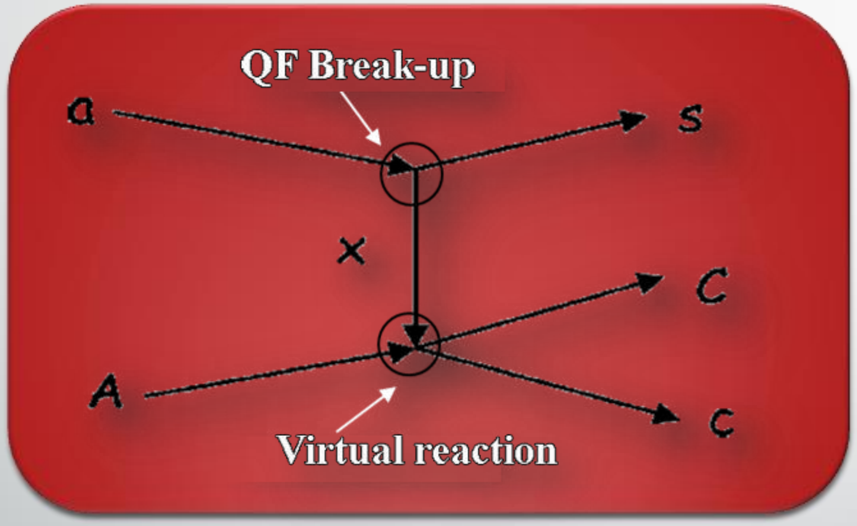
C. Spitaleri, *Problems of Fundamental Modern Physics, II,* (World Sci.,1991), p. 21.

C. Spitaleri et al., Phys. of Atomic Nuclei, 74 (2011) 1725

to determine the S(E) factor of a charged particle reaction **A+x→c+C**

# 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 papers* → *Spitaleri C. et al., PAN, 2011*
  *Tribble R. et al., Rep. Prog. Phys. 2014*
  *Spitaleri C. et al., EpJ A, 2019*

# Theorethical 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*

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# THM Cross Section

Virtual nature of x particle → A+x interaction is off–energy shell

Cross section of the bare nucleus but NO <u>absolute value → normalization to direct data available at higher energies</u>

Standard R-Matrix approach cannot be applied to extract the resonance parameters → Modified R-Matrix is introduced instead

$$\frac{d^2\sigma}{dE_{xA}d\Omega_s} = \mathrm{NF}\sum_i (2\mathrm{J}_i+1)$$

$$\times \left| \sqrt{\frac{\mathrm{k_f}(E_{xA})}{\mu_{cC}}} \frac{\sqrt{2P_{l_i}(k_{cC}R_{cC})}M_i(p_{xA}R_{xA})\gamma^i_{cC}\gamma^i_{xA}}{D_i(E_{xA})} \right|^2$$

where:

- $M_i\ (p_{xa}R_{xa})$ describes the transfer amplitude for the QF-process;
- $\gamma_{xa}$ and $\gamma_{Cc}$ represents the reduced partial widths for the resonant excited states that are the <u>same</u> of the direct measurements

*La Cognata et al., ApJ, 777, 143, 2013*

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# Study of the $^{17}O(n,\alpha)^{14}C$ reaction: extension of the Trojan Horse Method to neutron induced reactions

# Astrophysical Scenario

- **Inhomogeneus Big Bang Nucleosinthesys (IBBN)**

*The reaction $^{17}O(n,\alpha)^{14}C$ represents one of the main channel for $^{14}C$ production, a key element for the $^{22}Ne$ production via*

**$^{14}C(\alpha,\gamma)^{18}O(n,\gamma)^{19}O(\beta)^{19}F(n,\gamma)^{20}F(\beta)^{20}Ne(n,\gamma)^{21}Ne(n,\gamma)^{22}Ne$**

- **Weak component s-process**

*$^{17}O(n,\alpha)^{14}C$ and $^{17}O(\alpha,n)^{20}Ne$ since they act as a neutron poison and a recycle channel during s-process nucleosinthesys in massive stars ($M>8M_{SUN}$)*

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# Astrophysical Scenario

- Inhomogeneus B g Bang Nuc nthesys (IBBN)

*The ion $^{17}O(n,\alpha)^{14}C$ sents e main channel for $^{14}C$*

*p a k via*

$^{14}C(\alpha,\gamma)$ $(n,\gamma)^{22}Ne$

**Temperature → $0.8<T_8<11$ K**

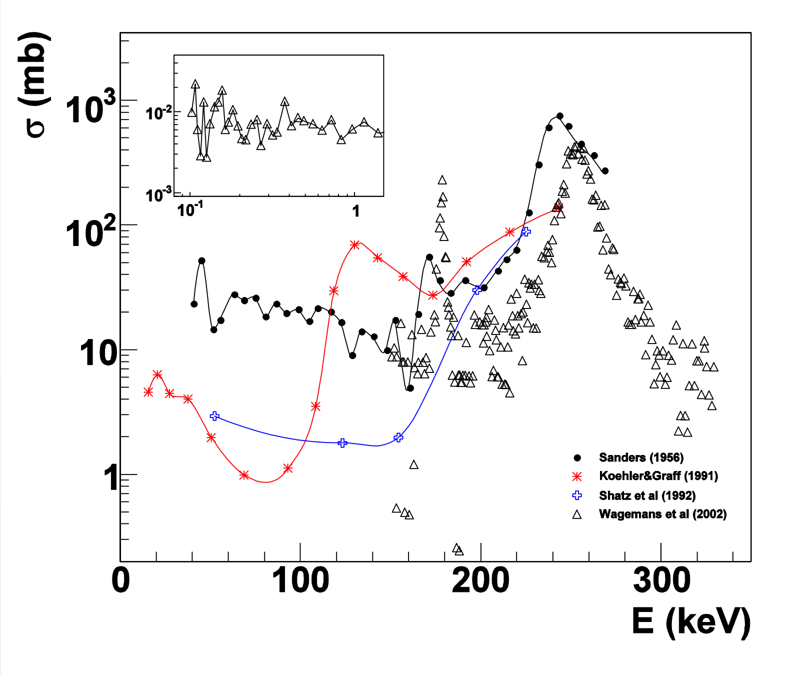
**Energy range→ ~0-100 keV**

*$^{17}O(n,\alpha)^{14}C$ and poison and a*

*recycle chann ing ss n thesys in sive stars*

*$M>8M_{SUN}$*

# Status of the Art




- R. M. Sanders, Phys. Rev., 104, 1434 (1956) INVERSE REACTION $^{14}C(\alpha,n)^{17}O$

* P.E.Koehler & S.M.Graff, Phys. Rev., C44(6), 2788 (1991)

○ H. Schatz et al., Astroph. J., 413, 750 (1993)

Δ J. Wagemans et al., Phys. Rev., C65(3), 34614 (2002)

| $E_{c.m.}$ (keV) | $^{18}O^*$ (MeV) | $J^\pi$ |
|---|---|---|
| -7 | 8.039 | $1^-$ |
| 75 | 8.125 | $5^-$ |
| 166 | 8.213 | $2^+$ |
| 236 | 8.282 | $3^-$ |

Subthreshold Level ← (-7 keV)

Suppressed due to the centrifugal barrier ← (75 keV)

Available in literature ← (166 keV, 236 keV)

F. Ajzenberg-Selove, Nucl. Phys., A475, 1 (1987)

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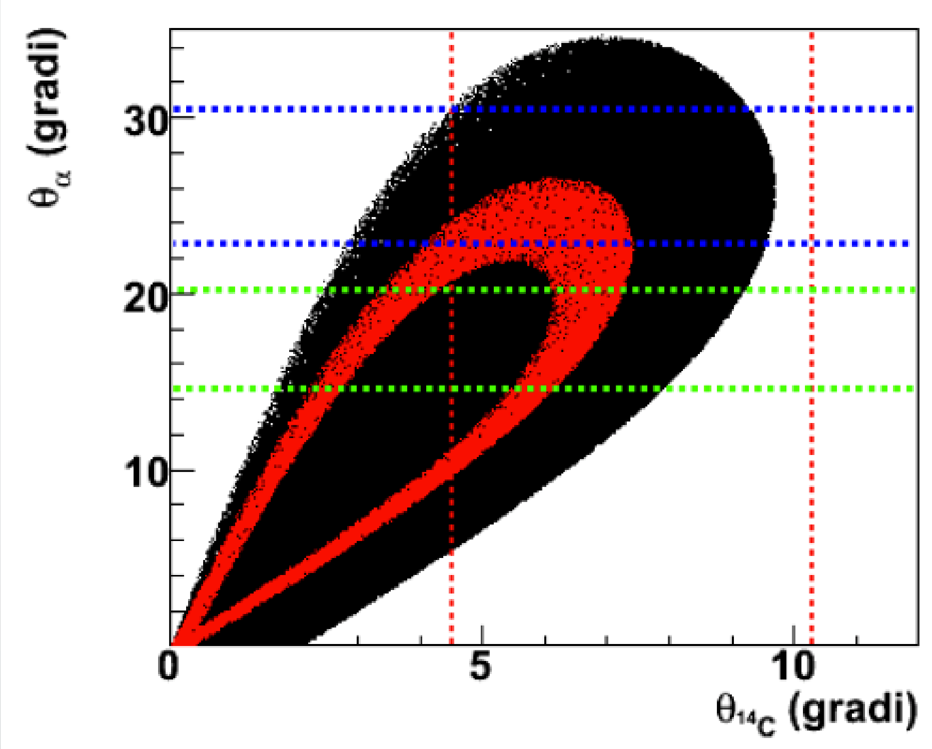
# Preliminary Study




$$E_{cm} + B_{xs} = E_{ax} \approx 2.45 MeV = E_{fascio} \frac{m_N}{m_N + m_{^{17}O}}$$

$^{17}O+^{2}H$, $E_{beam}$=43.3 MeV

Deuteron as source of virtual neutrons!!

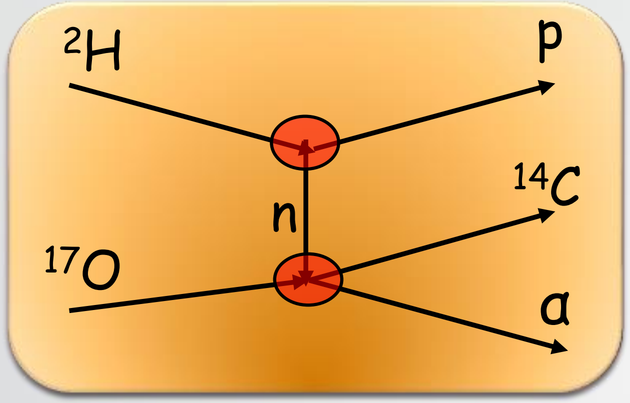
Black points: kinematic calculations
Red points: kinematic calculations + $|p_s|<5$ MeV/c

This allows then to determine the experimental apparatus:

$^{14}C$ detection→ $6°<\theta_C<10°$

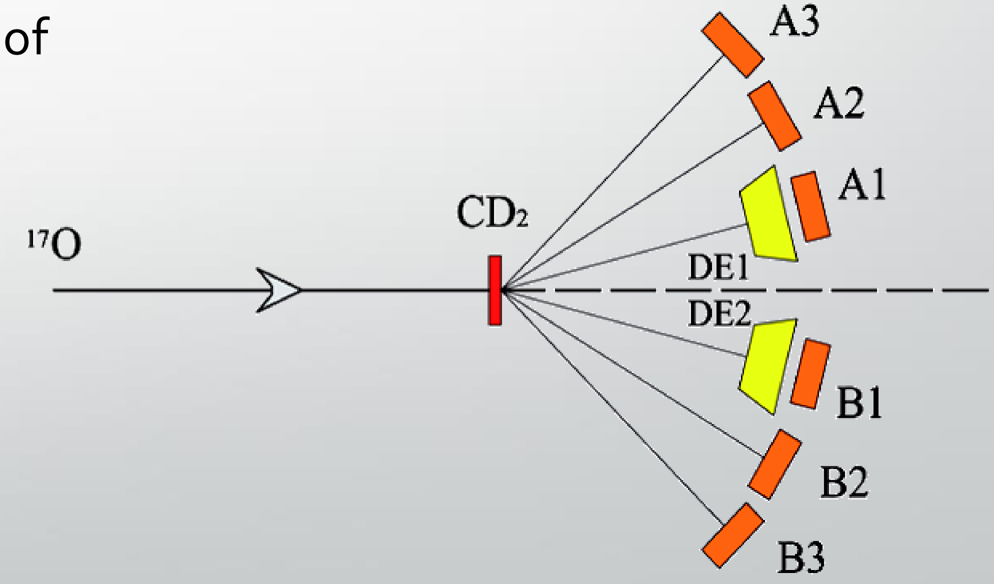
α detection→$15°<\theta_\alpha<20°$
→$23°<\theta_\alpha<31°$

# Experimental Setup



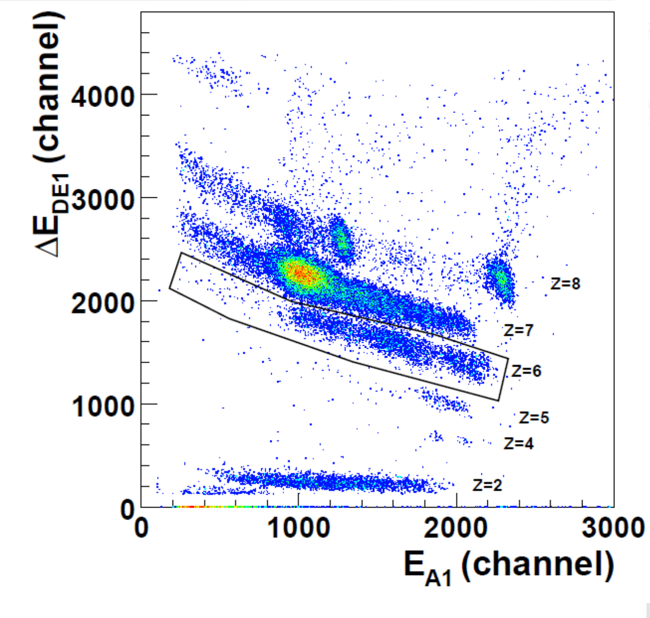

➢ The reaction $^{17}O(n,\alpha)^{14}C$ was studied via the $^{2}H(^{17}O,\alpha^{14}C)p$ , $V_{coul}$=2.3 MeV;
➢ The deuteron is the TH nucleus. Strong cluster n+p; B=2.2 MeV, $|p_s|$=0 MeV/c .

- ✓ Experiments performed at ISNAP at the University of Notre Dame (USA) and LNS of Catania;
- ✓ $E_{beam}(^{17}O)$= 43.5 MeV;
- ✓ Target thickness $CD_2$ ~150 μg/cm$^2$;
- ✓ IC filled with ~50 mbar isobutane gas;
- ✓ Angular position to cover the QF angular region
- ✓ Symmetric set-up in order to increase the statistic.

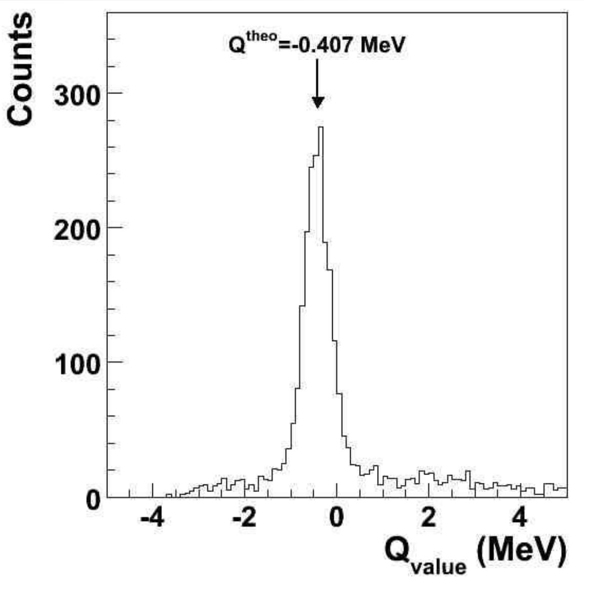


# Data Analysis: Channel Selection

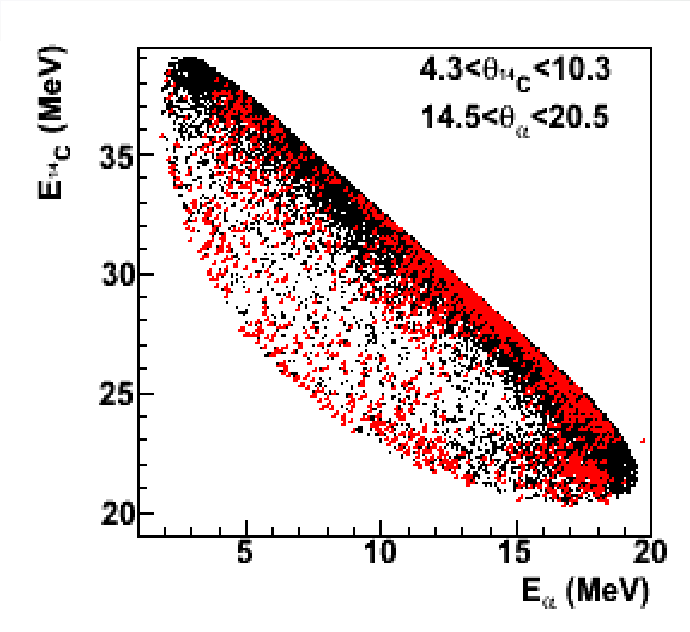
## $^{2}H(^{17}O,\alpha^{14}C)p$ -> $Q_{value}$=-0.407 MeV




» *Selection of the events with carbon in the final state*

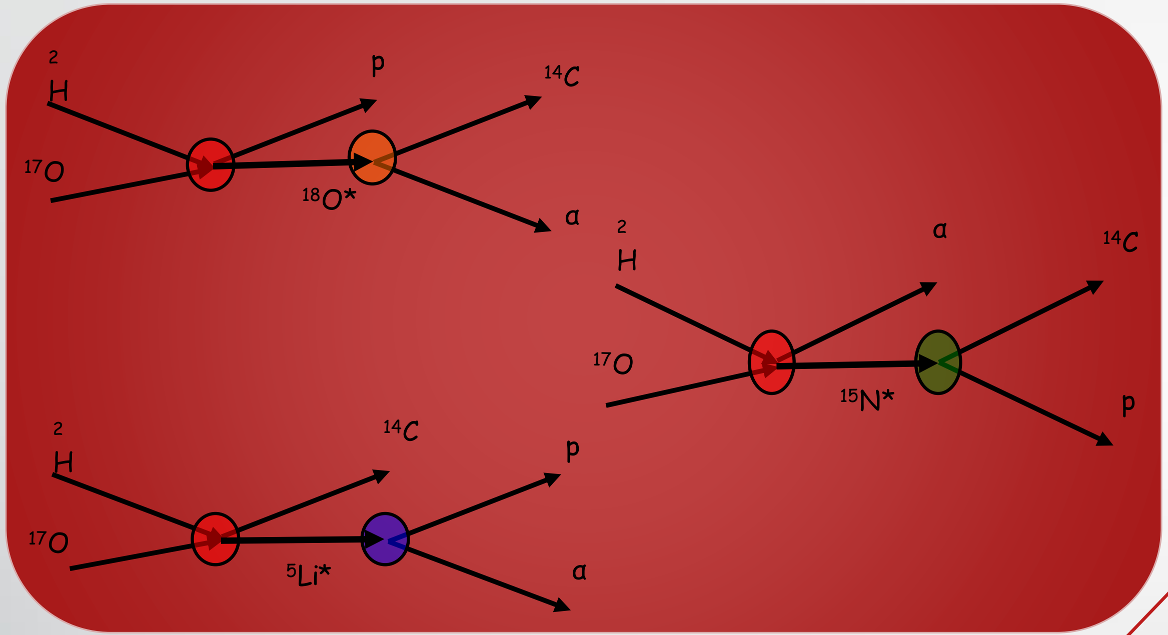


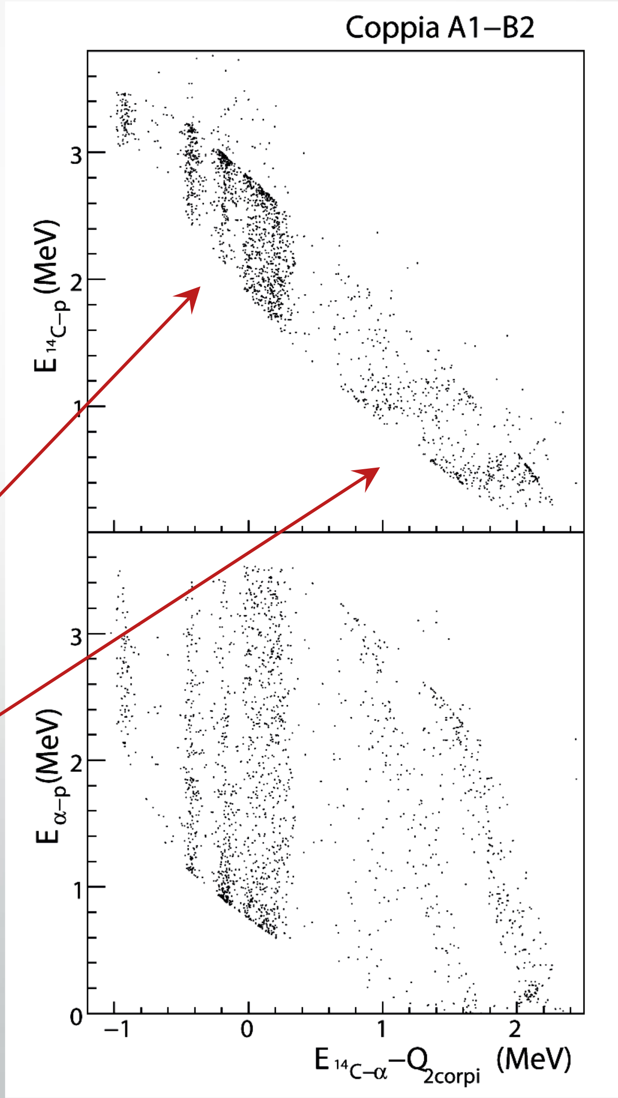

» *Presence of a peak centered at the expected value*




» *Comparison between experimental and simulated kinematical locus*

# Data Analysis: Sequential Mechanisms




» Presence of vertical loci corresponding to $^{18}O$;

» Presence of $^{15}N$ levels but far from the zone of interest;

» Absence of horizontal loci from $^{5}Li$.

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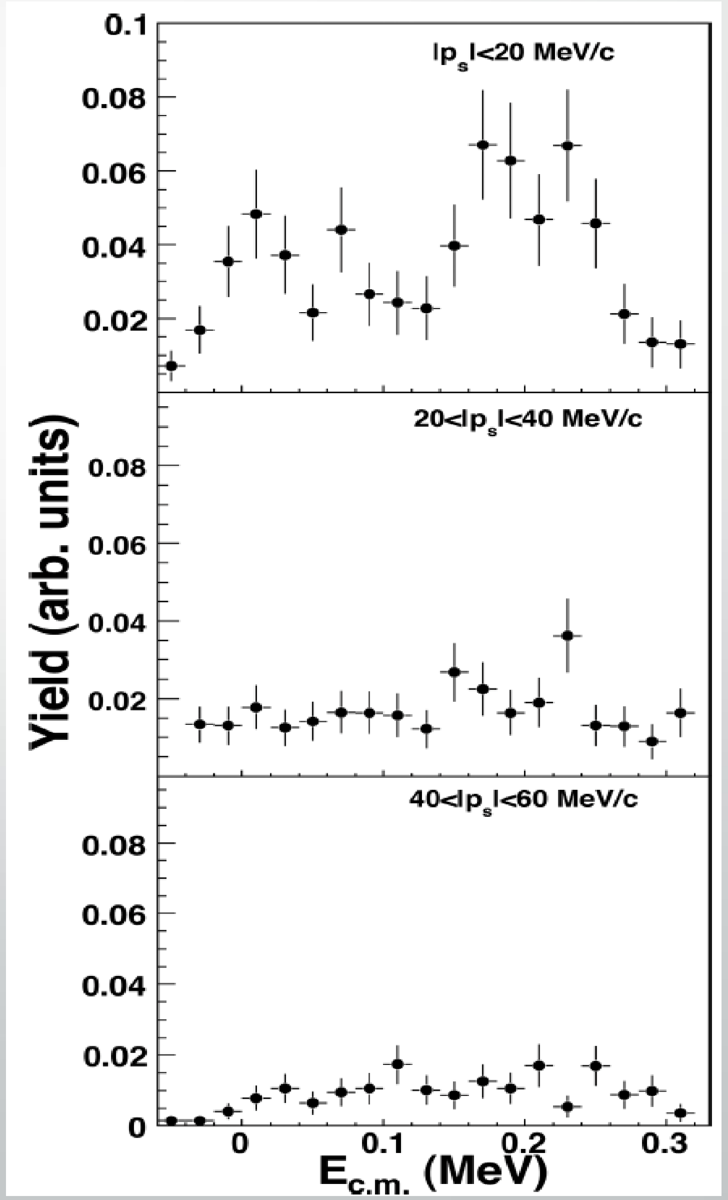
# Data Analysis: QF Selection

1) The experimental yield of the **$E_{c.m.}$(MeV)=$E_{\alpha 14C}$-1.818** has been studied**;**
2) Spectra are obtained with different condition on the *undetected* proton momentum;
3) The yield is enhanced around low-neutron momenta and decrease for 40<|$p_p$|<60 MeV/c;
4) The coincidence yield appears strongly influenced by the p-n momentum distribution in the deuteron (having its maximum at 0 MeV/c).



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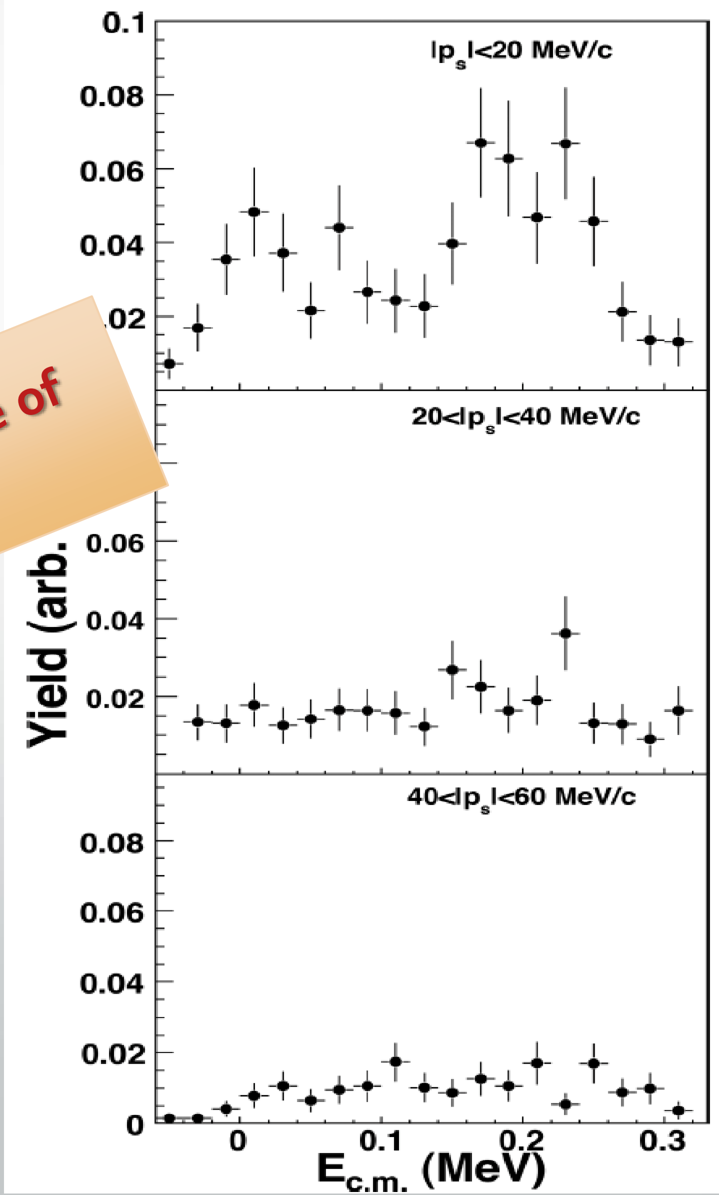
4) The coincidence yield a... influenced by th... ...tribution in the deuteron (... ...aximum at 0 MeV/c).

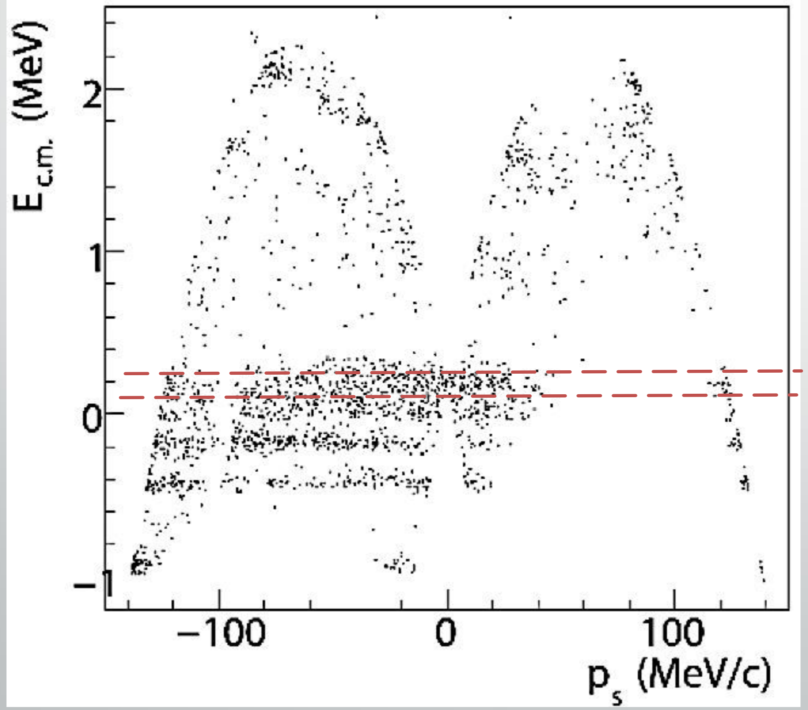
Necessary condition for the presence of the QF mechanism

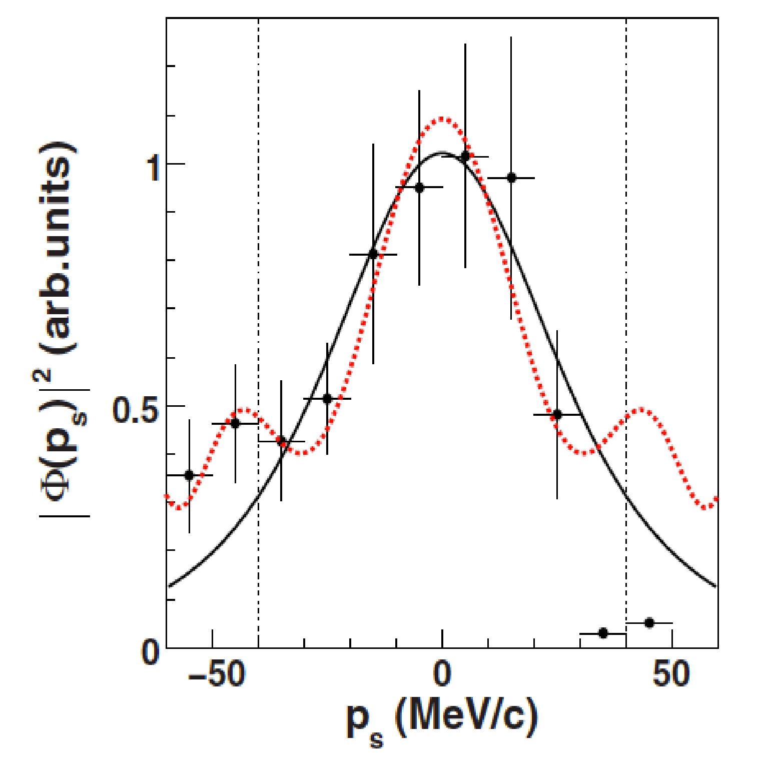


# Data Analysis: QF Selection

By following the PWIA approach it is possible to extract the experimental momentum distribution:

$$\left|\Phi(p_s)\right|^2 \propto \frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \Big/ KF$$




Theoretical Hulten Function

DWBA calculation (FRESCO code)

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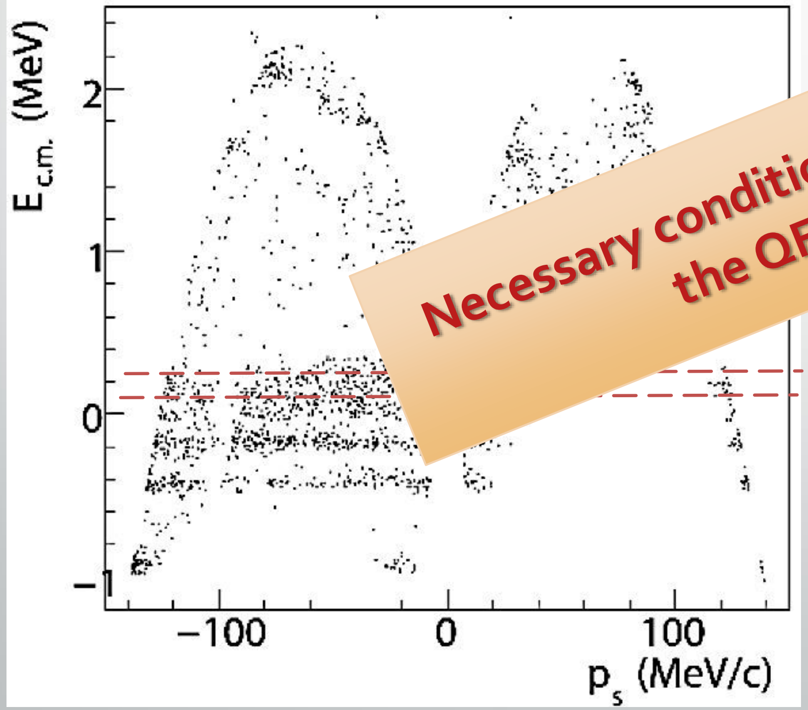
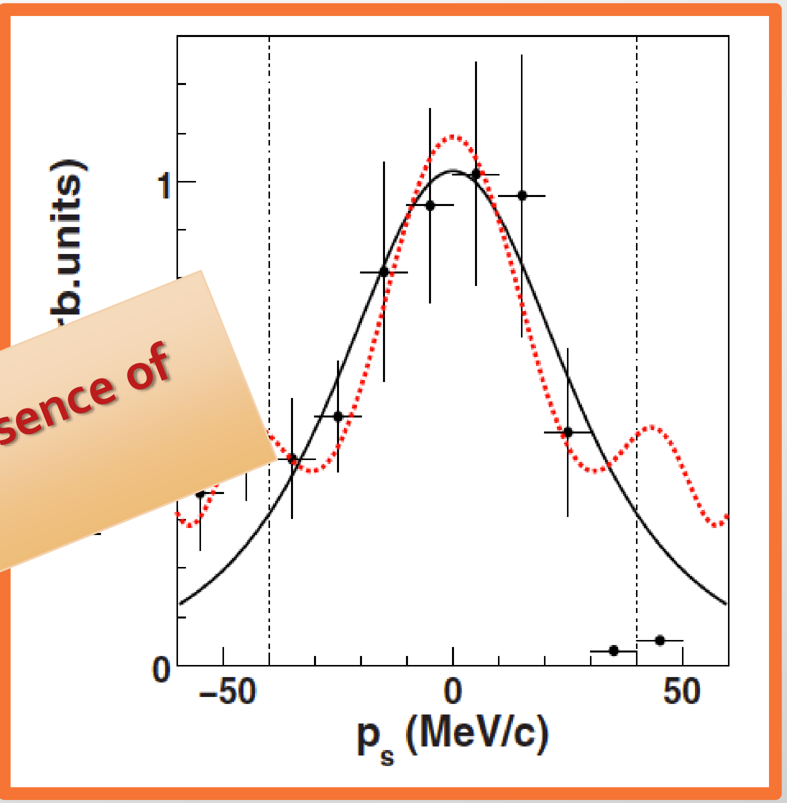



**Necessary condition for the presence of the QF mechanism**

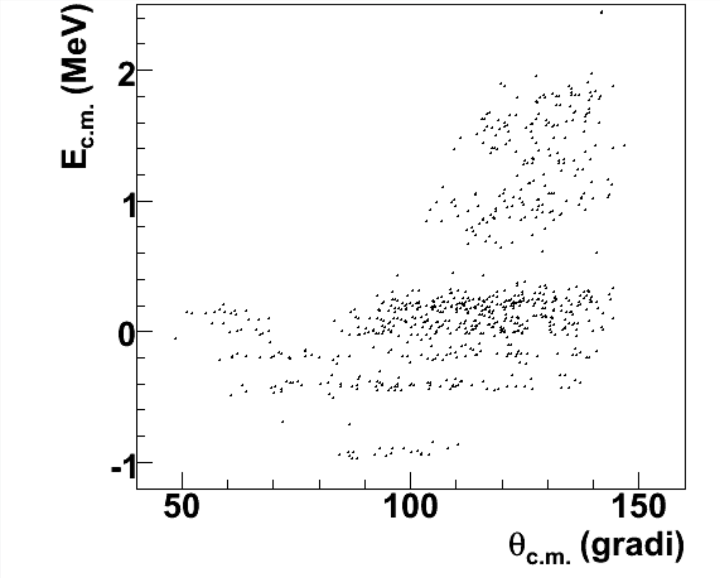



Theoretical Hulten Function

DWBA calculation (FRESCO code)

# Data Results: Angular Distributions

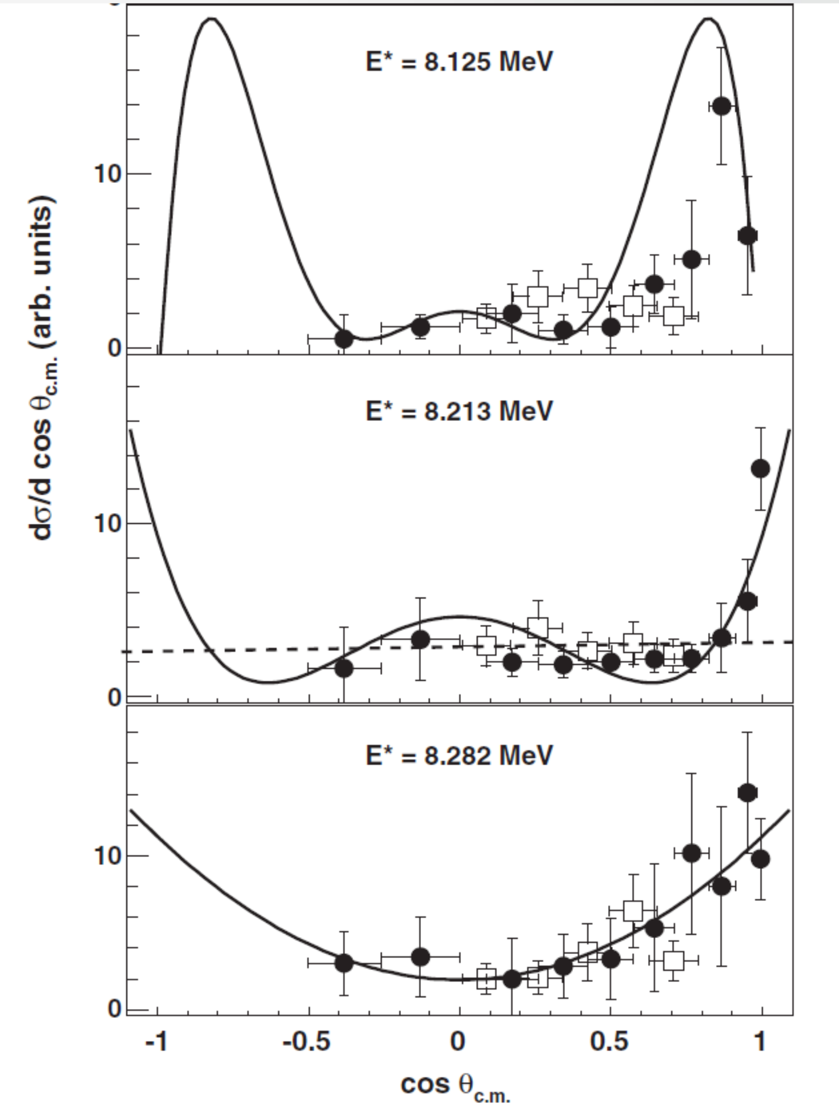
After the study of the 3-body channel and the QF selection, it is important to study the 2-body one. The angular range covered in the experiments in the c.m. system allows one to study the angular distributions




ℓ=3 distribution: no data present in literature (suppressed in direct measurements)

ℓ=2 distribution: no data present in literature

ℓ=1 distribution: will be compared with the available data




Gulino et al., PRC 87, 012801 (2013)

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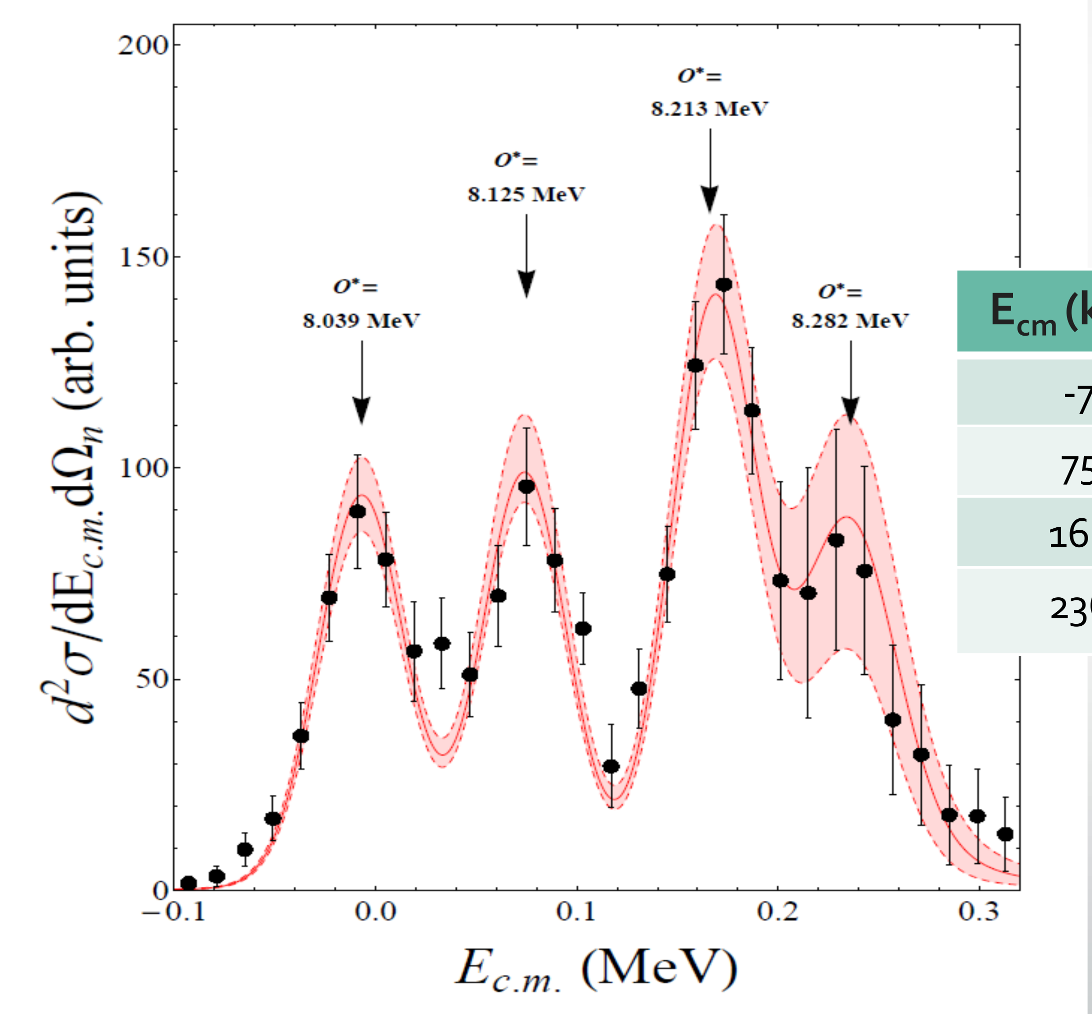
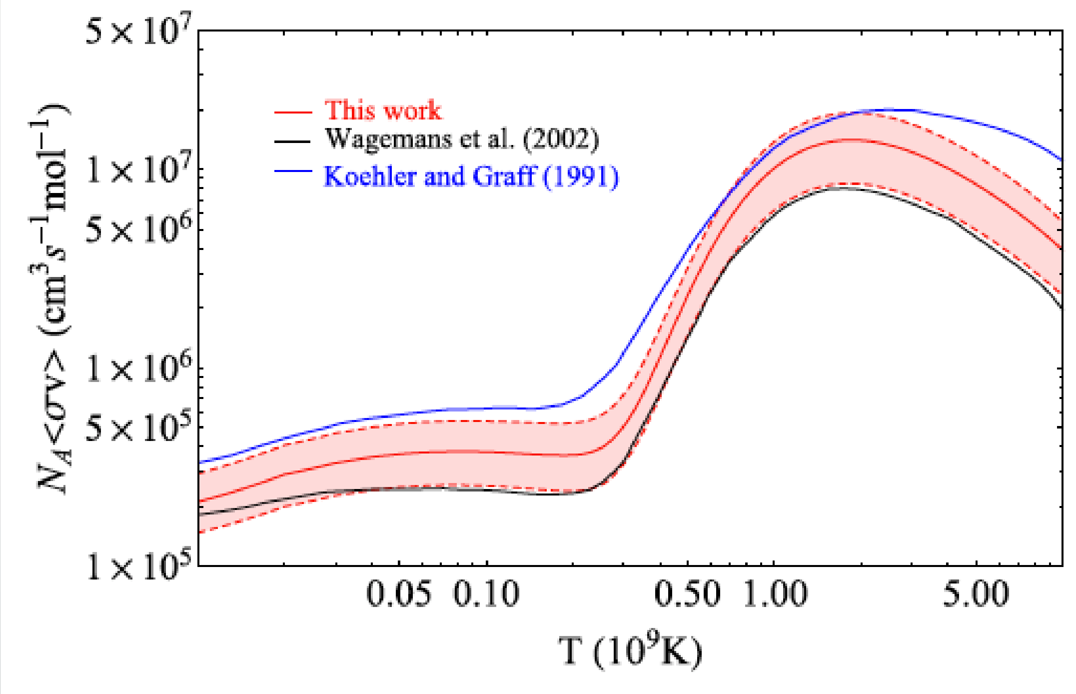
# Data Results: R-Matrix Fit



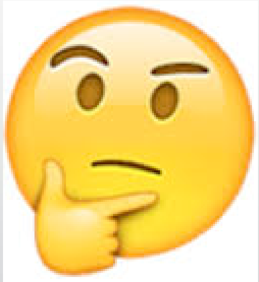

| $E_{cm}$ (keV) | $\Gamma_n$ (eV) | $\Gamma_\alpha$ (eV) | $\Gamma_{TOT}$ (eV) | $\Gamma_{wag.}$ (eV) |
|---|---|---|---|---|
| -7 | 0,01±0,001 | 2362±307 | 2362±307 | 2400 |
| 75 | 0,05±0,006 | 36±5 | 36±5 | - |
| 166 | 86±11 | 2171±282 | 2257±293 | 2258±135 |
| 236 | 1714±446 | 13021±3386 | 14735±3832 | 14739±590 |

*Guardo et al., Phys. Rev. C, 95, 025807, 2017*

# Data Results: Astrophysical Rate




**Possible impact on stellar nucleosynthesis?**



# Recent Results of THM

The Astrophysical Journal, 845:19 (13pp), 2017 August 10
https://doi.org/10.3847/1538-4357/aa7de7


**New Improved Indirect Measurement of the $^{19}F(p, \alpha)^{16}O$ Reaction at Energies of Astrophysical Relevance**

I. Indelicato[1], M. La Cognata[1], C. Spitaleri[1,2], V. Burjan[3], S. Cherubini[1,2], M. Gulino[1,4], S. Hayakawa[5], Z. Hons[3], V. Kroha[3], L. Lamia[1], M. Mazzocco[6,7], J. Mrazek[3], R. G. Pizzone[1], S. Romano[1,2], E. Strano[6,7], D. Torresi[6,7], and A. Tumino[1,4]
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*Received 2017 May 30; revised 2017 July 3; accepted 2017 July 3; published 2017 August 8*

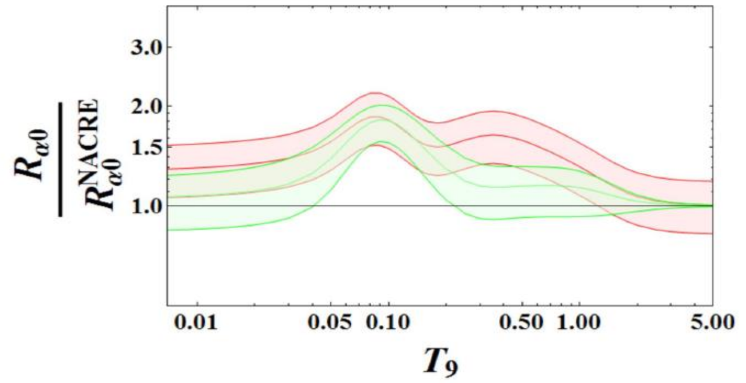
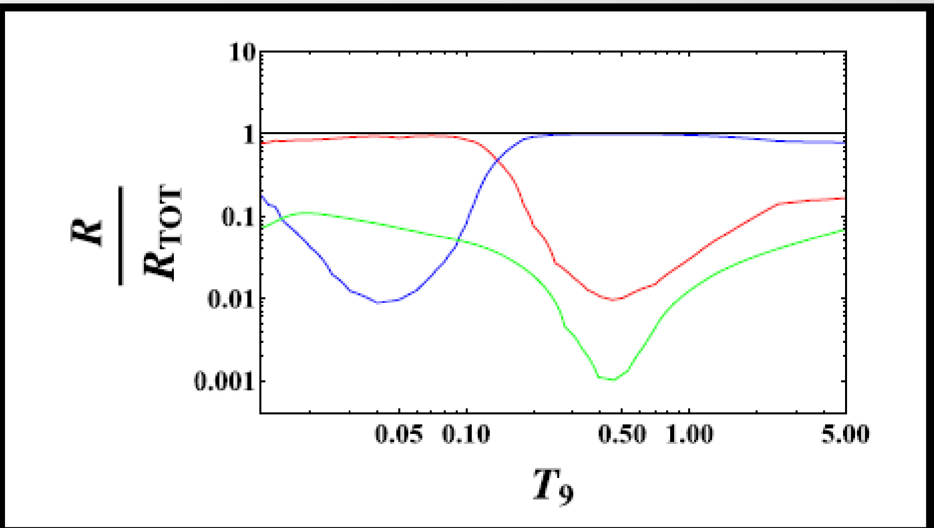



**Figure 15.** Ratio of the reaction rate calculation obtained from the THM astrophysical factor (red band) to the rate recommended in NACRE (Angulo et al. 1999). $T_9$ is the temperature in GK ($T_9 = T/10^9$ K). The black line corresponds to $R/R_{\alpha 0}^{nacre} = 1$. For comparison, the $R/R_{\alpha 0}^{nacre}$ ratio given in La Cognata et al. (2015) is shown as a green band.

Three open channels:

- $^{19}F(p,\alpha_0)^{16}O$
- $^{19}F(p,\alpha_\pi)^{16}O$
- $^{19}F(p,\alpha_\gamma)^{16}O$



# Recent Results of THM

THE ASTROPHYSICAL JOURNAL, 860:61 (11pp), 2018 June 10 https://doi.org/10.3847/1538-4357/aac207


CrossMark

## 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. Mijatoviċ[5], M. Milin[9], Đ. Miljaniċ[5,10], L. Prepolec[5], G. G. Rapisarda[1], S. Romano[1,2], M. L. Sergi[1,2], N. Skukan[5], N. Soiċ[5], V. Tokiċ[5], A. Tumino[1,6], and M. Uroiċ[5]

THE ASTROPHYSICAL JOURNAL, 836:57 (6pp), 2017 February 10 https://doi.org/10.3847/1538-4357/836/1/57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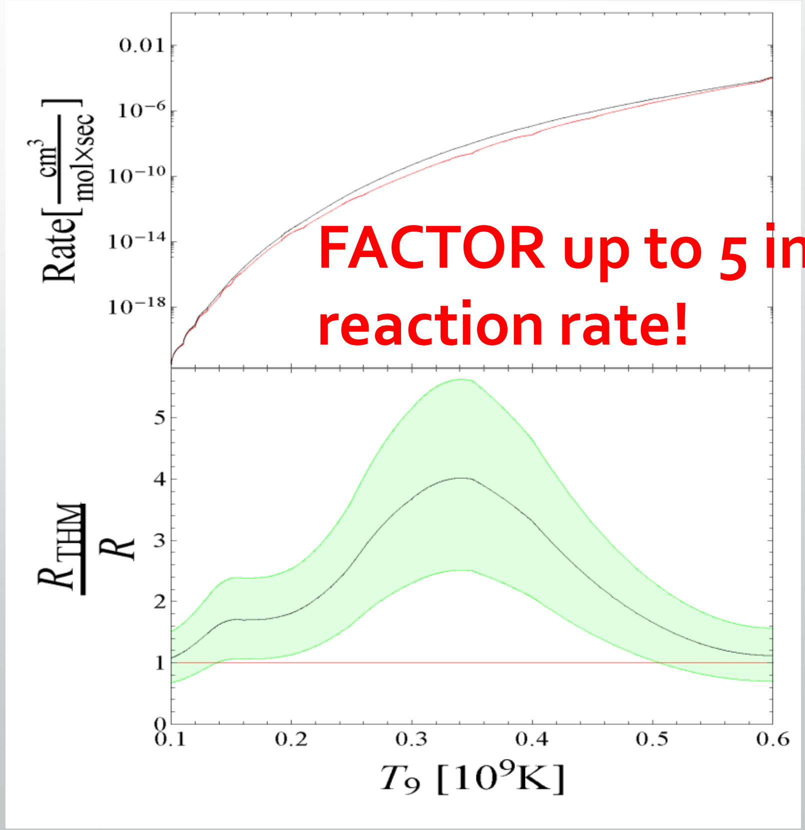
## First Measurement of the $^{19}F(\alpha, p)^{22}Ne$ Reaction at Energies of Astrophysical Relevance

R. G. Pizzone[1], G. D'Agata[1,2], M. La Cognata[1], I. Indelicato[1], C. Spitaleri[1,2], S. Blagus[3], S. Cherubini[1,2], P. Figuera[1], L. Grassi[3], G. L. Guardo[1], M. Gulino[1,4], S. Hayakawa[1,5], R. Kshetri[1,6], L. Lamia[1,2], M. Lattuada[1,2], T. Mijatović[3], M. Milin[7], Đ. Miljanić D.[3,8], L. Prepolec[3], G. G. Rapisarda[1], S. Romano[1,2], M. L. Sergi[1], N. Skukan[3], N. Soić[3], V. Tokić[3], A. Tumino[1,4], and M. Uroić[3]



# Recent Results of THM

nature
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## 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

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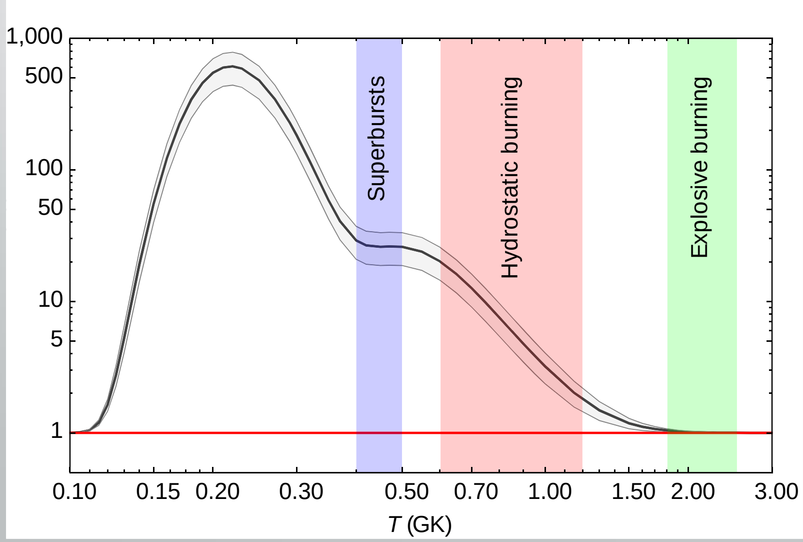


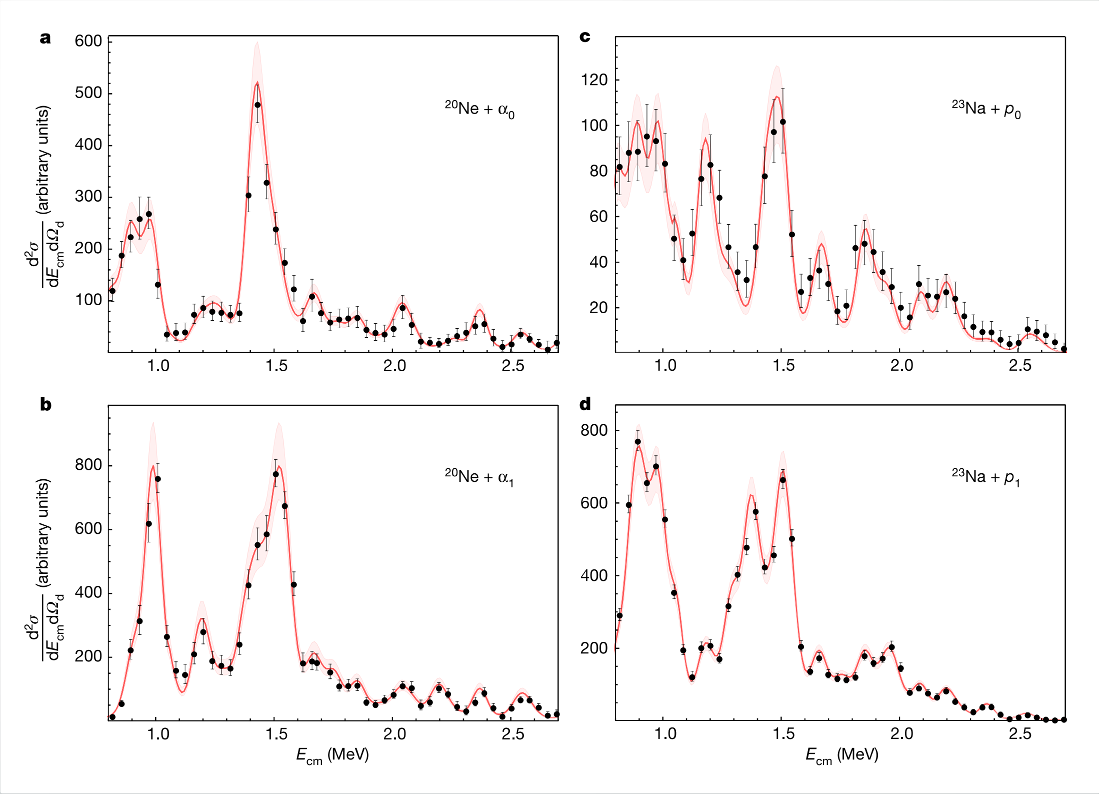

# Recent Results of THM

The Astrophysical Journal, 846:65 (6pp), 2017 September 1
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## A Trojan Horse Approach to the Production of $^{18}F$ in Novae

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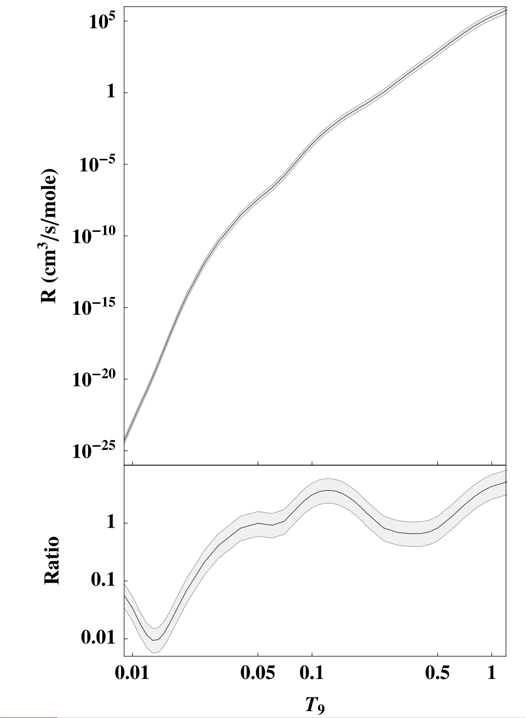


***THM successfully applied to RIBs***

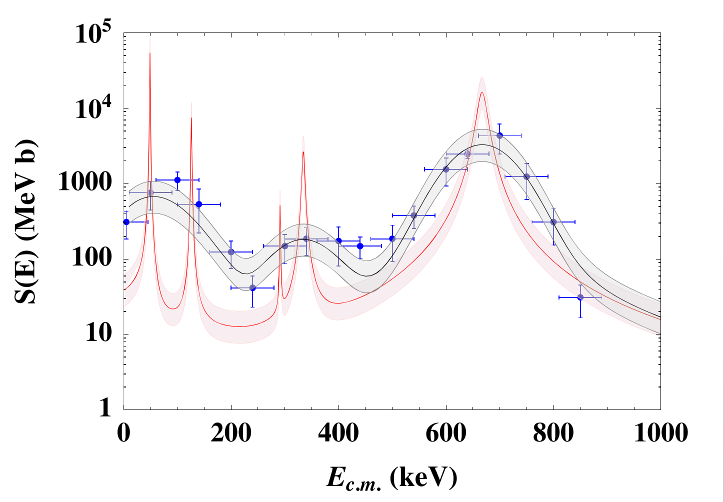


**Figure 2.** R-matrix analysis of the THM astrophysical factor (blue points) as in Figure 1. The evaluated uncertainty in the R-matrix fit is reported as a shadowed gray area and as a red band for the corresponding deconvoluted S(E)-factor.

**Experiment in CNS RIKEN and Texas A&M**

# Recent Results of THM

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, $\alpha$)$^{4}$He Reaction Cross Section at BBN Energies

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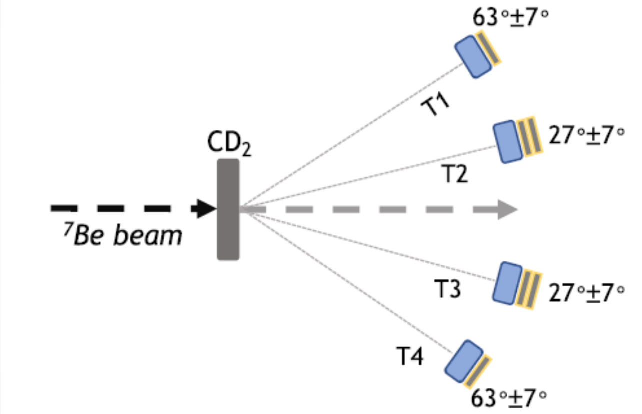
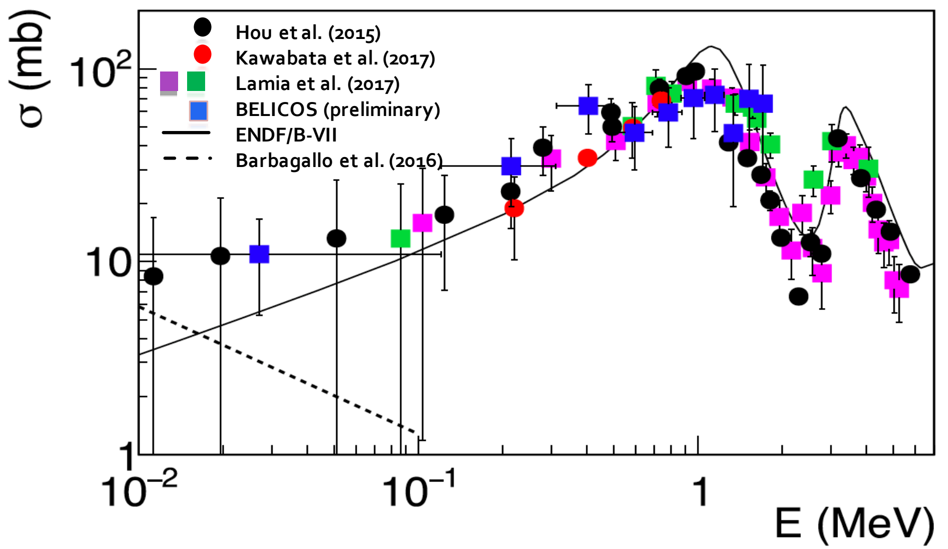



***Application of THM with RIBs and neutron induced reactions***




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, $\alpha$)$^{4}$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],
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H. Yamaguchi[5], and G. L. Zhang[16]

# Advantages of THM

A - It is possible measure the bare nucleus cross section $s_b$ ( or the bare nucleus Astrophysical Factor $S_b(E)$ ) at Gamow energy for reactions involving charged particles and neutron.

<u>No extrapolation</u>

B - It is possible to measure excitation function in a " relatively" short time because typical order of magnitude for a three- body cross- section is mb;

C - One of the few ways to measure the electron screening effect; comparison with direct data;

D - Application to the radioactive beam measurements;

# Main limitations of THM

A- Preliminary study of quasi-free mechanism and tests of validity are necessary.

- Presence of different 3-body reaction mechanisms (Sequential Decay – Quasi-Free)

B- No absolute cross section is measurable:

- The excitation functions at energies above/below Coulomb barrier must be known from direct measurements;

C- Measurements with high angular and energy resolutions are needed;

D- Theoretical analysis is needed:

- PWIA, MPWBA

**TH Method is complementary to direct measurements as well as other indirect methods.**

AstroFisica Nucleare

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Thank you for your attention