Advanced techniques and indirect methods

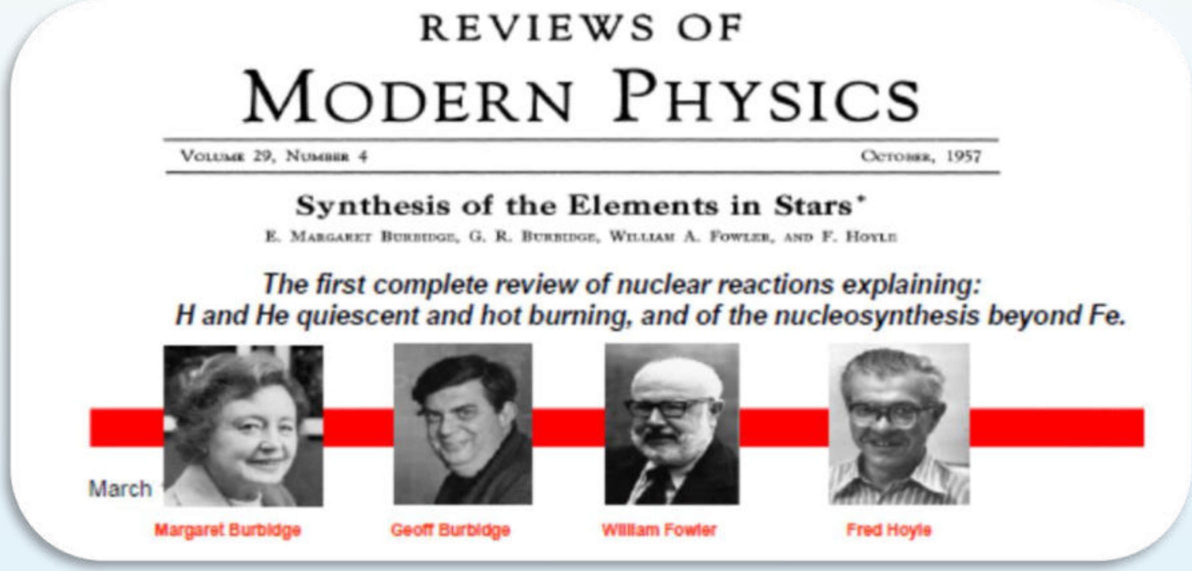
G.L. Guardo

on behalf of the AsFiN collaboration

Experimental Nuclear Astrophysics

… Everything starts from the B^2FH 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

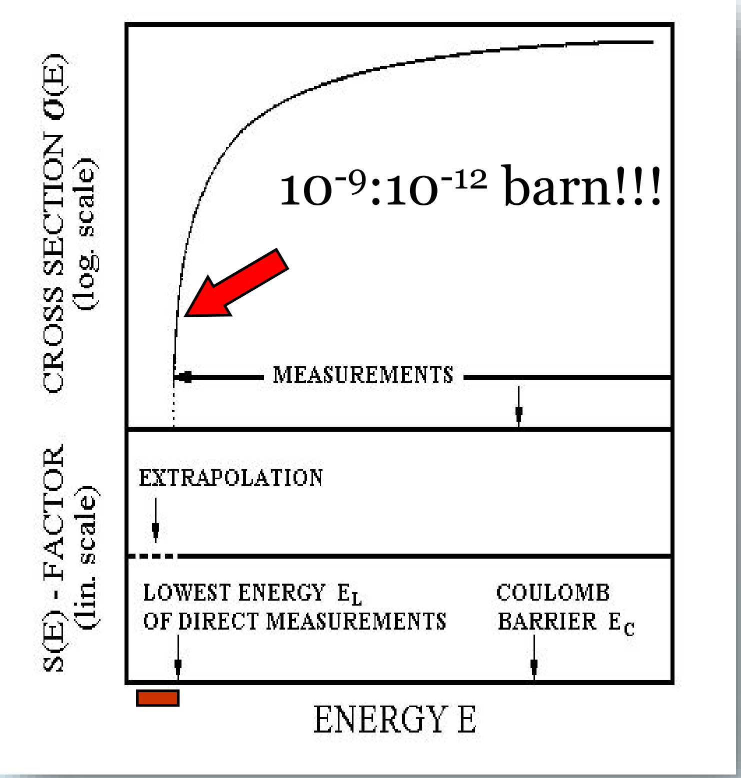


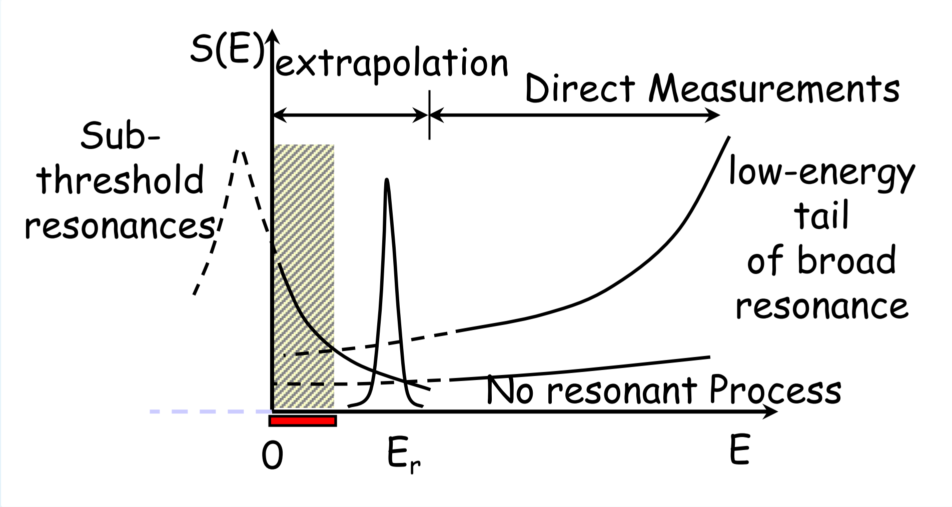
The elements composing everything from planets to life were forged inside earlier generations of stars!

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

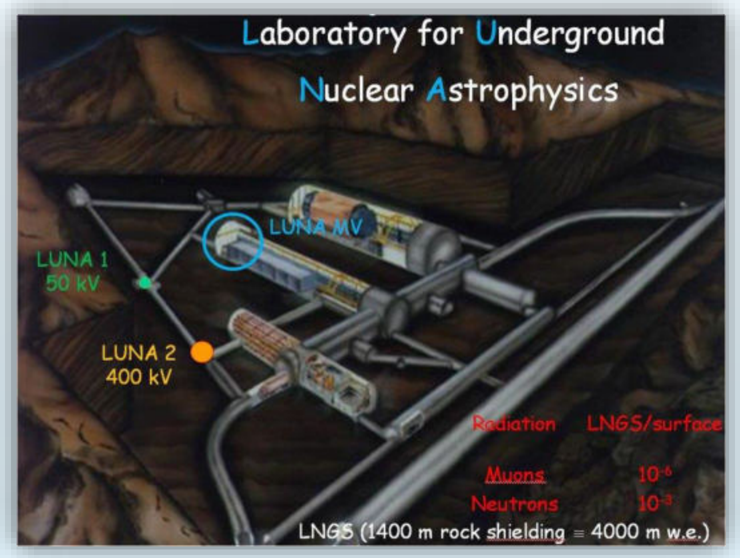




$$S(E) = E\sigma(E)\exp(2\pi\eta)$$

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.

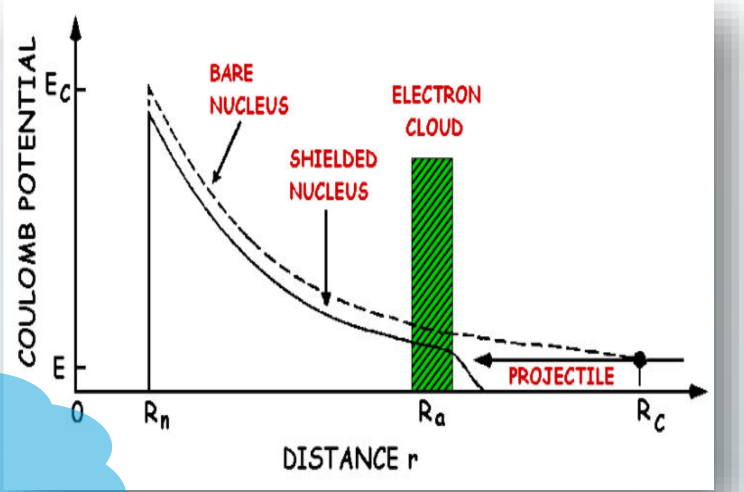


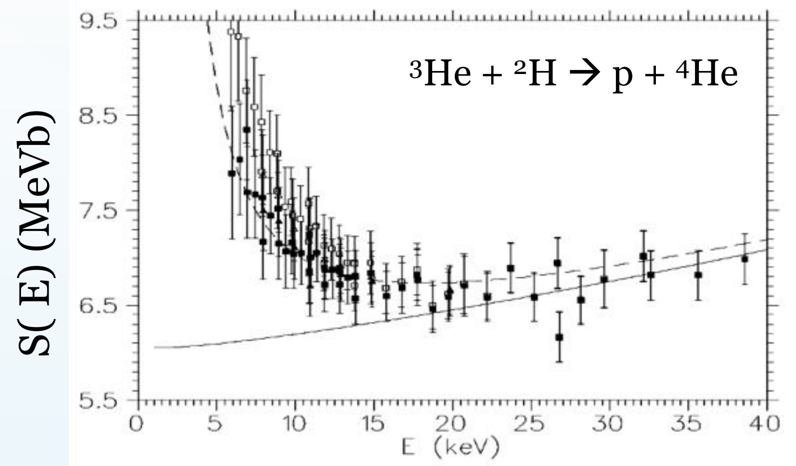
- **Longer measurements**
- **Higher beam currents**
- **4π detectors**
- **Pure targets**
- **Underground laboratories**

Electron screening

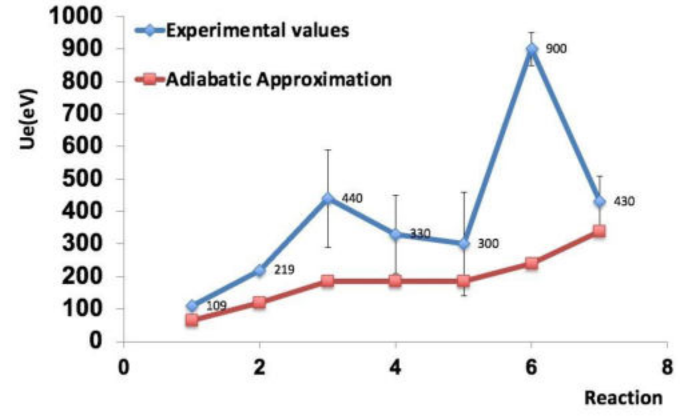
Due to the electron cloud surrounding the interacting ions the projectile feels a reduced barrier

See A. Cvetinovic & M. Lipoglavsek talks





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

- **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)**

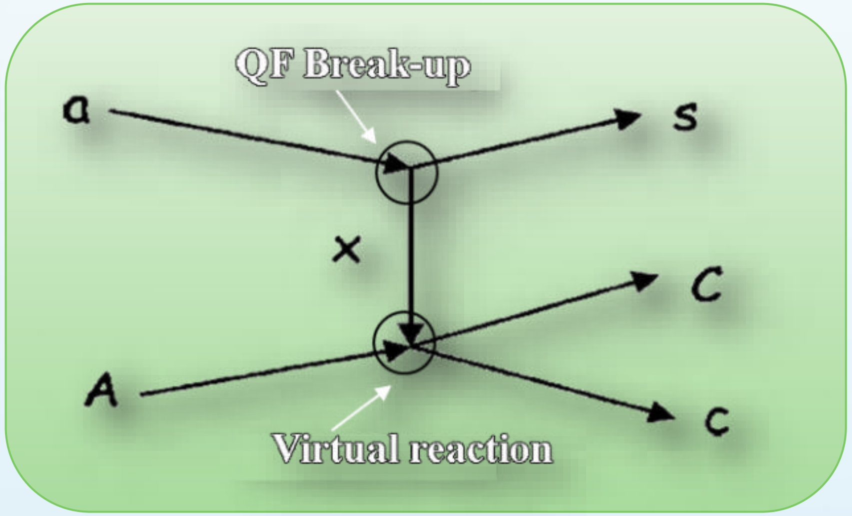
  C. Spitaleri, *Problems of Fundamental Modern Physics, II,* (World Sci.,1991)

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

AsFiN

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

TH cross section

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

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

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;
- γ_{xa} and γ_{Cc} represents the reduced partial widths for the resonant excited states that are the same of the direct measurements

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

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **Astrophysical Scenario**

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 ($M>8M_{SUN}$)

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **Astrophysical Scenario**

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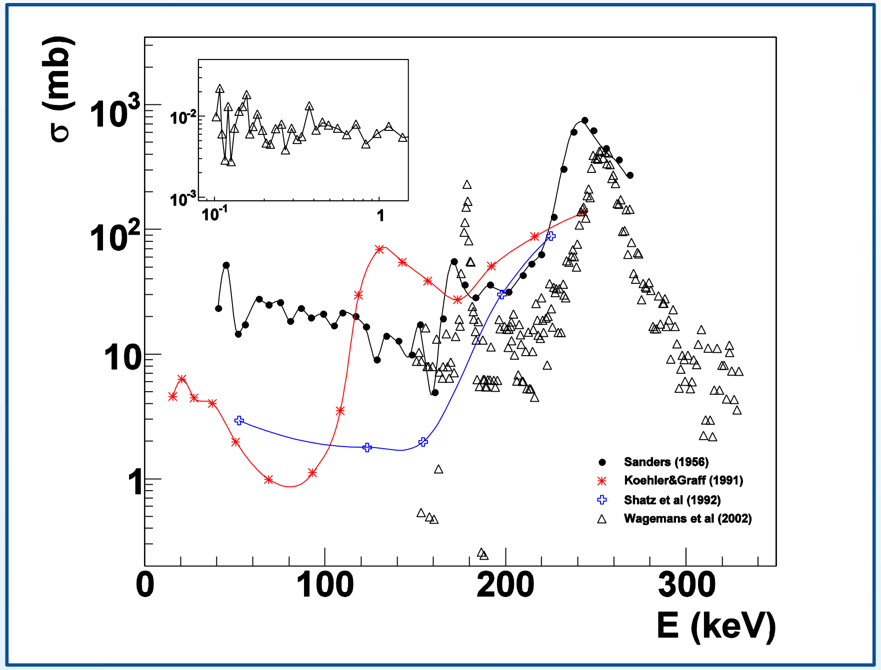
$^{17}O(n,\alpha)^{14}C$ and $^{17}O(\alpha,n)^{20}Ne$ since they act as a neutron poison and a recycle channel during s-process nucleosinthesys in massive stars ($M>8M_{SUN}$)

↓

Temperature → $0.8<T_8<11$ K
Energy range→ ~0-100 keV

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **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^π
-7	8.039	1^-
75	8.125	5^-
166	8.213	2^+
236	8.282	3^-

Subthreshold Level (-7 keV)

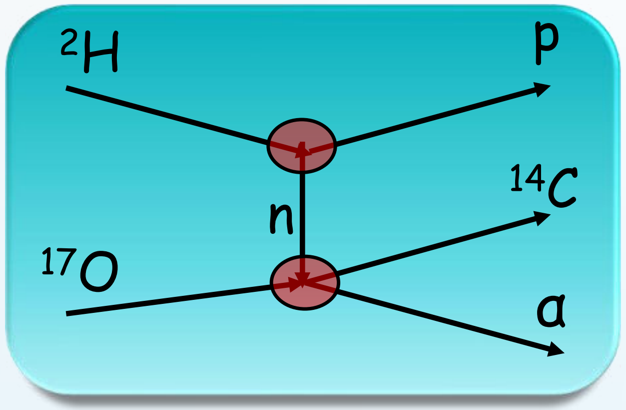
Suppressed due to the centrifugal barrier (75 keV)

Available in literature (166 keV, 236 keV)

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

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

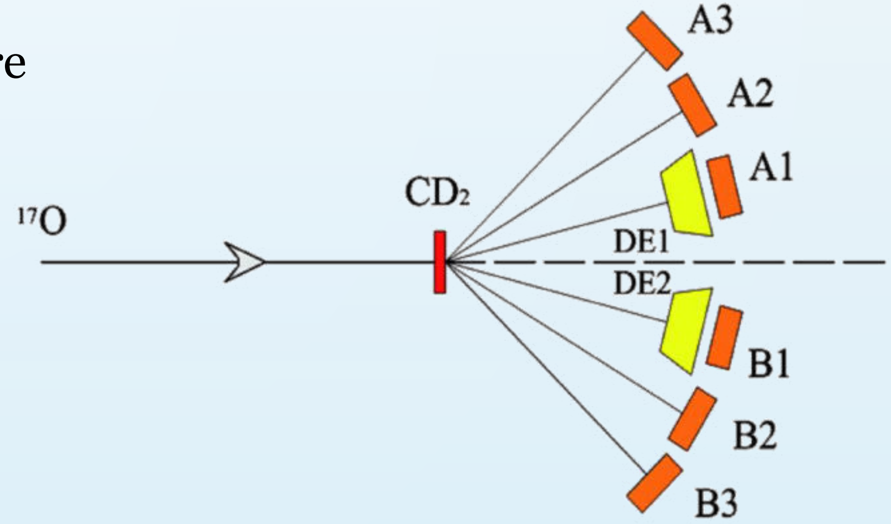
- ## Experimental setup



➢ 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 .

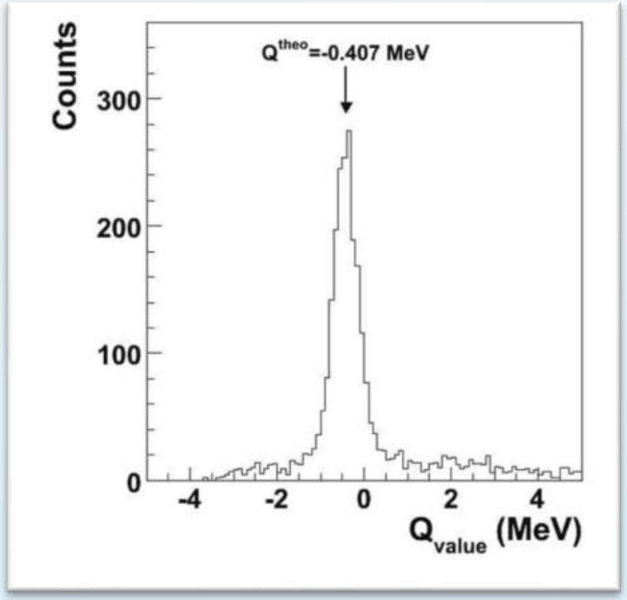
- ✓ Experiments performed at ISNAP at the University of Notre Dame (USA) and LNS of Catania;
- ✓ $E_{beam}(^{17}O)$= 43.5 MeV;
- ✓ Target thickness CD_2 ~150 μg/cm²;
- ✓ IC filled with ~50 mbar isobutane gas;
- ✓ Angular position to cover the QF angular region
- ✓ Symmetric set-up in order to increase the statistic.



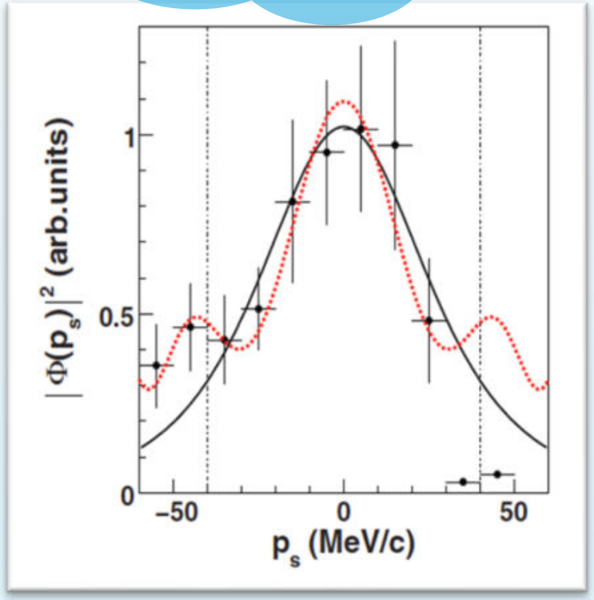
$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **Data reduction & analisys**

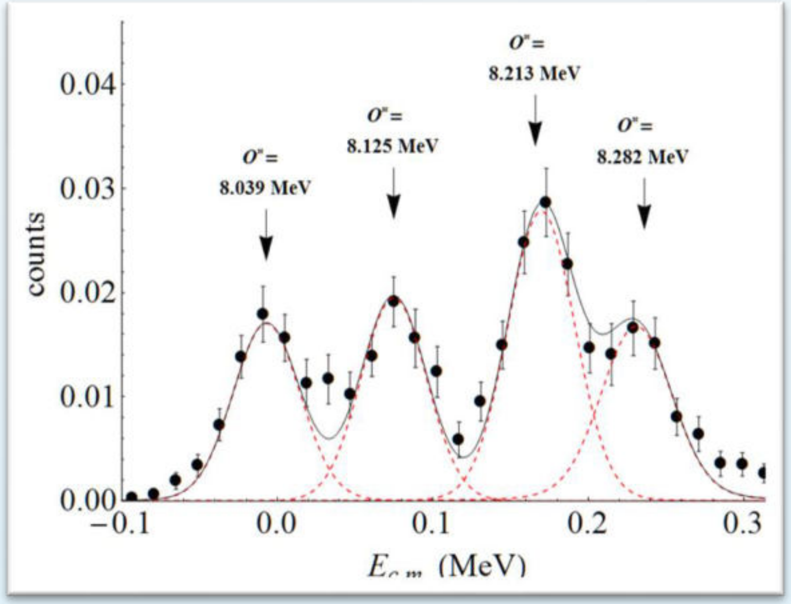
See N. Vukman talk



» *Channel selection*



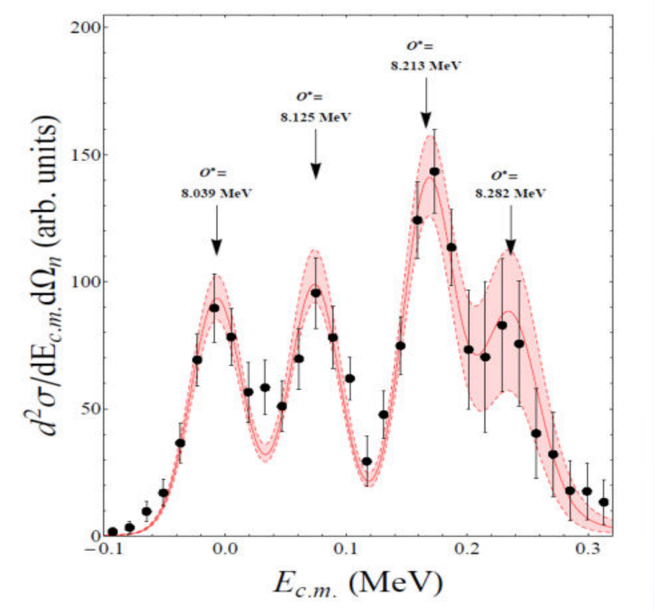
» *QF mechanism selection*

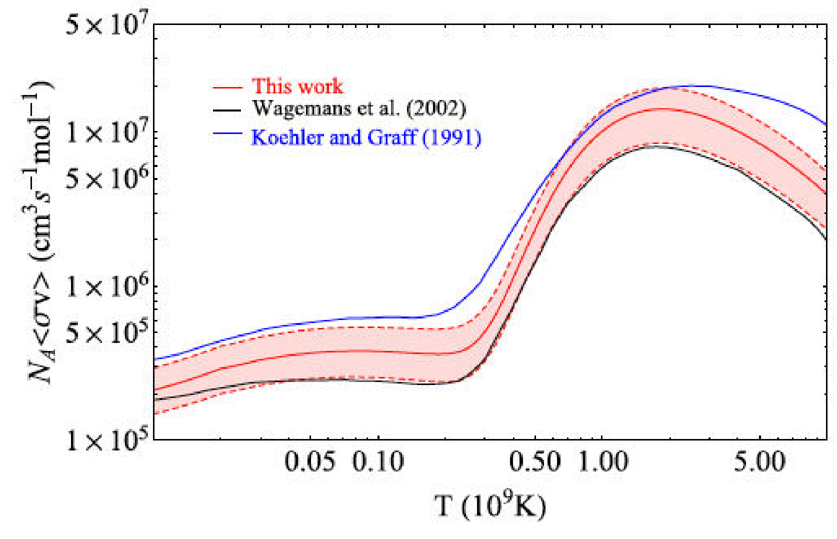


» *Three-body yield determination*

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **Data results**





E_{cm} (keV)	Γ_n (eV)	Γ_α (eV)	Γ_{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

Recent results of THM

THE ASTROPHYSICAL JOURNAL, 845:19 (13pp), 2017 August 10 https://doi.org/10.3847/1538-4357/aa7de7

CrossMark

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

Three open channels:

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

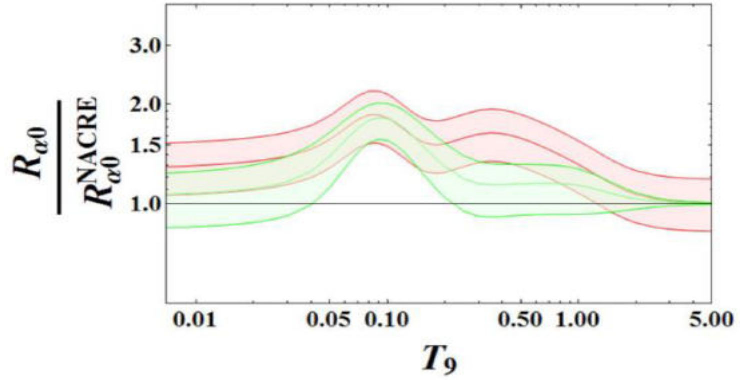
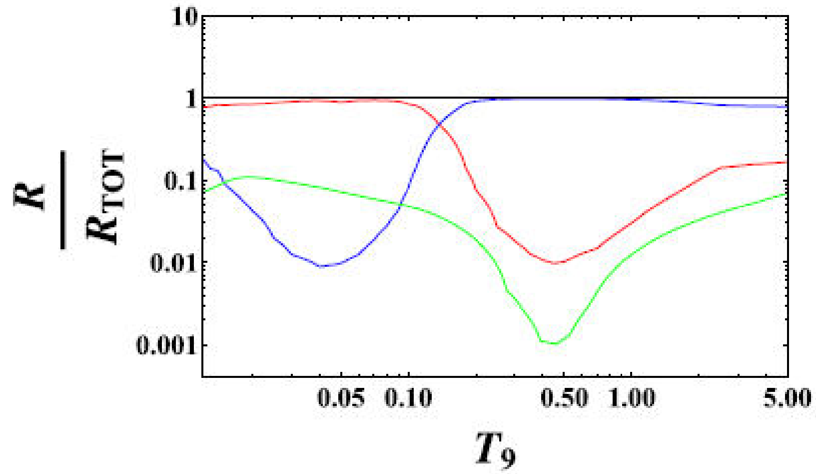


Figure 15. Ratio of the reaction rate calculation obtained from the THM astrophysical factor (red band) to the rate recommended in NACRE (Angulo et al. 1999). T_9 is the temperature in GK ($T_9 = T/10^9$ K). The black line corresponds to $R/R_{\alpha 0}^{nacre} = 1$. For comparison, the $R/R_{\alpha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



Recent results of THM

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

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The ^{19}F(α, 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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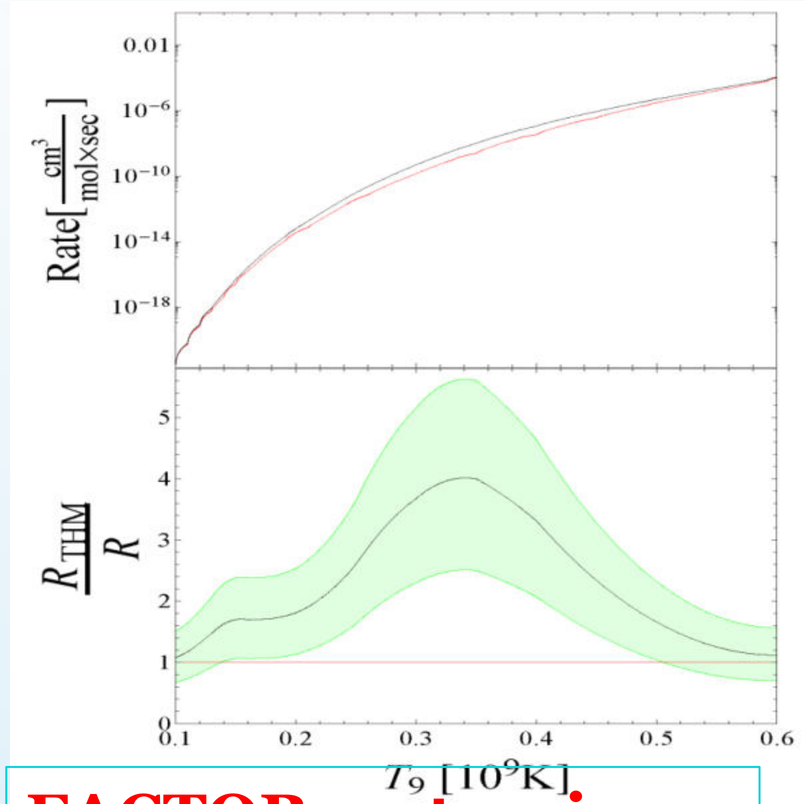
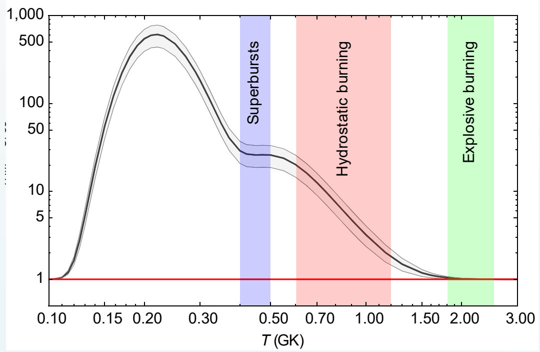
First Measurement of the ^{19}F(α, p)^{22}Ne Reaction at Energies of Astrophysical Relevance

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]



FACTOR up to 5 in reaction rate!

Recent results of THM



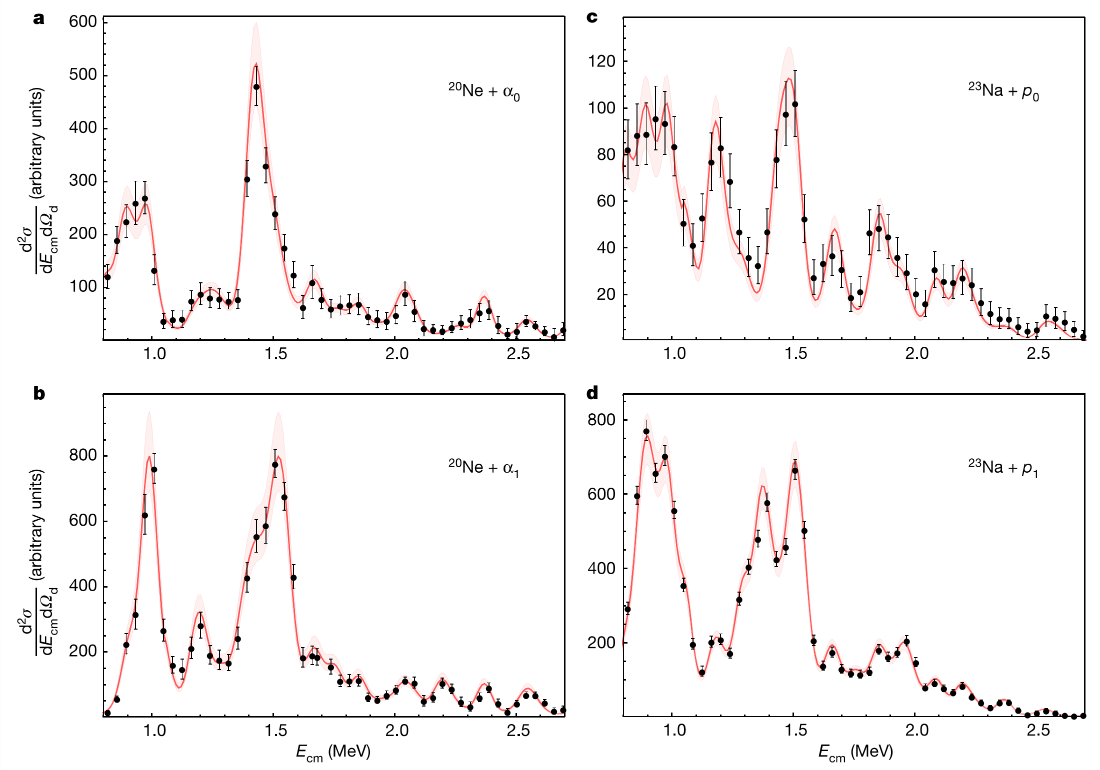
nature
International journal of science

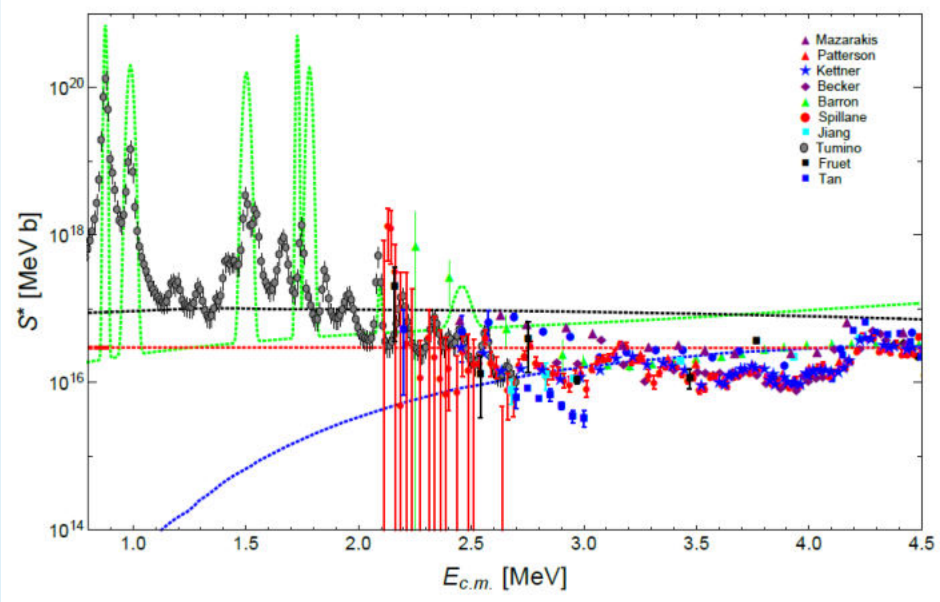
Letter | Published: 23 May 2018

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 effect
Red => Caughland & Fowler 1988
Black => Godbey 2019

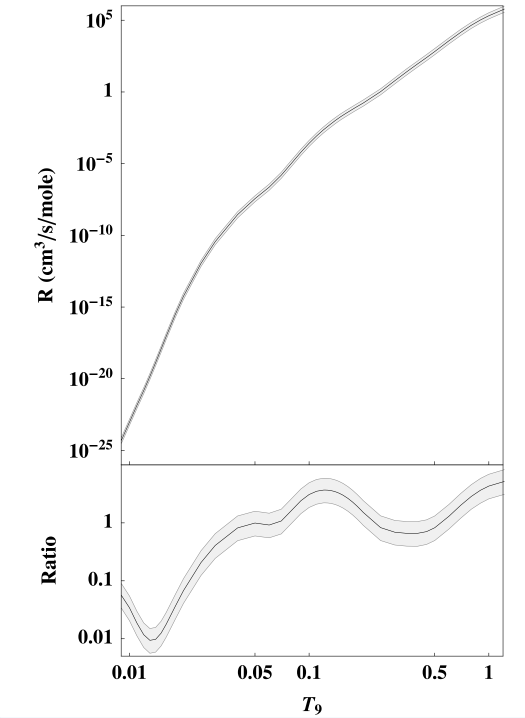
See A. Spiridon talk

Recent results of THM

THM successfully applied to RIBs

Experiment in CNS RIKEN and Texas A&M

THE ASTROPHYSICAL JOURNAL, 846:65 (6pp), 2017 September 1
https://doi.org/10.3847/1538-4357/aa845f



A Trojan Horse Approach to the Production of ^{18}F in Novae

M. La Cognata[1], R. G. Pizzone[1], J. José[2,3], M. Hernanz[3,4], S. Cherubini[1,5], M. Gulino[1,6], G. G. Rapisarda[1,5], and C. Spitaleri[1,5]
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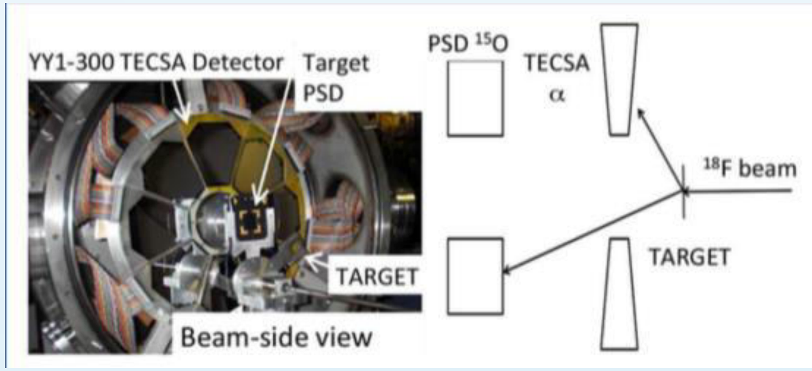

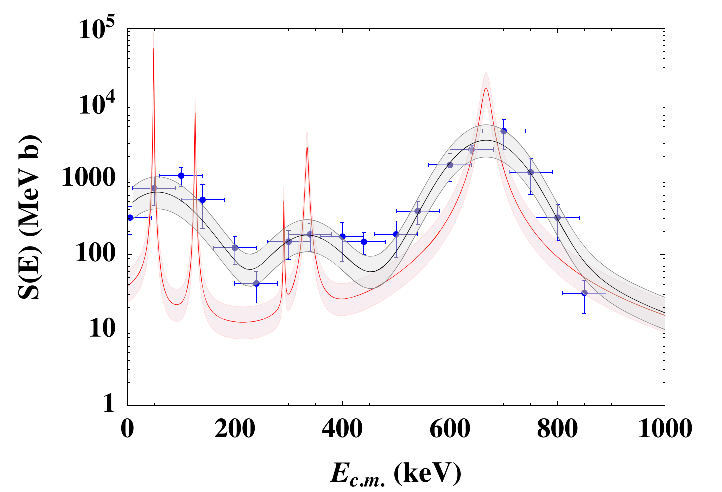

Figure 2. R-matrix analysis of the THM astrophysical factor (blue points) as in Figure 1. The evaluated uncertainty in the R-matrix fit is reported as a shadowed gray area and as a red band for the corresponding deconvoluted S(E)-factor.

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

CrossMark

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]
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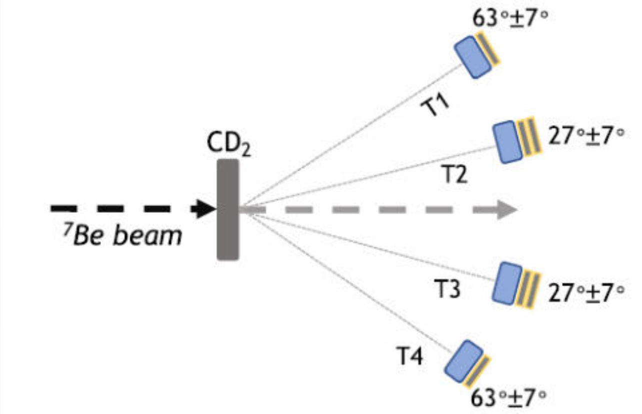

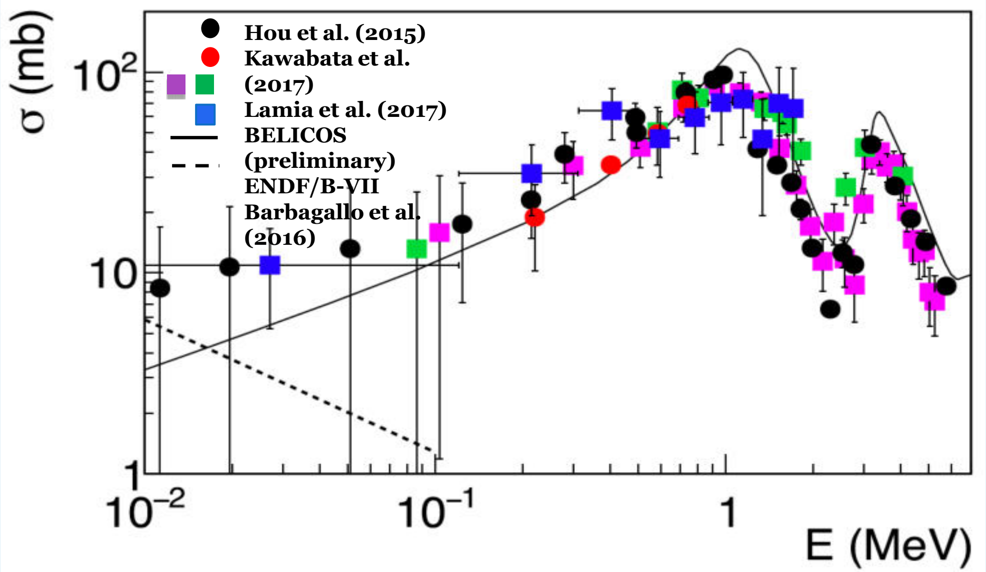

THE ASTROPHYSICAL JOURNAL, 879:23 (8pp), 2019 July 1 https://doi.org/10.3847/1538-4357/ab2234

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

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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.

B - No extrapolation

C - 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;

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

E - Application to the radioactive beam measurements.

Main limitation of THM

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

B - Presence of different 3-body reaction mechanisms

(Sequential Decay – Quasi-Free)

C - Absolute cross section isnot easily measurable

D - The excitation functions at energies around Coulomb barrier must be known from direct measurements;

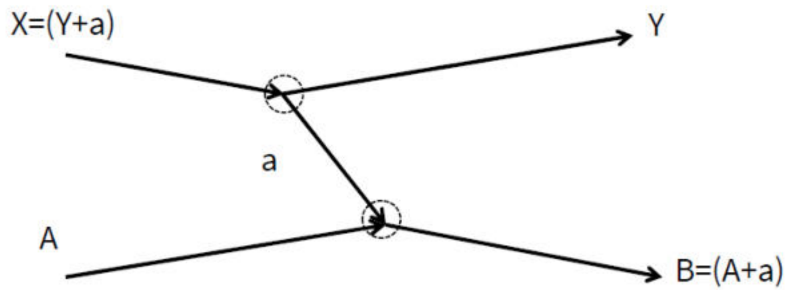
D - Measurements with high angular and energy resolutions are needed;

E - Theoretical analysis is needed: PWIA, MPWBA, DWBA...

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

Asymptotic Normalitation Coefficient

Studies performed by means of «simple» transfer reactions



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

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

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»

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

$$= \sum_{j_B,j_x} \left(C_{Aa,l_B,j_B}^{B}\right)^2 \left(C_{Ya,l_x,j_x}^{X}\right)^2 R_{l_B,j_B,l_x,j_x}$$

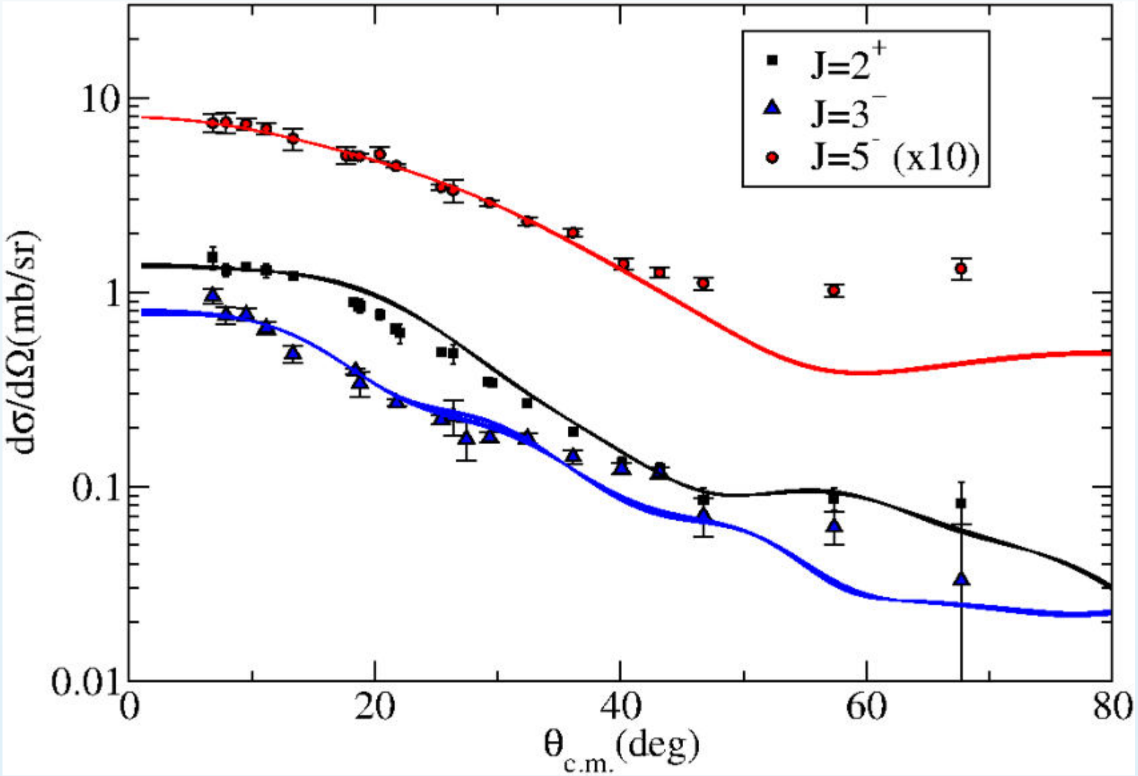
$^{17}O(n,\alpha)^{14}C$ reaction: a case study

• Experimental setup

- ✓ Experiments performed at NPI-CAS at Rez, Prague (Czech Republic);
- ✓ $E_{beam}(^{2}H)$= 16.3 MeV;
- ✓ Gas target ^{17}O, 90% pure;
- ✓ 8 point-like silicon telescope;
- ✓ Angular coverage: 6-67 degree in lab system

$^{17}O(n,\alpha)^{14}C$ reaction: a case study

- **ANC extraction from $^{17}O(d,p)^{18}O$ transfer reaction**



$E_{^{18}O}$ (MeV)	J^π	l	$\lvert C\rvert^2$ (fm^{-1})	Orbital
8.125	5^-	3	$3.06\pm0.46\cdot10^{-8}$	1f5/2
			$2.53\pm0.38\cdot10^{-8}$	1f7/2
8.213	2^+	2	$2.85\pm0.43\cdot10^{-5}$	2d3/2
			$2.87\pm0.43\cdot10^{-5}$	2d5/2
8.282	3^-	1	$3.20\pm0.48\cdot10^{-4}$	2p3/2
			$3.17\pm0.47\cdot10^{-4}$	2p1/2

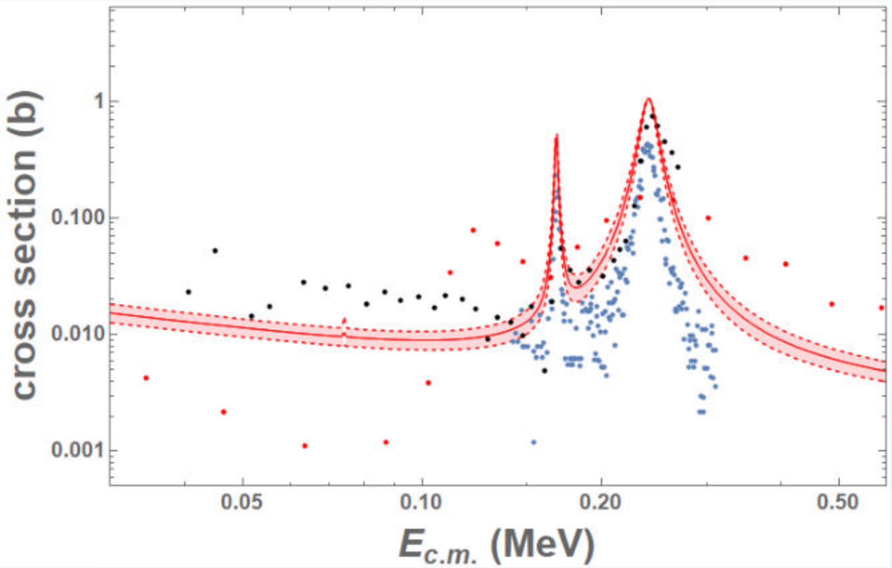
$^{17}O(n,\alpha)^{14}C$ reaction: a case study

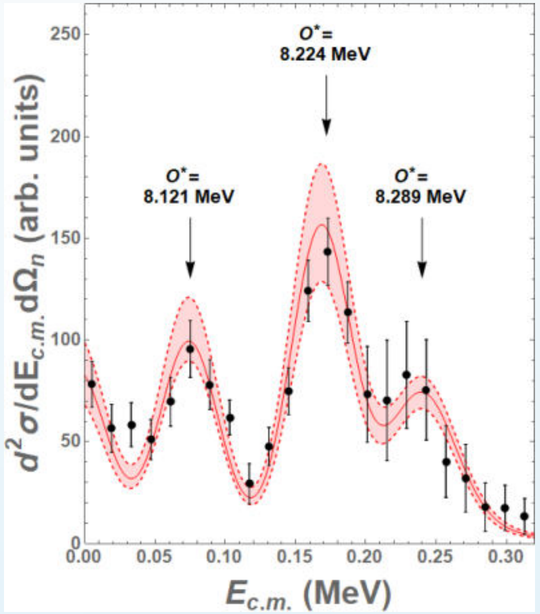
- **Direct and THM data comparison**

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

• 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)





E_{cm} (keV)	Koehler & Graff (1991)	Wagemans et al. (2002)	Guardo et al. (2017)	This Work
75	–	–	36±5 eV	33±5 eV
178	1280±1000 eV	2258±235 eV	2260±300 eV	2150±323 eV
244	8000±1000 eV	14739±590 eV	14700±3800 eV	16670±2500 eV

AsFiN

Recent results of ANC

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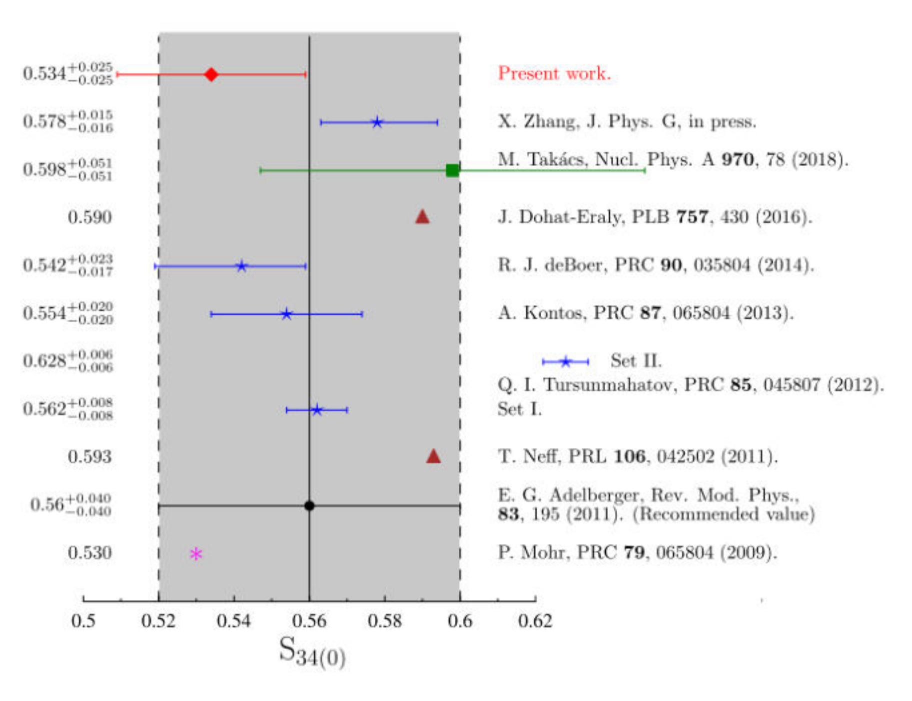
Astrophysical S-factor for the $^3He(\alpha,\gamma)^7Be$ reaction via the asymptotic normalization coefficient (ANC) method

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 $^6Li(p,\gamma)^7Be$ reaction using the asymptotic normalization coefficient method

G. G. Kiss,[1,*] M. La Cognata,[2,†] R. Yarmukhamedov,[3,‡] K. I. Tursunmakhatov,[3,4] I. Wiedenhöver,[5] L. T. Baby,[5] S. Cherubini,[2,6] A. Cvetinović,[2] G. D'Agata,[7] P. Figuera,[2] G. L. Guardo,[2,6] M. Gulino,[2,8] S. Hayakawa,[9] I. Indelicato,[2,6] L. Lamia,[2,6,10] M. Lattuada,[2,6] F. Mudò,[2,6] S. Palmerini,[11,12] R. G. Pizzone,[2] G. G. Rapisarda,[2,6] S. Romano,[2,6,10] M. L. Sergi,[2,6] R. Spartà,[2,6] C. Spitaleri,[2,6] O. Trippella,[11,12] A. Tumino,[2,8] M. Anastasiou,[5] S. A. Kuvin,[5] N. Rijal,[5] B. Schmidt,[5] S. B. Igamov,[3] S. B. Sakuta,[13] Zs. Fülöp,[1] Gy. Gyürky,[1] T. Szücs,[1] Z. Halász,[1] E. Somorjai,[1] Z. Hons,[7] J. Mrázek,[7] R. E. Tribble,[14] and A. M. Mukhamedzhanov[14]



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

Recent results of ANC

PHYSICAL REVIEW C **103**, 015806 (2021)

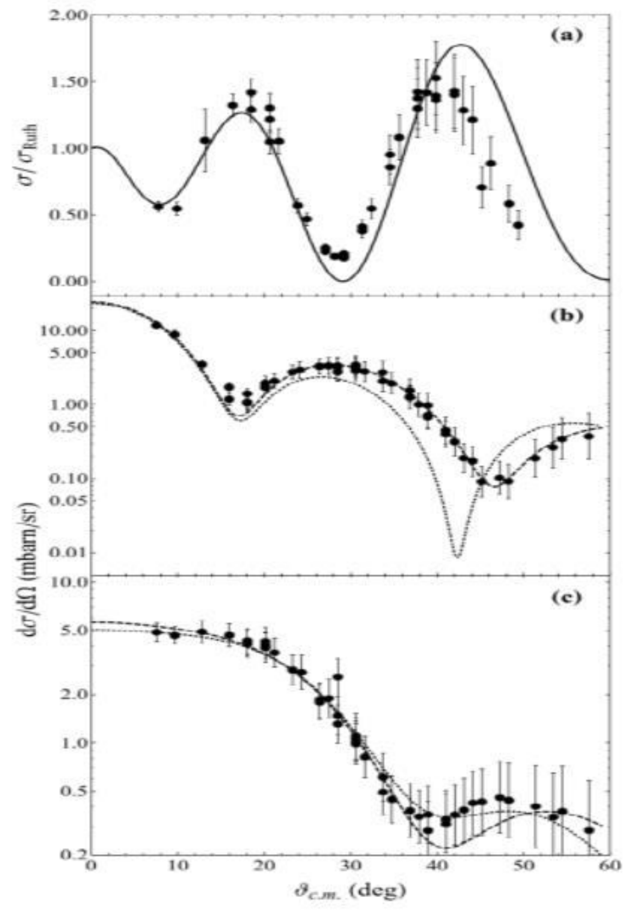
^{26}Si(p, γ)^{27}P direct proton capture by means of the asymptotic normalization coefficients method for mirror nuclei

G. D'Agata,[1,*] A. I. Kilic,[1] V. Burjan,[1] J. Mrazek,[1] V. Glagolev,[1] V. Kroha,[1] G. L. Guardo,[2] M. La Cognata,[2] L. Lamia,[2,3,4] S. Palmerini,[5,6] R. G. Pizzone,[2] G. G. Rapisarda,[2] S. Romano,[2,3,4] M. L. Sergi,[2,3] R. Spartà,[2,3] C. Spitaleri,[2] I. Siváček,[1,7] and A. Tumino[2,8]

TABLE IV. The ^{26}Si(p, γ)^{27}P reaction rate (in $\frac{cm^3}{mol \times sec}$) for the ground-state direct capture and the first excited state resonant contribution, extracted using Eqs. (12)–(14). The present data are compared with the ones coming from [26], derived in the same way but using the different Γ_γ, Γ_p, and $S(0)$.

	Reaction rate ground state (this work)				Reaction rate first excited state (this work)			
T_9	Lower Limit	Value	Upper Limit	Ref. [26]	Lower Limit	Value	Upper Limit	Ref. [26]
0.1	8.48×10^{-14}	9.57×10^{-14}	1.25×10^{-13}	6.68×10^{-14}	2.09×10^{-12}	2.91×10^{-12}	3.84×10^{-12}	1.41×10^{-12}
0.2	2.71×10^{-09}	3.06×10^{-09}	4.01×10^{-09}	2.13×10^{-09}	7.63×10^{-05}	1.06×10^{-04}	1.40×10^{-04}	5.15×10^{-05}
0.3	4.02×10^{-07}	4.53×10^{-07}	5.94×10^{-07}	3.17×10^{-07}	1.94×10^{-02}	2.71×10^{-02}	3.58×10^{-02}	1.32×10^{-02}
0.4	9.28×10^{-06}	1.05×10^{-05}	1.37×10^{-05}	7.31×10^{-06}	2.74×10^{-01}	3.81×10^{-01}	5.03×10^{-01}	1.85×10^{-01}
0.5	8.57×10^{-05}	9.66×10^{-05}	1.27×10^{-04}	6.75×10^{-05}	1.24	1.72	2.28	8.38×10^{-01}
0.6	4.64×10^{-04}	5.24×10^{-04}	6.86×10^{-04}	3.66×10^{-04}	3.23	4.49	5.93	2.18
0.7	1.78×10^{-03}	2.01×10^{-03}	2.63×10^{-03}	1.40×10^{-04}	6.17	8.58	$1.13 \times 10^{+01}$	4.17
0.8	5.39×10^{-03}	6.08×10^{-03}	7.96×10^{-03}	4.25×10^{-03}	9.76	$1.36 \times 10^{+01}$	$1.79 \times 10^{+01}$	6.60
0.9	1.37×10^{-02}	1.54×10^{-02}	2.02×10^{-02}	1.08×10^{-02}	$1.37 \times 10^{+01}$	$1.90 \times 10^{+01}$	$2.51 \times 10^{+01}$	9.23
1.0	3.05×10^{-02}	3.44×10^{-02}	4.51×10^{-02}	2.40×10^{-02}	$1.76 \times 10^{+01}$	$2.44 \times 10^{+01}$	$3.23 \times 10^{+01}$	$1.19 \times 10^{+01}$
1.2	1.14×10^{-01}	1.28×10^{-01}	1.68×10^{-02}	8.97×10^{-02}	$2.47 \times 10^{+01}$	$3.44 \times 10^{+01}$	$4.54 \times 10^{+01}$	$1.67 \times 10^{+01}$
1.4	3.24×10^{-01}	3.66×10^{-01}	4.79×10^{-01}	2.56×10^{-01}	$3.04 \times 10^{+01}$	$4.23 \times 10^{+01}$	$5.59 \times 10^{+01}$	$2.06 \times 10^{+01}$
1.6	7.67×10^{-01}	8.65×10^{-01}	1.13	6.04×10^{-01}	$3.47 \times 10^{+01}$	$4.82 \times 10^{+01}$	$6.36 \times 10^{+01}$	$2.34 \times 10^{+01}$
1.8	1.58	1.78	2.34	1.25	$3.75 \times 10^{+01}$	$5.22 \times 10^{+01}$	$6.89 \times 10^{+01}$	$2.53 \times 10^{+01}$
2.0	2.95	3.32	4.36	2.32	$3.93 \times 10^{+01}$	$5.47 \times 10^{+01}$	$7.22 \times 10^{+01}$	$2.66 \times 10^{+01}$

REACTION RATE CALCULATED AT GAMOW ENERGIES!!!



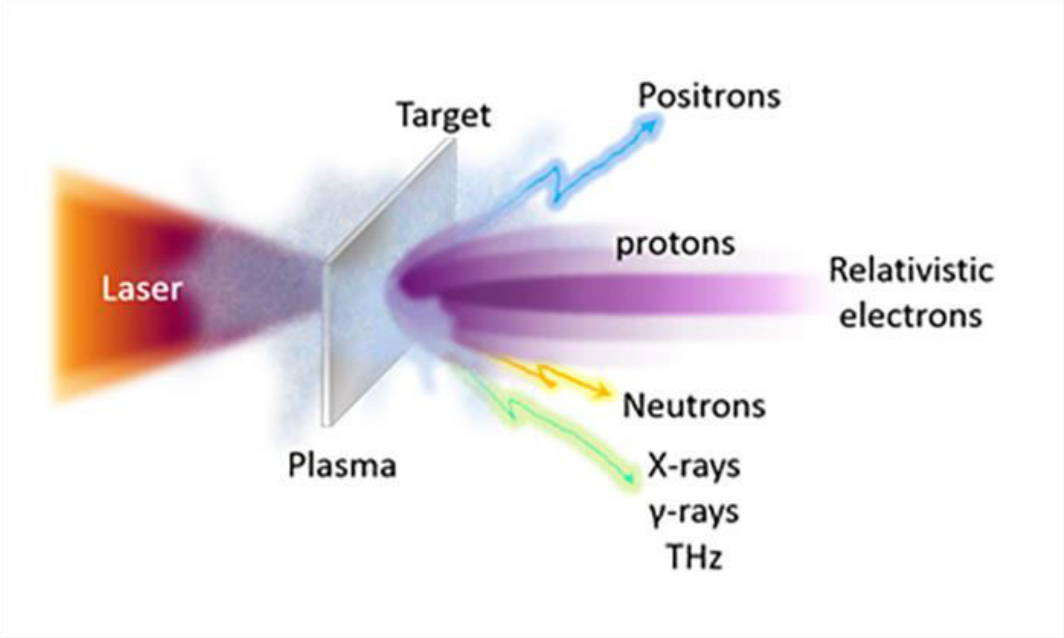
Laser-induced Experiments

An effective approach to improve our knowledge on fusion reactions in stars can be to mimic the stellar conditions by generating a controlled laboratory plasma with thermodynamical status not too different from the stellar conditions.

Laser-induced Experiments

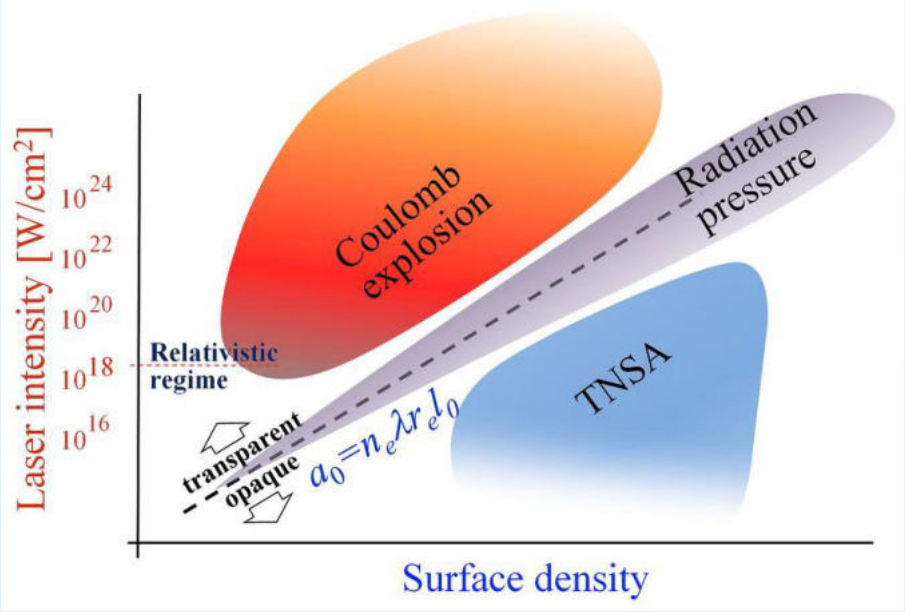
An effective approach to improve our knowledge on fusion reactions in stars can be to mimic the stellar conditions by generating a controlled laboratory plasma with thermodynamical status not too different from the stellar conditions.

The advent of novel techniques in laser amplification on one hand opened the way to the the implementation of high-power high-intensity lasers in many facilities around the world and on the other it forced a steep development on the diagnostics side, de facto unlocking the feasibility of **new paradigms of research**.



Nuclear Astrophysics with Laser Beams

The most common scenario on laser-ion acceleration relies on focusing a high intensity laser pulse into a target made of the species of interest. Depending on the intensity and on the surface density of the target, different acceleration mechanisms are involved. The most studied scenario today relies on the Target Normal Sheath Acceleration mechanism originated by high-intensity laser pulses focused on thin targets.



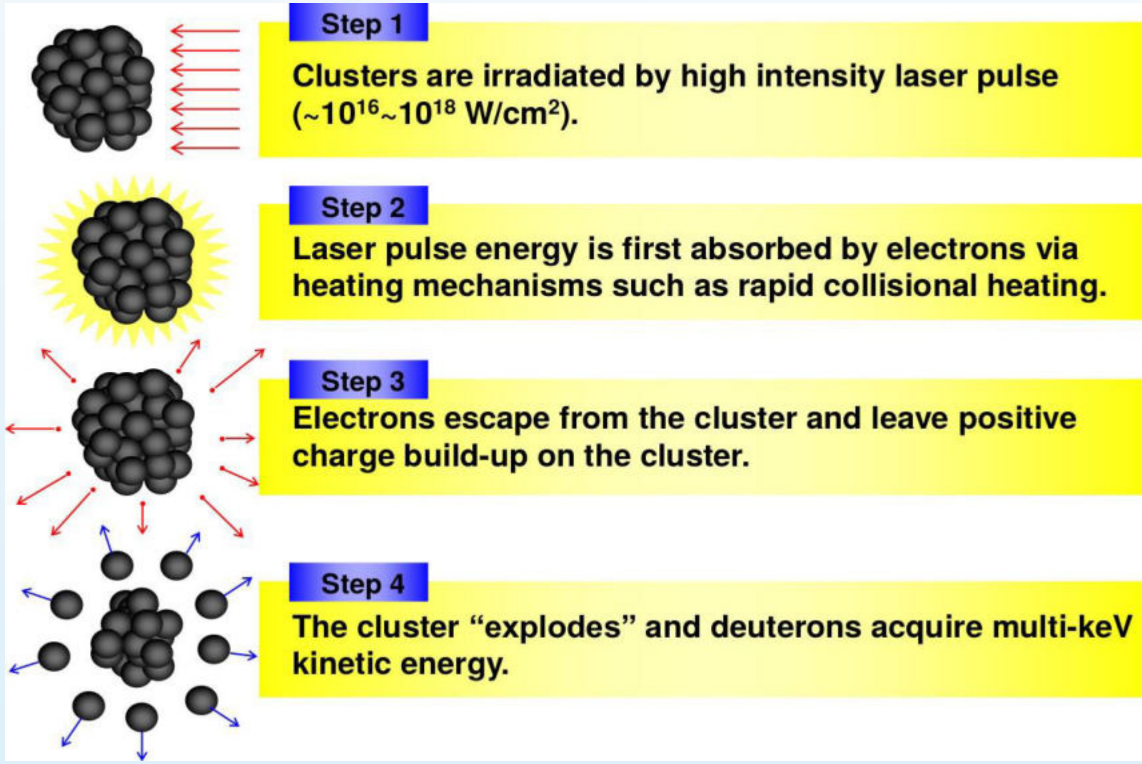
These methods will open the way for a new approach to study Nuclear Astrophysics Reaction such as:

- deuterium- deuterium
- deuterium-^{3}He
- proton-lithium
- proton-boron
- ^{12}C-^{12}C
- ^{16}O-^{16}O
- and much more….

Coulomb Explosion

THE COULOMB EXPLOSION PARADIGMA

The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of plasmas with multi-keV temperature. These energies overlap with the typical temperatures of stellar environments where thermonuclear reactions occur, thus making this paradigm a ***perfect scenario for nuclear astrophysics research***.

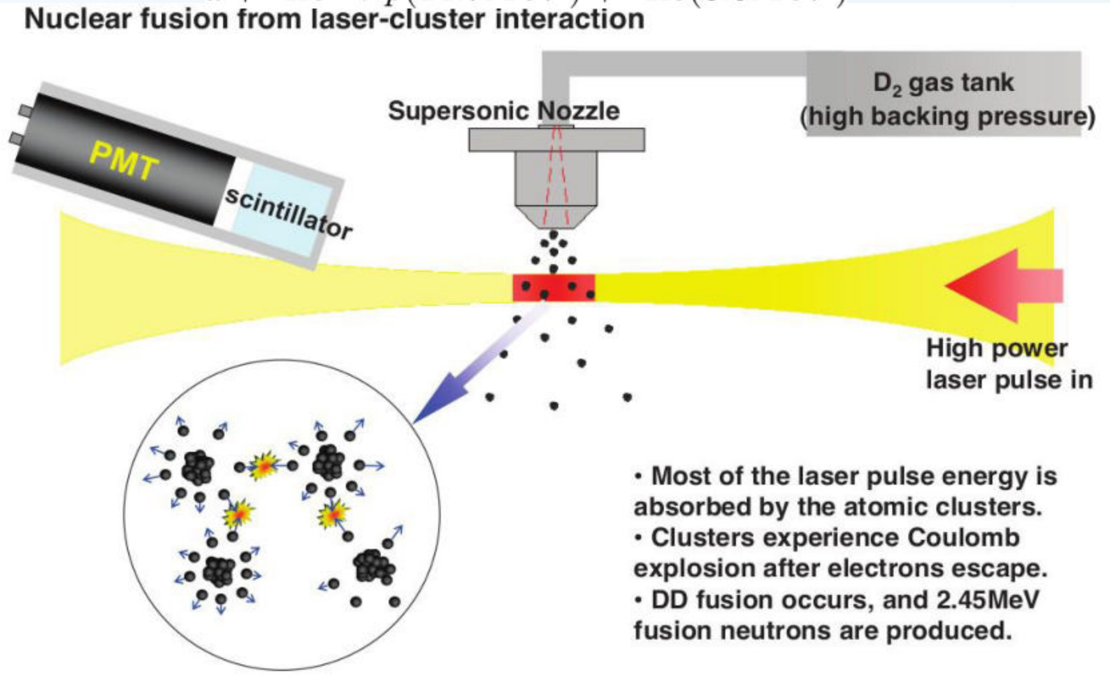


Example: deuterium-deuterium fusion

$$d + d \rightarrow {}^3\mathrm{He}(0.82MeV) + n(2.45MeV)$$

$$d + d \rightarrow p(3.02MeV) + t(1.01MeV)$$

$$d + {}^3\mathrm{He} \rightarrow p(14.7MeV) + {}^4\mathrm{He}(3.6MeV)$$

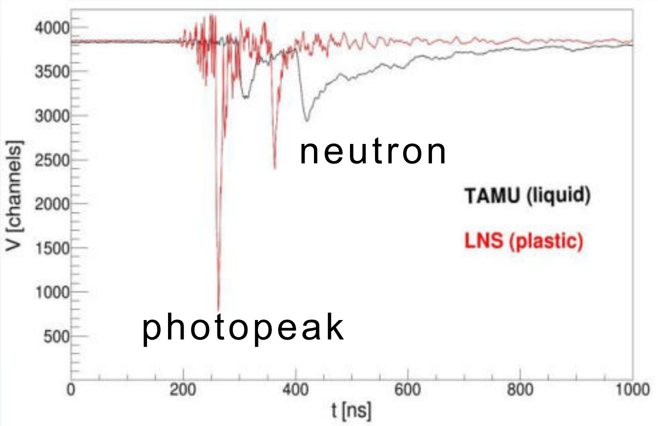


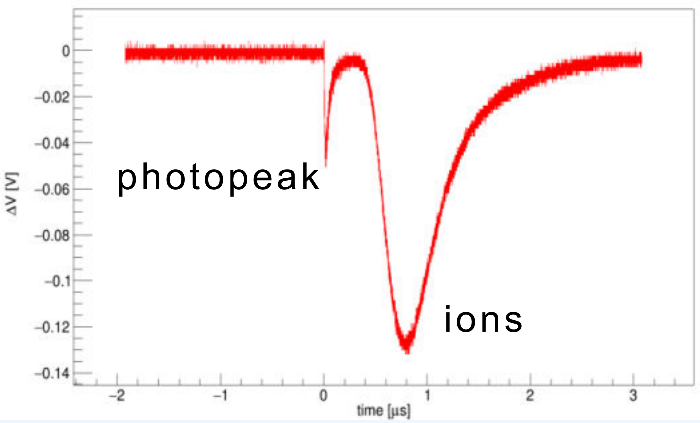
Kinetic Energy < 10^2 keV

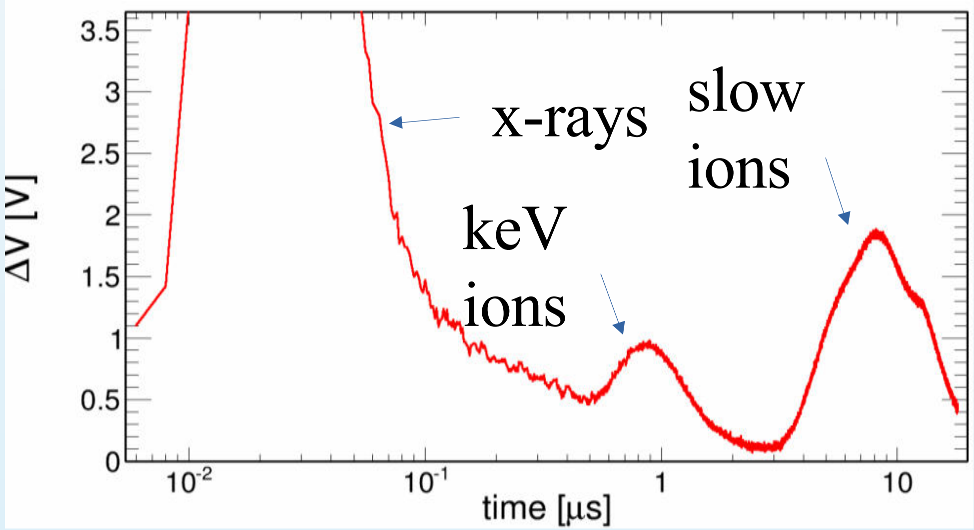
Density ~ 10^{18} atoms/cm^3

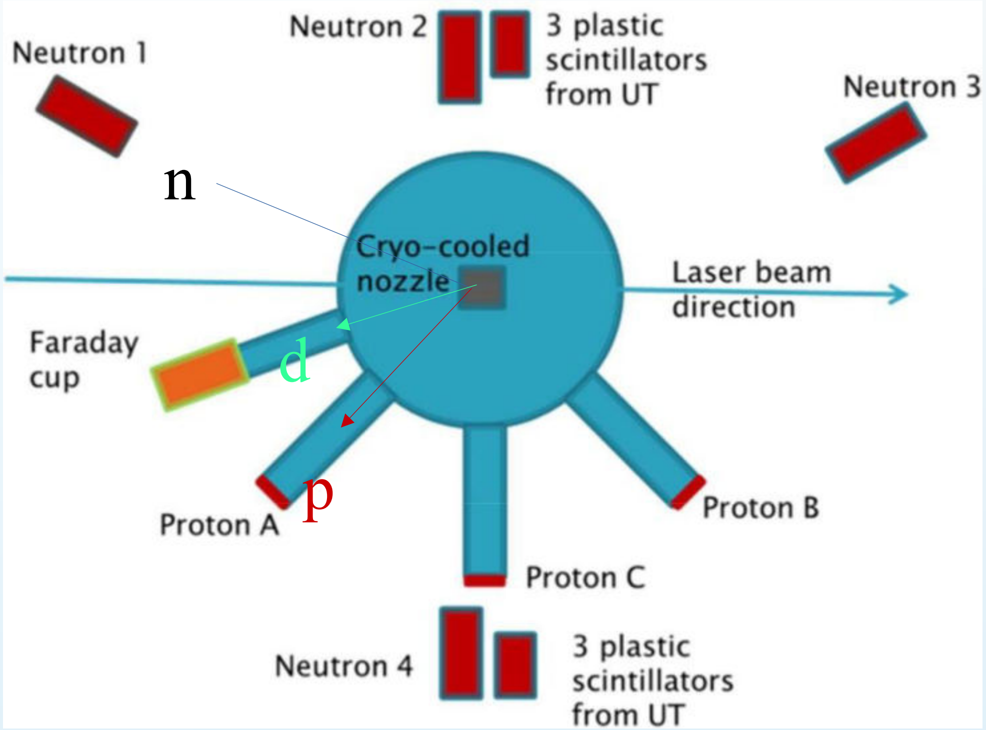
10^5-10^7neutrons per shot

Experimental approach









CE Results

PHYSICAL REVIEW C

covering nuclear physics

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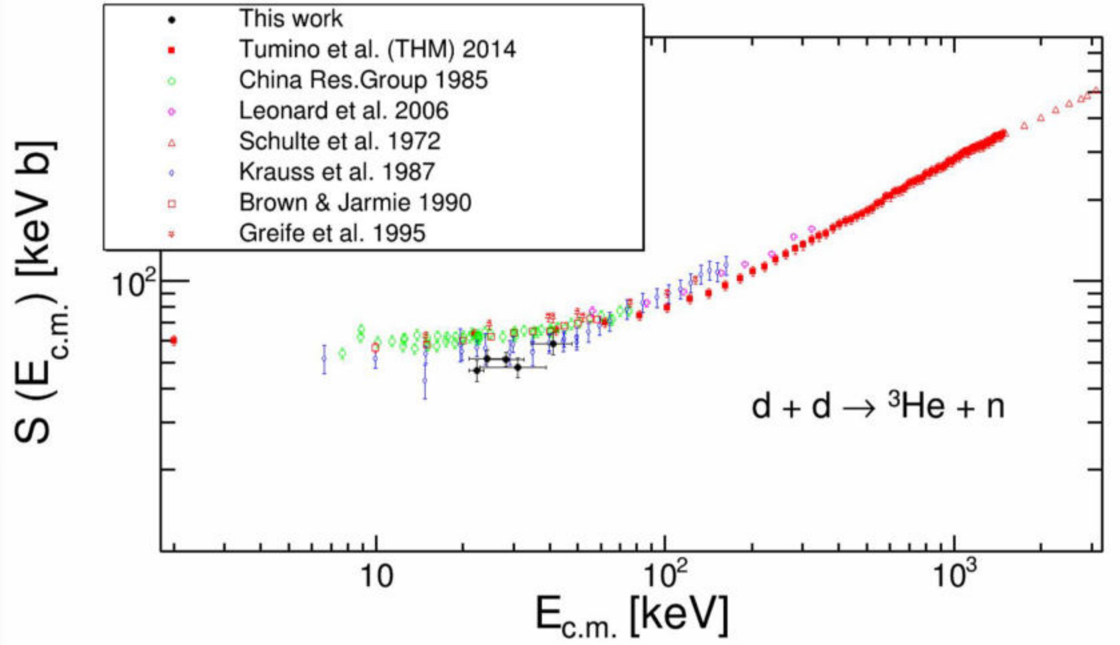
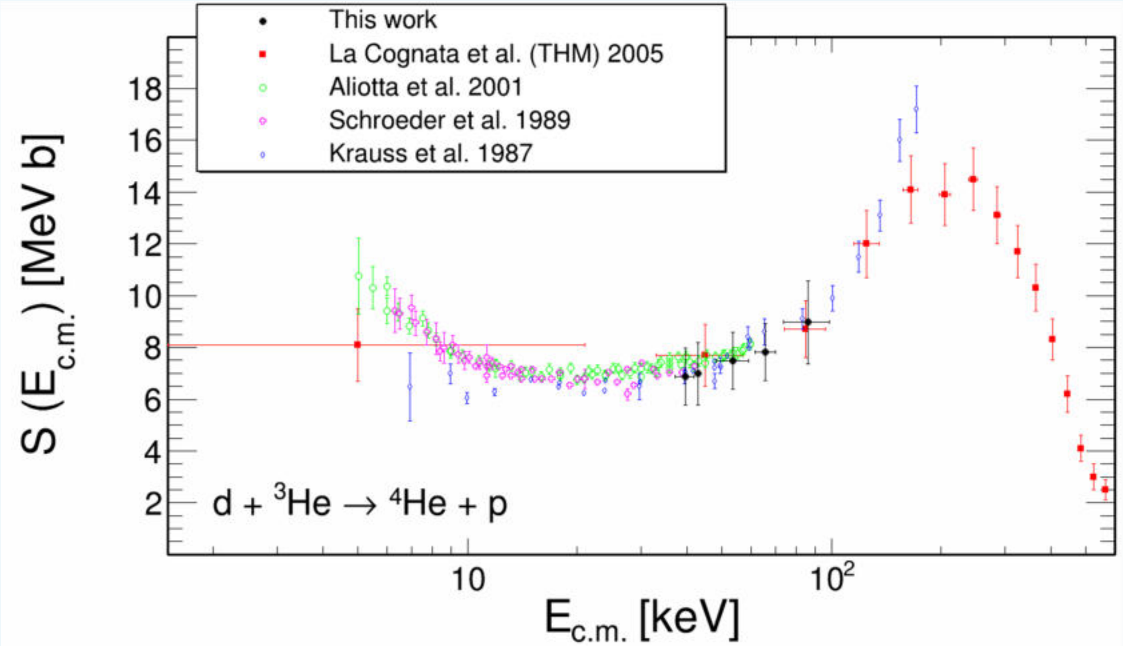
Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

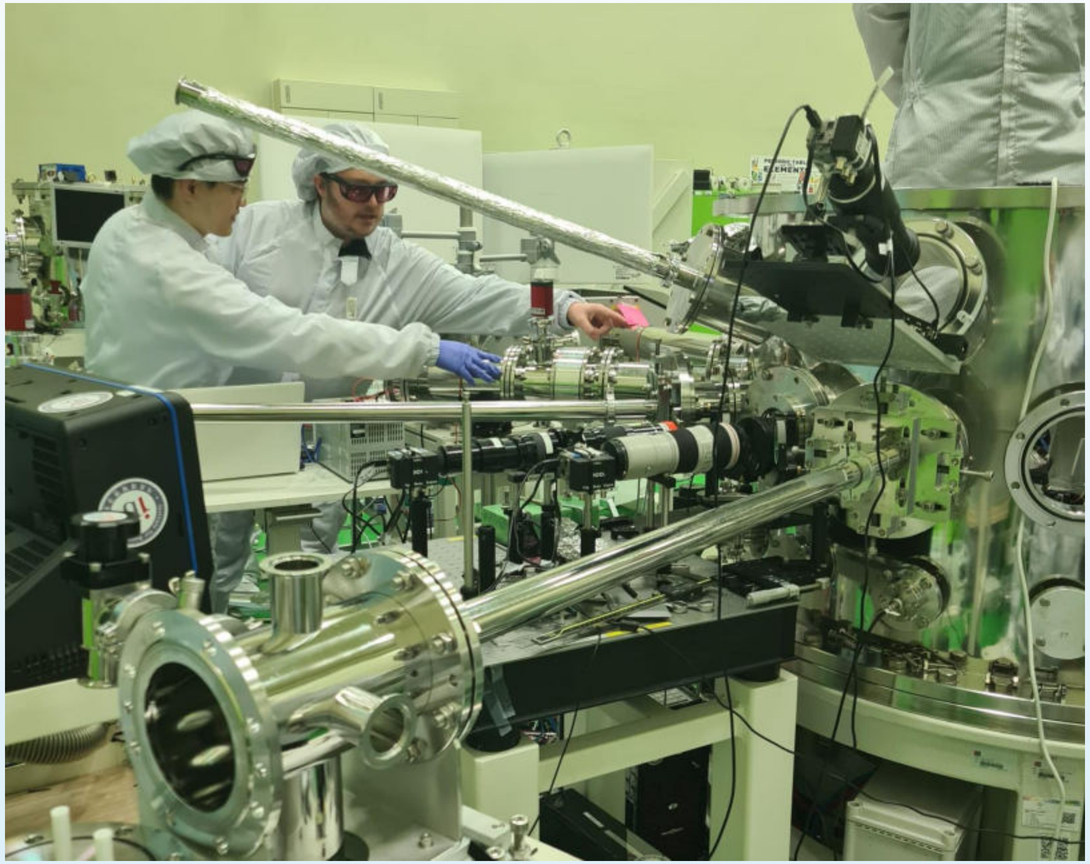
Phys. Rev. C **93**, 045808 – Published 19 April 2016

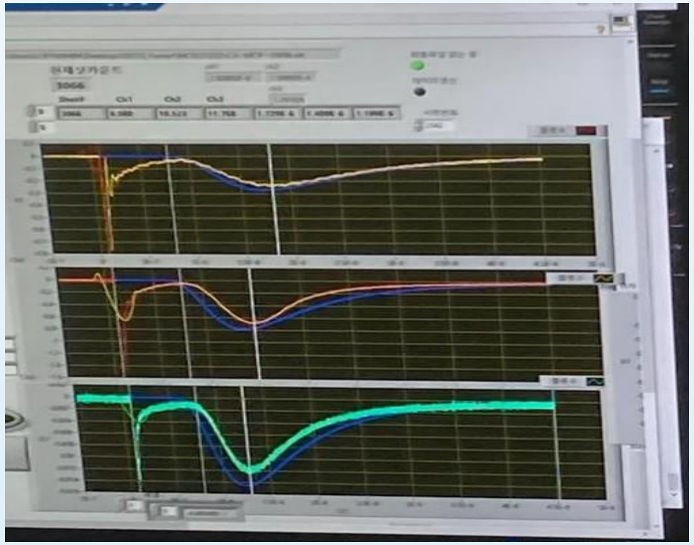




GIST Experiment

Over 3000 shots, with T control between kT~ 1 keV and kT~ 40 keV

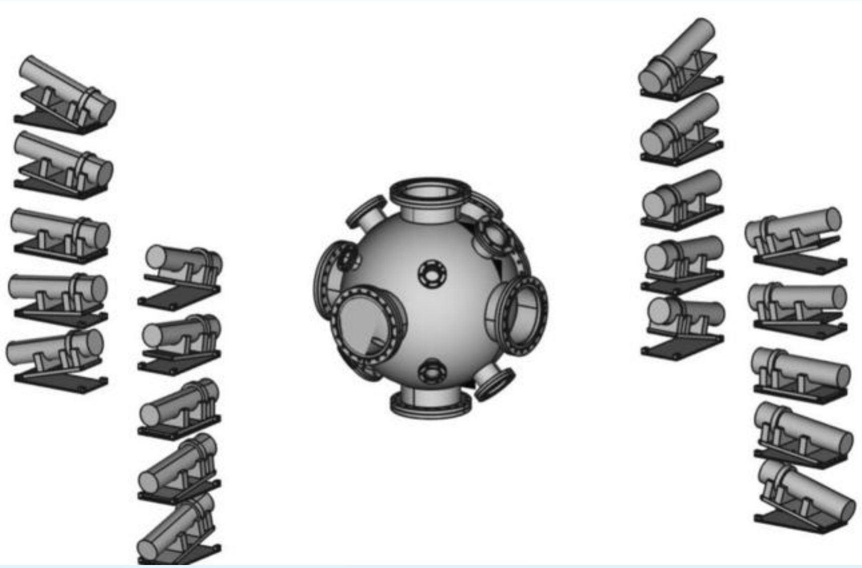




Versatile Array for Laser-induced Astrophysics Research

Science-driven, portable, cost-efficient

- cryo-cooled supersonic nozzle
- compact interaction chamber
- neutron ToF detectors (plastic/liquid scintillators)
- charged particle ToF detectors (SiC/CVD diamond detectors + FCs)
- 2 TPS
- (CR39 for checks/normalization)



The AsFiN Collaboration

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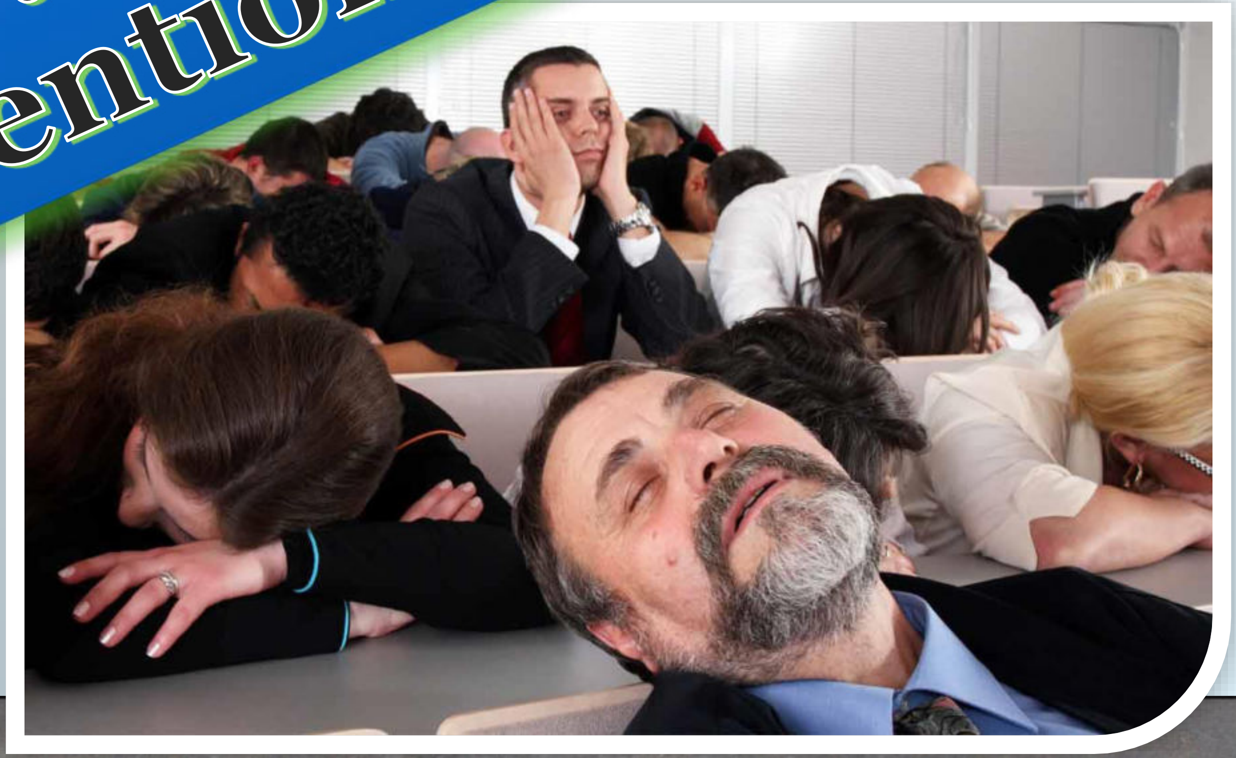


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