2018 European Nuclear Physics Conference

September 2nd-7th, 2018: Bologna, Italy
San Domenico Center

Uncovering carbon burning in stars

Aurora Tumino

Outline

Nuclear astrophysics and low-energy experiments
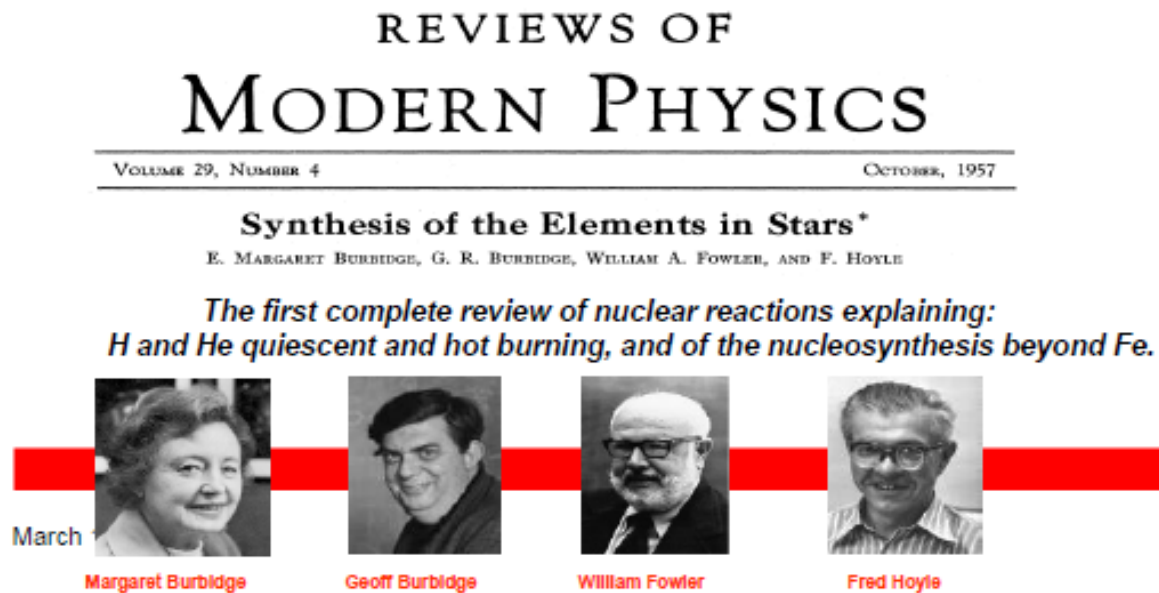
C-burning: astrophysical motivations and state-of-the-art measurements

The THM $^{12}C(^{12}C,a)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ experiment

Results and conclusions

... 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

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4   OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

The first complete review of nuclear reactions explaining:
H and He quiescent and hot burning, and of the nucleosynthesis beyond Fe.

March

**Margaret Burbidge**   **Geoff Burbidge**   **William Fowler**   **Fred Hoyle**

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

Nuclear reactions responsible for both ENERGY PRODUCTION and NUCLEOSYNTHESIS

Nuclear Astrophysics

Nuclear Astrophysics to measure relevant two body cross sections at astrophysical energies

Astrophysical energies are determined by the Gamow peak: the most effective energy region for thermonuclear reactions
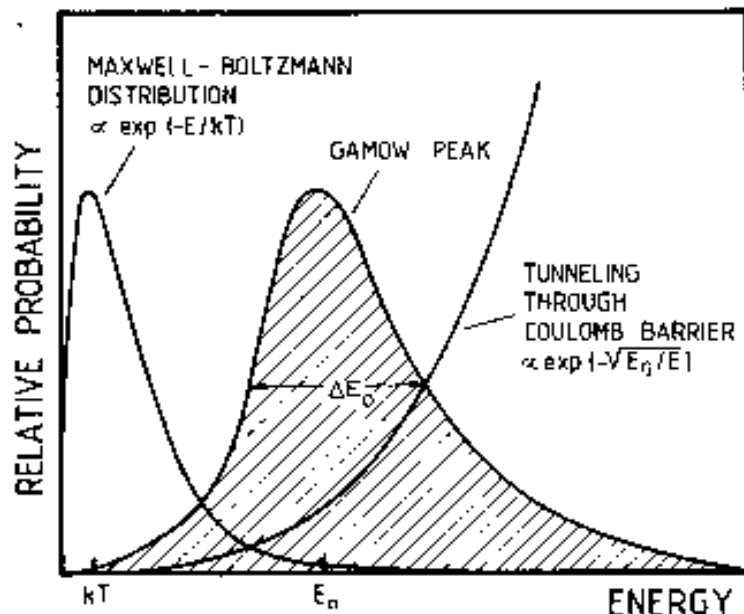
The Gamow energy $E_0 = f(Z_1, Z_2, T)$ varies depending on the reaction and/or the temperature, usually from tens to hundreds of keV, but also MeV.

- Cross section ~ picobarn due to the Coulomb barrier between the interacting nuclei

$\Rightarrow$ Low signal-to-noise ratio

$\Rightarrow$ access to low energy usually via extrapolation from higher energies using the
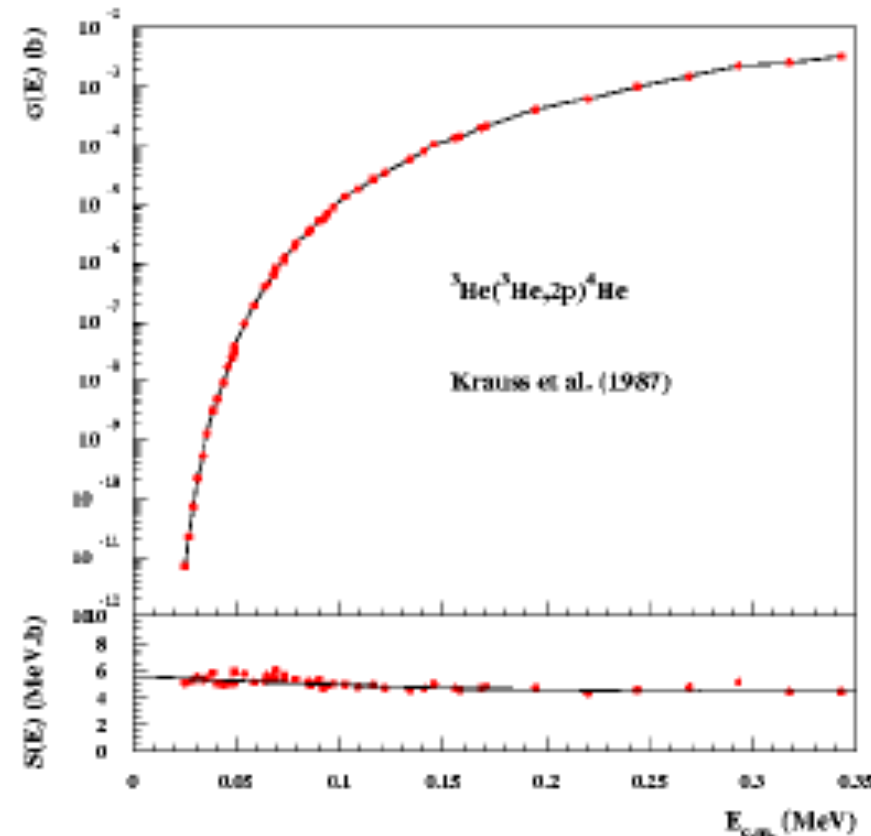
ASTROPHYSICAL FACTOR

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

S(E) is a smoothly varying function of the energy than the cross section $\sigma(E)$

...but large uncertainties in the extrapolation

- Electron screening that enhances the behaviour of the bare S(E)

$^3He(^3He,2p)^4He$

Krauss et al. (1987)

$\rightarrow$ Direct measurement straightforward but challenging at low energy and altered by electron screening

12C+12C fusion

Great interest in a wide range of stellar burning scenarios in carbon-rich environments such as **late evolutionary stages of stars with more than 8 $M_{\odot}$**
superbursts from accreting neutron stars
ignition conditions of Sne Ia

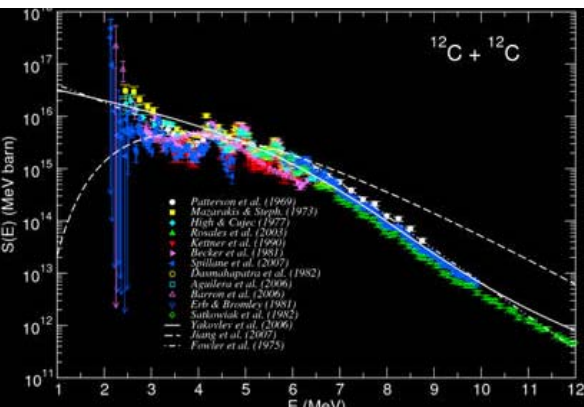Carbon burning temperature from 0.4 to 1.2 GK $\rightarrow$ E_{cm} from 1 to 2 MeV

Principal reactions:

$^{12}C(^{12}C,\alpha)^{20}Ne$	+ 4.617 MeV	
$^{12}C(^{12}C,p)^{23}Na$	+ 2.241 MeV	The most frequent results of the interaction
$^{12}C(^{12}C,n)^{23}Mg$	- 2.599 MeV	
$^{12}C(^{12}C,\gamma)^{24}Mg$	+13.933 MeV	
$^{12}C(^{12}C,2\alpha)^{20}Ne$	-0.113 MeV	

Considerable efforts to measure the $^{12}C+^{12}C$ cross section at astrophysical energies

M.G. Mazarakis & W.E. Stephensen, Phys. Rev. C 7 1280 (1973)
. Kettner et al., Phys. Rev. L   77)
H.W. Becker et al., Z. Phys.   981)
L. Barron-Palos et al., Nucl.   79, 318 (2006)
E.F. Aguleira et al.,Phys. R   3, 064601 (2006)
T. Spillane et al., Phys. R   73, 064601 (2006)
T. Spillane et al., Phys. Rev.   98, 122501 (2007)
Bucher et al., Phys. Rev. L   251102 (2015)
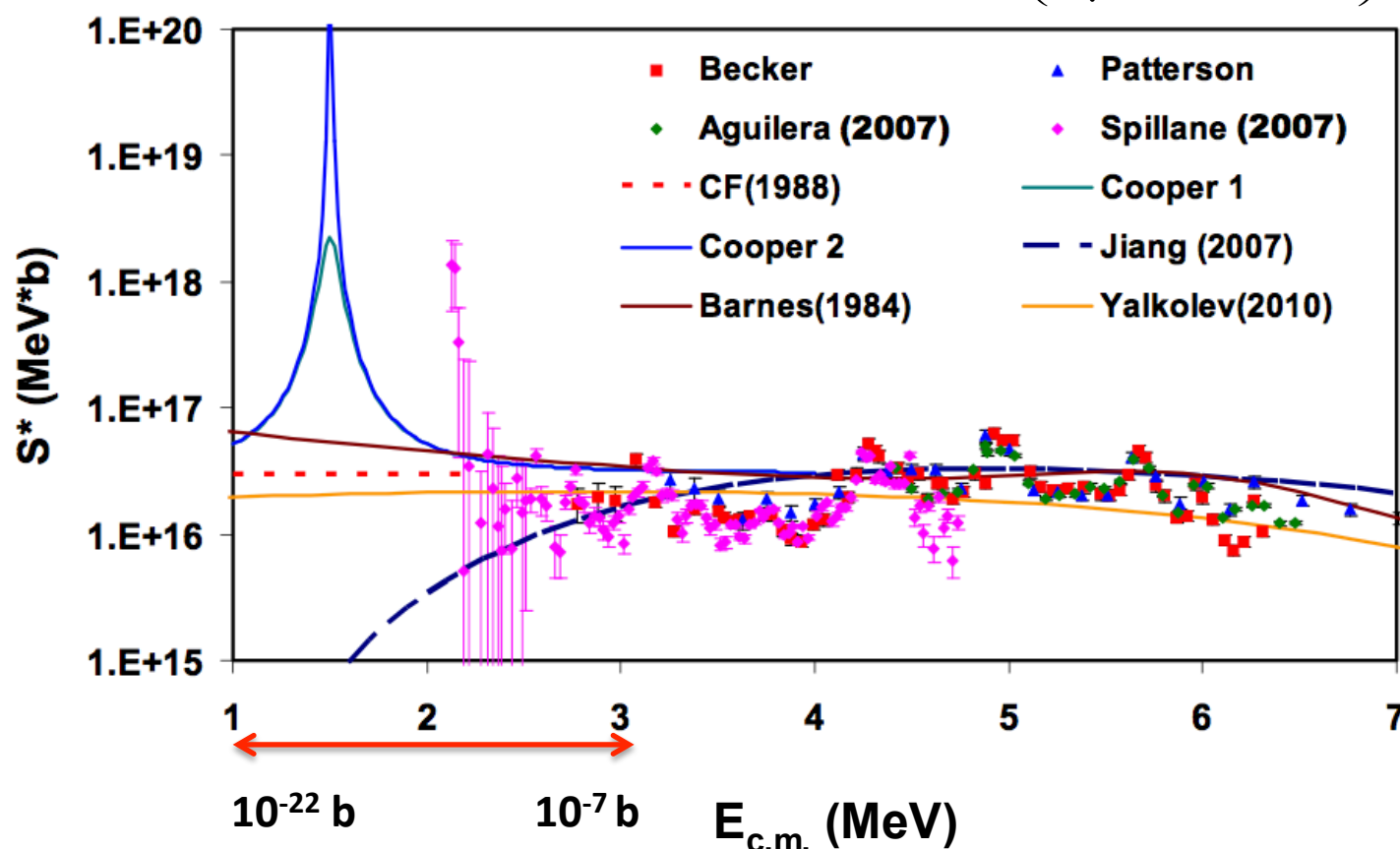C.L. Jiang et al., Phys. R   1 (2018)
… … …

C-burning: State-of-the-art

Resonances at nearly every 300 keV down to E_{cm} = 2.14 MeV. They would increase the present nonresonant reaction rate of the alpha(proton) channel by a factor of 5(2) .

extrapolations differ by
3 orders of magnitude

large uncertainties
in astrophysical models
of stellar evolution
and nucleosynthesis

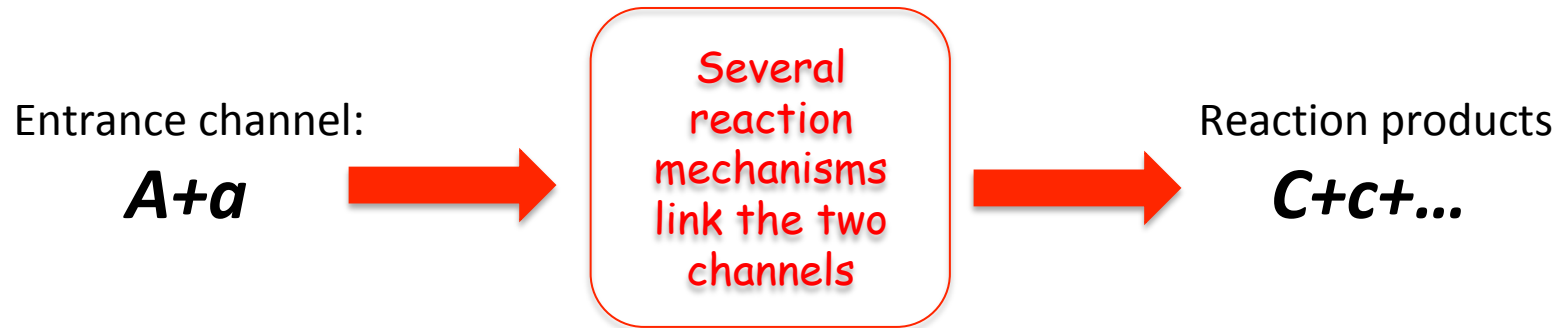$$S^*(E) = \sigma(E)E \exp\left(\frac{87.21}{\sqrt{E}} + 0.46E\right)$$

Legend:
- Becker
- Aguilera (2007)
- CF(1988)
- Cooper 2
- Barnes(1984)
- Patterson
- Spillane (2007)
- Cooper 1
- Jiang (2007)
- Yalkolev(2010)

S* (MeV*b)

1.E+20
1.E+19
1.E+18
1.E+17
1.E+16
1.E+15

$E_{c.m.}$ (MeV)

10^{-22} b 10^{-7} b

No definite conclusion!
→Thus, further measurements extending down to at least 1 MeV would be extremely important.

Indirect Methods for Nuclear Astrophysics

Quite straightforward experiment, no Coulomb suppression, no electron screening but ...

Entrance channel:

$$A+a$$

Several reaction mechanisms link the two channels

Reaction products

$$C+c+...$$

The reaction theory is needed to select only one reaction mechanism. However, nowadays powerful techniques and observables for careful data analysis and theoretical investigation.

In particular the Trojan Horse Method already successfully applied to more than 30 astrophysical relevant reactions

For review see:
R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901
C. Spitaleri et al., EpJ 2016

Our Experiment with theTHM

^{12}C(^{12}C,α)^{20}Ne and ^{12}C(^{12}C,p)^{23}Na reactions via the <u>Trojan Horse Method</u> applied to the ^{12}C(^{14}N,α^{20}Ne)^{2}H and ^{12}C(^{14}N,p^{23}Na)^{2}H three-body processes

^{2}H from the ^{14}N as spectator s

Observation of ^{12}C cluster transfer in the ^{12}C(^{14}N,d)^{24}Mg* reaction   (R.H. Zurmûhle et al. PRC 49(1994) 5)

QUASI-FREE MECHANISM

✓ only ^{12}C - ^{12}C interaction

✓ d = spectator

E_{14N} =30 MeV> E_{Coul}

⟹   NO Coulomb suppression

NO electron screening

Direct breakup

^{14}N   d

^{12}C

^{12}C

^{24}Mg*

a,p

^{20}Ne, ^{23}Na

C. Spitaleri et al., Phys. Rev. C 63, 005801 (2001)
R. Tribble et al. Rep. Prog. Phys. 77 106901 (2014)

$$E_{QF} = E_{14N} \frac{m_{12_C}}{m_{14_N}} \cdot \frac{m_{12_C}}{m_{12_C} + m_{12_C}} - 10.27 \text{ MeV}$$

Theoretical approach to the THM

$$A + a \rightarrow c + C + s \;\rightarrow\; \rightarrow\; \rightarrow \qquad A + x \rightarrow c + C$$
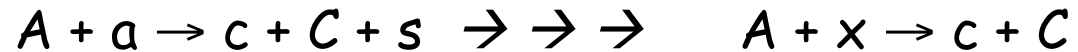
PWIA hypotheses:

- beam energy > $a = x \oplus s$ breakup Q-value
- projectile wavelength $k^{-1} \ll x - s$ intercluster distance

KF kinematical factors

$|\Phi|^2$ momentum distribution of s inside a

➔ the 3-body cross section factorizes:

$$\frac{d^3\sigma}{d\Omega_c \, d\Omega_C \, dE_c} \propto KF \cdot \left|\Phi(p_s)\right|^2 \frac{d\sigma^{off}}{d\Omega}$$

$d\sigma^{off}/d\Omega$ Nuclear cross section for the $A+x \rightarrow C+c$ reaction

A. Tumino et al., PRL 98, 252502 (2007)

$d\sigma^{off}/d\Omega \rightarrow d\sigma/d\Omega$ (on shell)
the penetration factor P_l has to be introduced:

$$\frac{d\sigma}{d\Omega} = \sum_l P_l \frac{d\sigma_l^N}{d\Omega}$$

but <u>No absolute value of the cross section → normalization to direct data available at higher energies</u>

The A + a(x+s) → F*(c + C) + s process is a transfer to the continuum where particle x is the transferred particle
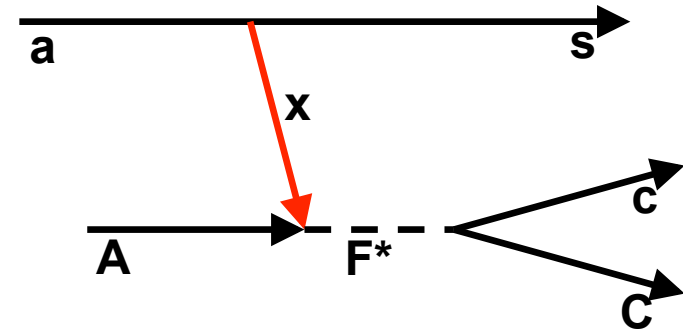
Standard R-Matrix approach cannot be applied to extract the resonance parameters → Modified R-Matrix is introduced instead

In the case of a resonant THM reaction the cross section takes the form

$$\frac{d^2\sigma}{dE_{Cc}\,d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\,|M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) that can be easily calculated → The resonance parameters can be extracted
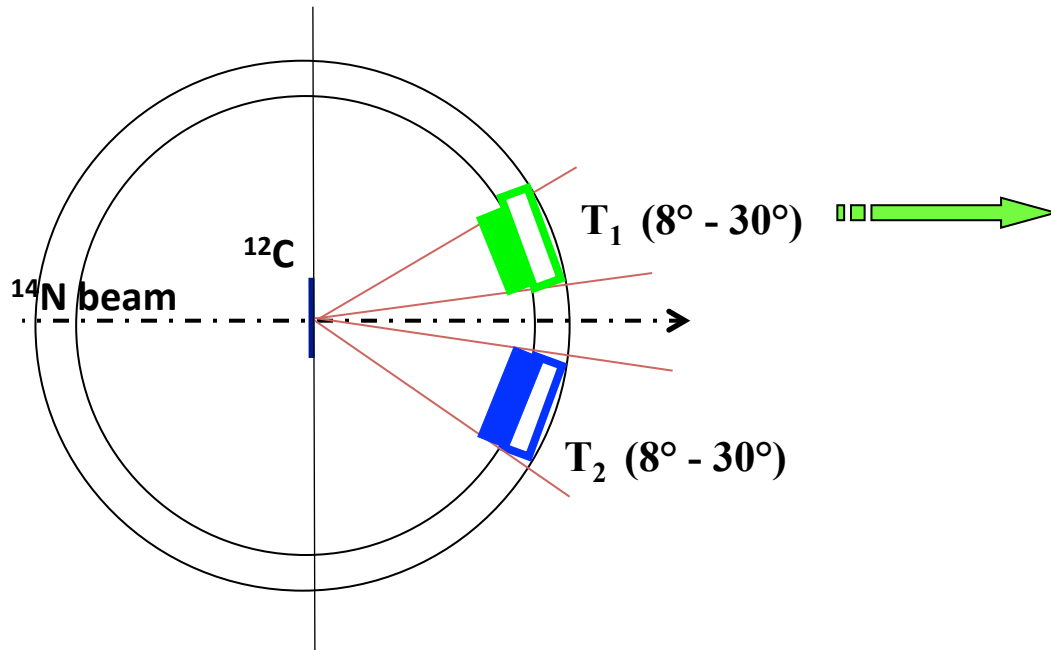
<u>Advantages</u>:
- possibility to measure down to zero energy
- No electron screening
- HOES reduced widths are the same entering the OES S(E) factor (New!)

The 14N+12C experiment at LNS

$E_{14N} = 30$ MeV

Particle identification supplied by silicon telescopes:
38 μm silicon detector as ΔE- and 1000 μm Position
Sensitive Detector (PSD) as E-detector

^{12}C

^{14}N beam

T_1 (8° - 30°)

T_2 (8° - 30°)
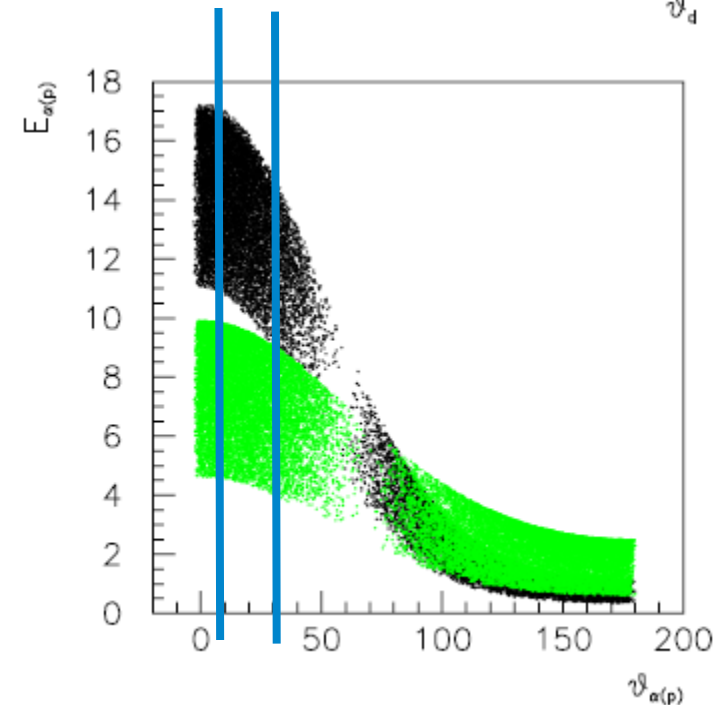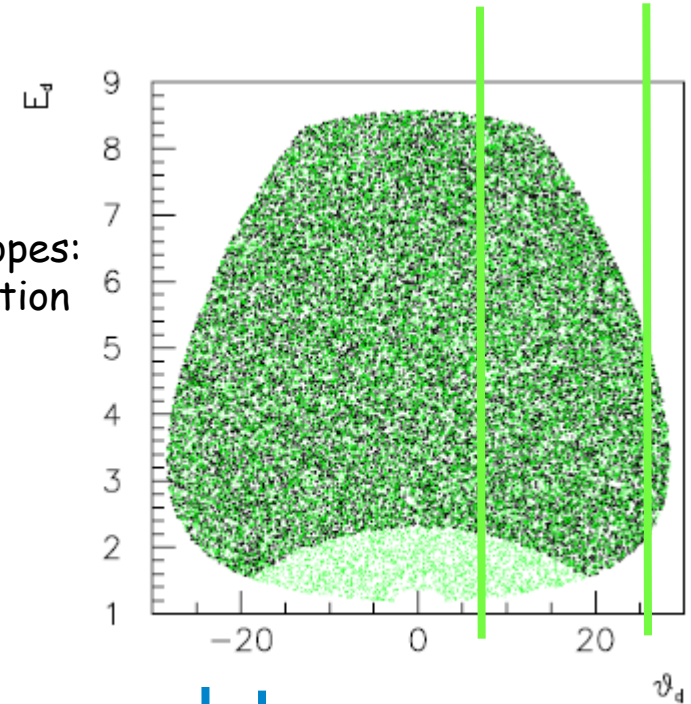
^{20}Ne+α+d and ^{23}Na+p+d reaction channels reconstructed
when detecting the ejectile of the two-body reactions
(either α (black dots) or p (green dots)) in coincidence
with the spectator d particle.
No detection of ^{20}Ne or ^{23}Na quite low energy → too
high detection threshold

Selection of the 3-body channels
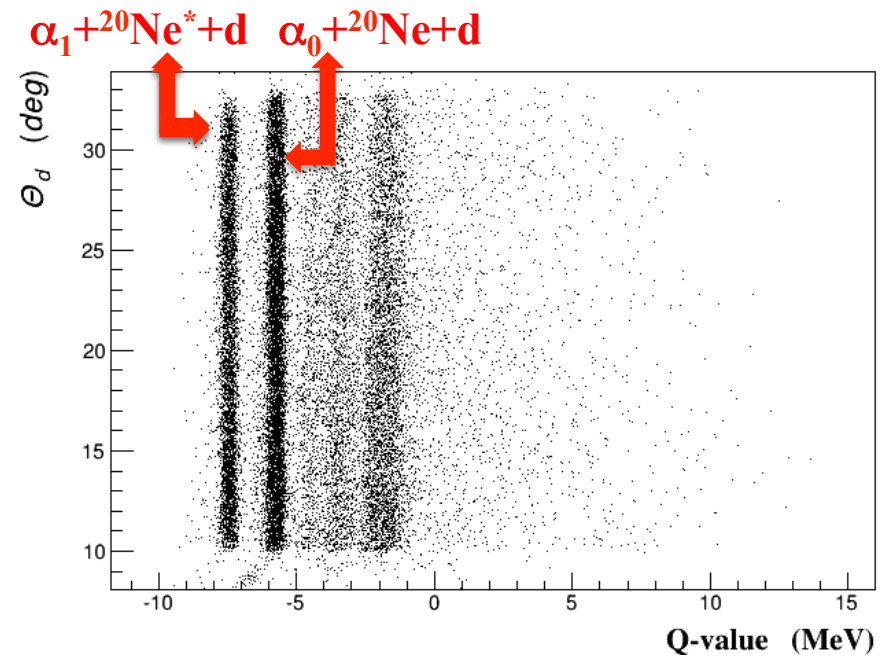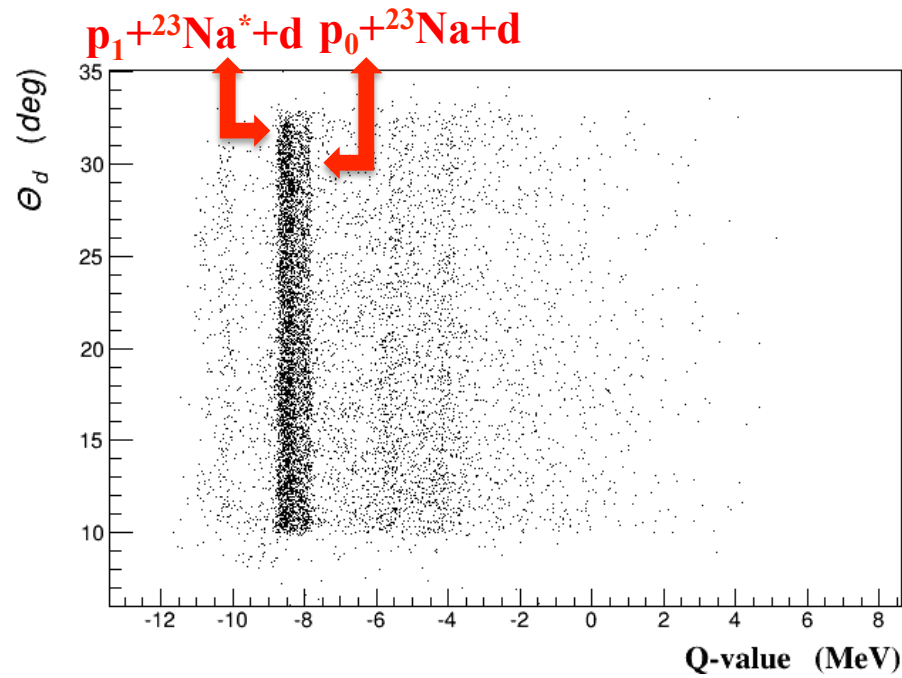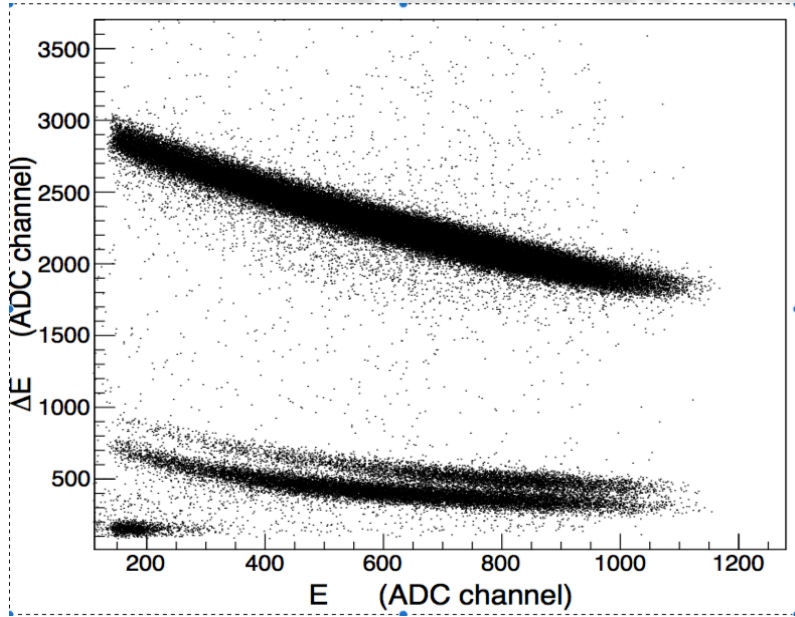
Comparison between the experimental momentum distribution and the theoretical one

$$|\Phi(\vec{p_d})|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_d d\Omega_{p,\alpha} dE_d}}{(KF)\left(\dfrac{d\sigma_{12C12C}}{d\Omega}\right)^N}$$

On-the-energy-shell bound state wave number ((see I.S. Shapiro, Soviet Physics Uspekhi Vol. 10, n. 4 (1968) and earlier works): $(2\mu_{d12C}B_{d12C})^{1/2} = 181$ MeV/c.
Staying within this value is the condition for the QF mechanism to be dominant

Solid line: momentum distribution of d inside ^{14}N from the Wood-Saxon ^{12}C-d bound state potential with standard geometrical parameters
$r_0 = 1.25$ fm, a=0.65 fm and $V_0 = 54.427$ MeV
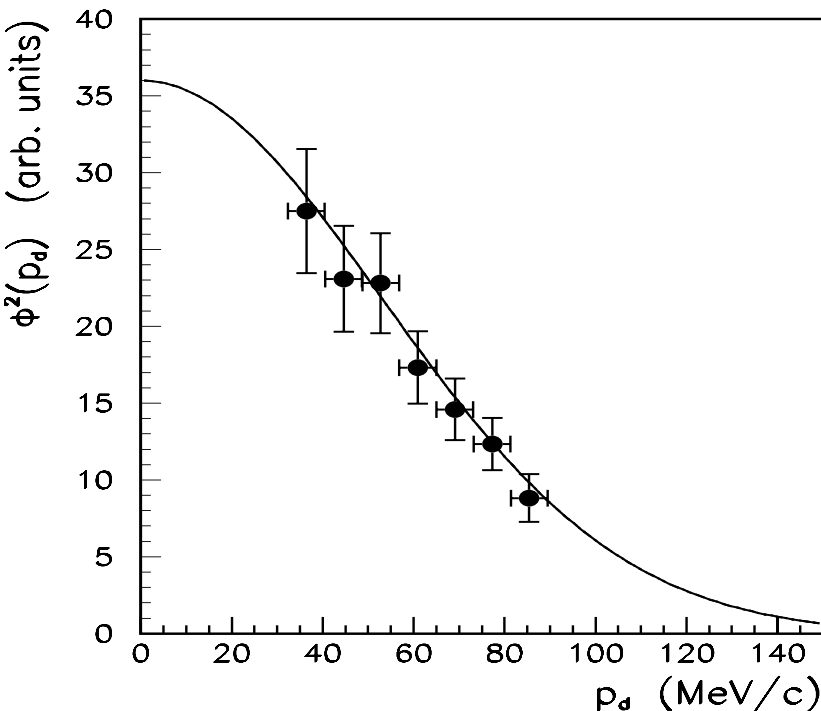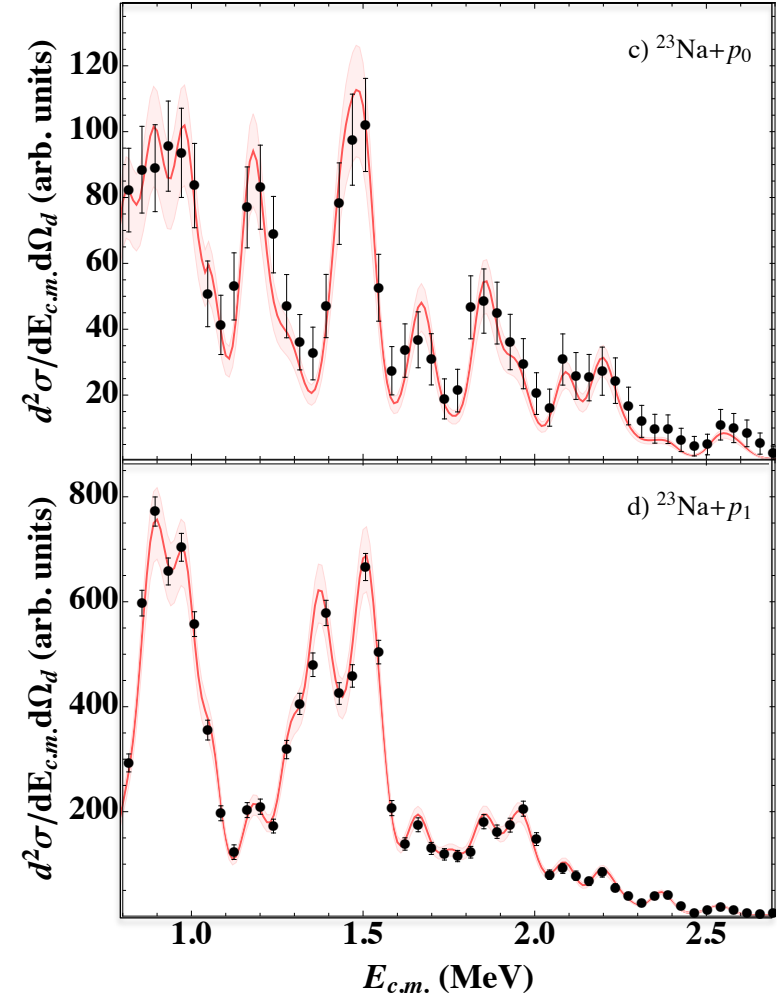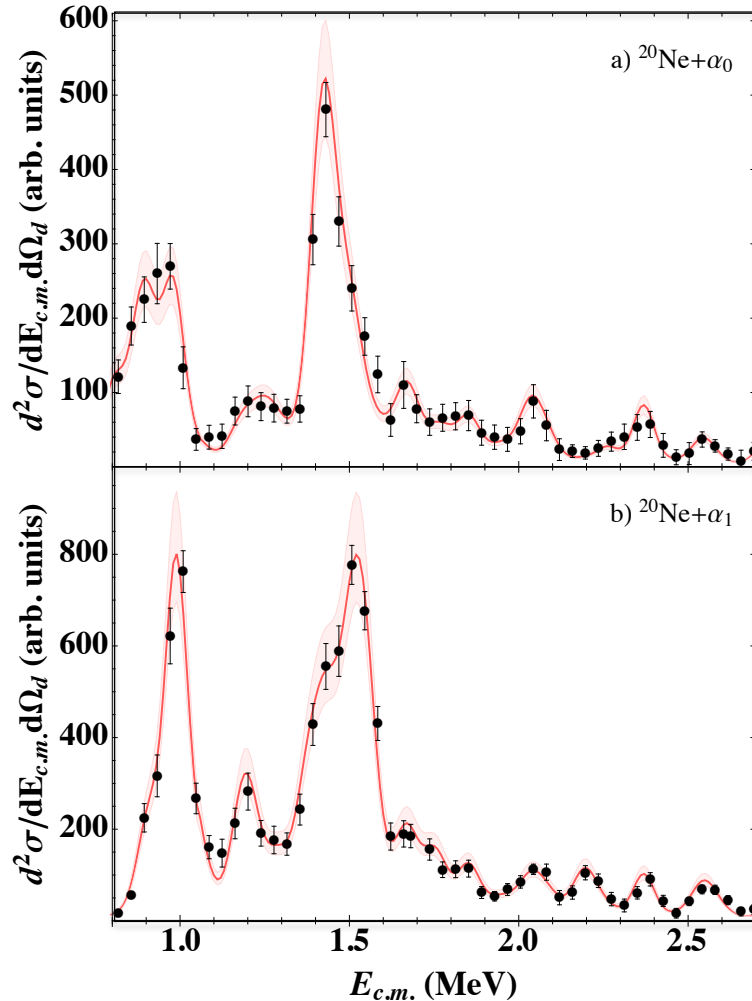

Plane Waves reliable also because:

- $p_d < (2\mu_{d12C}B_{d12C})^{1/2} = 181$ MeV/c $\rightarrow$ Proved that the shape of the momentum distribution is insensitive to the theoretical framework used for its derivation (agreement between PWA and DWBA)

- the ^{14}N beam energy of 30 MeV corresponds to a quite high momentum transfer $q_t = 500$ MeV/c giving an associate de Broglie wavelenght of 0.4 fm (< 3 fm=^{12}C+d)

Extraction of the two-body cross section

$$\frac{d\sigma_3}{dE} = KF\left|\varphi(p_s)\right|^2 \frac{d\sigma}{dE}$$

a) ^{20}Ne+α_0

b) ^{20}Ne+α_1

$d^2\sigma/dE_{c.m.}d\Omega_d$ (arb. units)

$E_{c.m.}$ (MeV)

A. Tumino et al., Nature 557, 687 (2018)

c) ^{23}Na+p_0

d) ^{23}Na+p_1

$d^2\sigma/dE_{c.m.}d\Omega_d$ (arb. units)

$E_{c.m.}$ (MeV)

Red lines and bands: R-matrix fits for all channels at the same time

Reduced widths for known levels are used as free parameters to reproduce their total and partial widths as in Abegg & Davis, PRC 1991 → →
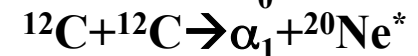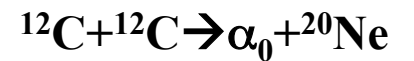
Comparison between two-body cross sections in the astrophysical region

Red lines: R-matrix fits on all channels at the same time in the full energy range of interest →

$$\frac{d^2\sigma}{dE_{xA}d\Omega_s} = NF \sum_i (2J_i + 1) \times \left| \sqrt{\frac{k_f(E_{xA})}{\mu_{cC}}} \frac{\sqrt{2P_{l_i}(k_{cC}R_{cC})}M_i(p_{xA}R_{xA})\gamma_{cC}^i\gamma_{xA}^i}{D_i(E_{xA})} \right|^2$$

$$k_f(E_{xA}) = \sqrt{2\mu_{cC}(E_{xA} + Q)}/\hbar$$

^{12}C+^{12}C→α_0+^{20}Ne
^{12}C+^{12}C→α_1+^{20}Ne*

$D_i(E_{xA})$ = Standard R-matrix denominator of four-channel formulas

^{12}C+^{12}C→p$_0$+^{23}Na
^{12}C+^{12}C→p$_1$+^{23}Na*

34 levels enter the R-matrix fit with energy and spin taken from the literature. Total and α_0-reduced widths are known for almost all levels, while the other widths are taken as free parameters.

IMPORTANT: reduced widths are the same for the extraction of the S(E) factors → From the fitting of the experimental THM cross section they can be obtained and used to deduce the OES S(E) factor.
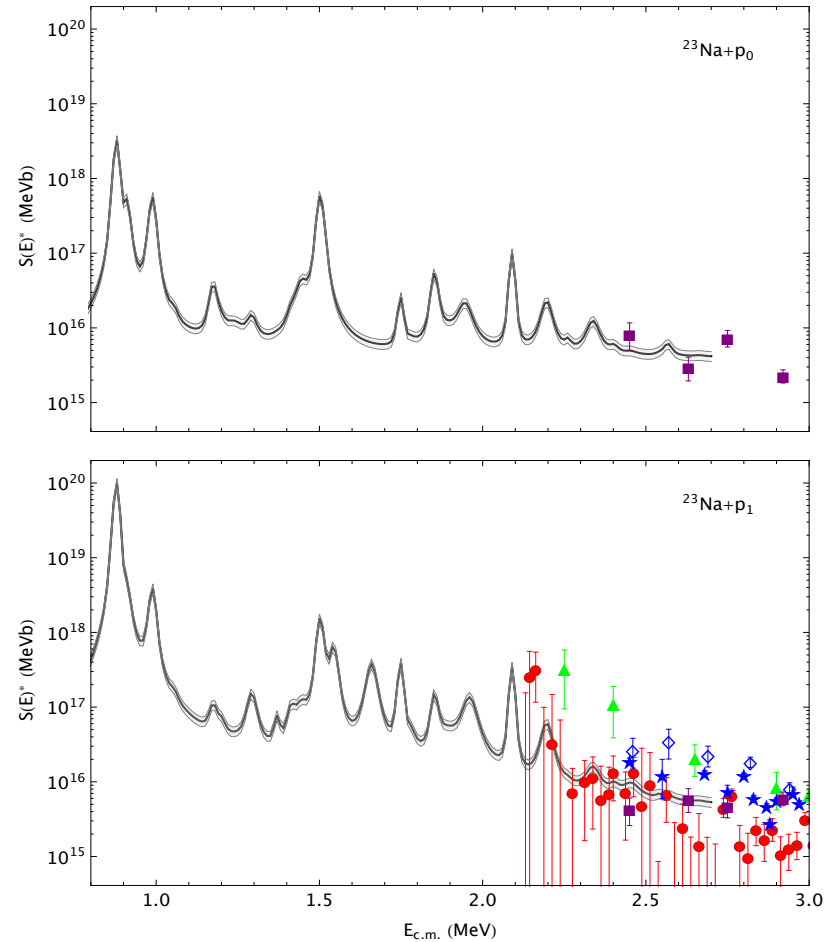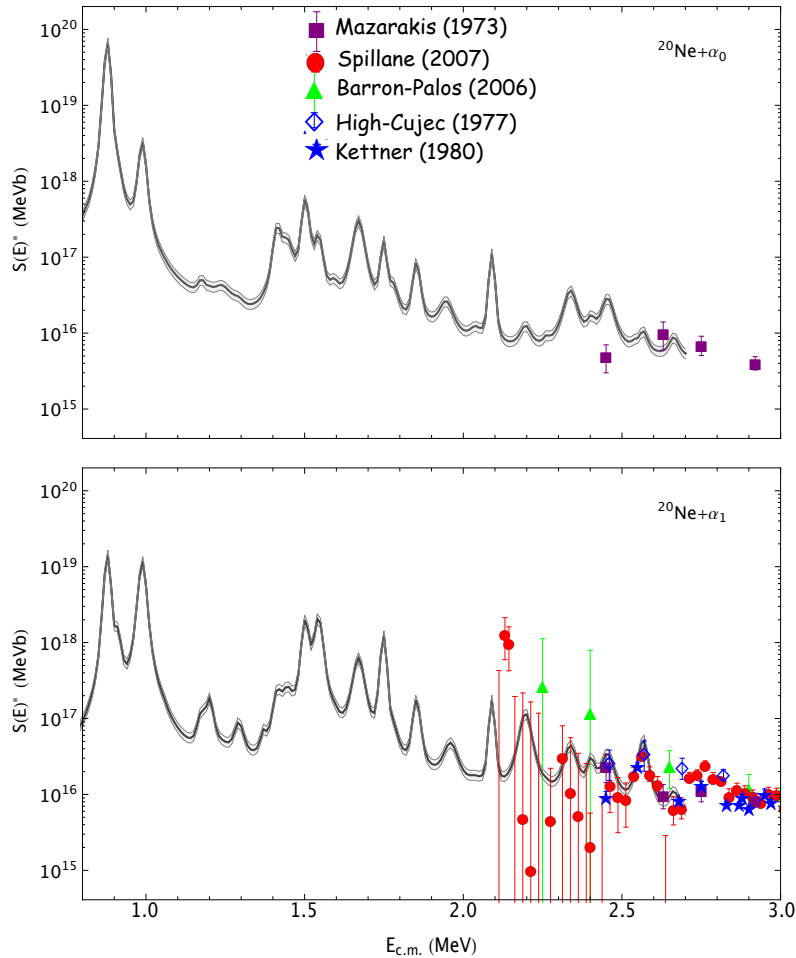
S(E)* factors

$$S(E)^* = E\sigma(E)\exp(87.21E^{-1/2} + 0.46E) \quad (MeVb)$$

Normalization to direct data done in the E_{cm} window 2.50–2.63 MeV of the ^{20}Ne + α_1

A. Tumino et al., Nature 557, 687 (2018)

Legend:
- Mazarakis (1973)
- Spillane (2007)
- Barron-Palos (2006)
- High-Cujec (1977)
- Kettner (1980)

Panels: ^{20}Ne+α_0, ^{23}Na+p$_0$, ^{20}Ne+α_1, ^{23}Na+p$_1$

Agreement between THM and direct data within the experimental errors except around 2.14 MeV, where THM data do not confirm the claim of a strong resonance;
nearby one at 2.095 MeV about one order of magnitude less intense in the ^{20}Ne + α_1 channel and with similar intensity in the ^{23}Na + p_1 one

LETTER

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

A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

12C+12C Reaction Rate
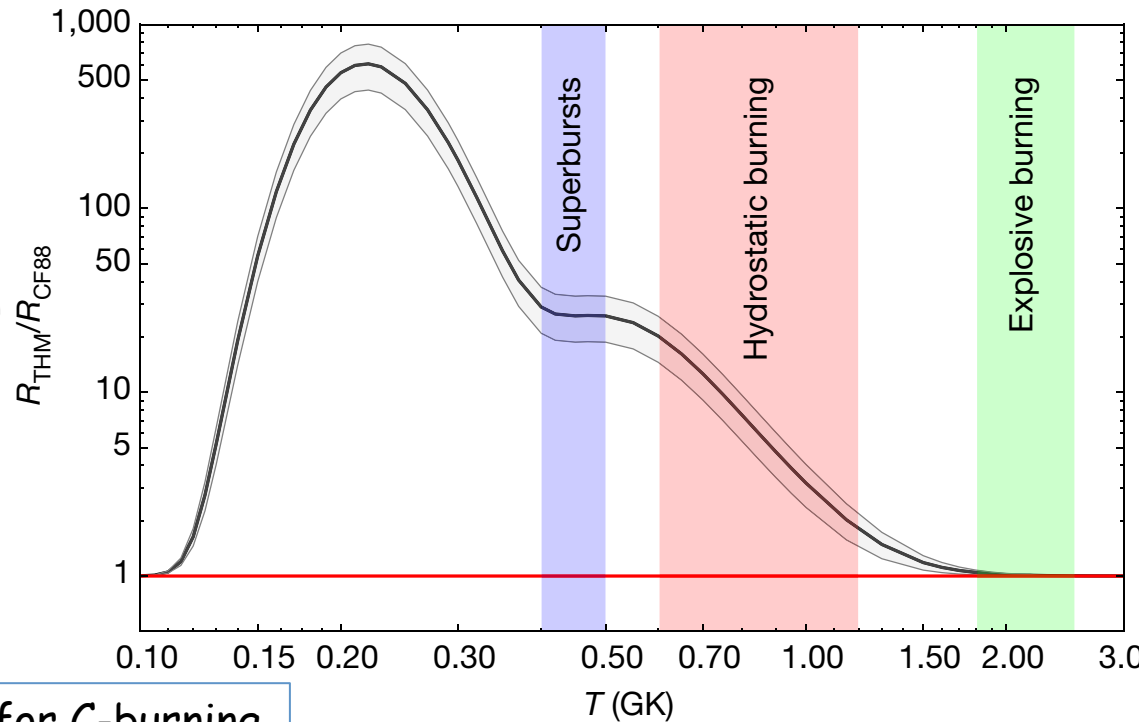
Color shadings mark typical regions for C-burning

Compared to CF88, the present rate increases from a factor of 1.18 at 1.2 GK to a factor of more than 25 at 0.5 GK

Conclusions

<u>First measurement</u> of the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ via the <u>Trojan Horse Method</u> with ^2H from ^{14}N as spectator s

<u>First measurement</u> of the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ at astrophysical energies

Clear evidence of resonant behaviour, also around 1.5 MeV, with a stronger contribution around 900 keV. This behaviour dominates the reaction rate from 0.4 to 1.2 GK.

Need to rerun the astrophysical codes for hydrostatic C-burning
C-burning missing heat source for superbursts?
What about M_up?
Ignition conditions of Sne Ia?

A lot of application to do in the near future ...

THE ASFIN GROUP

C. Spitaleri, S. Cherubini, G. D'Agata, L. Guardo, M.Gulino, I. Indelicato, M. La Cognata, L.Lamia, R.G.Pizzone, S.M.R.Puglia, G.G. Rapisarda, S.Romano, M.L.Sergi, R. Spartà, A.Tumino

I N F N, Laboratori Nazionali del Sud, Università di Catania, Italy, and Università di Enna "Kore", Italy

THANK YOU FOR YOUR ATTENTION!