Nuclear physics in stellar lifestyles with the Trojan Horse Method

Aurora Tumino

Outline

- Need of indirect techniques in Nuclear Astrophysics
- Trojan Horse Method (THM)
- Physics case: carbon burning in massive stars

Charged particle cross section measurements at astrophysical energies

σ ~ picobarn due to the Coulomb barrier between the interacting nuclei

$\Rightarrow$ Low signal-to-noise ratio

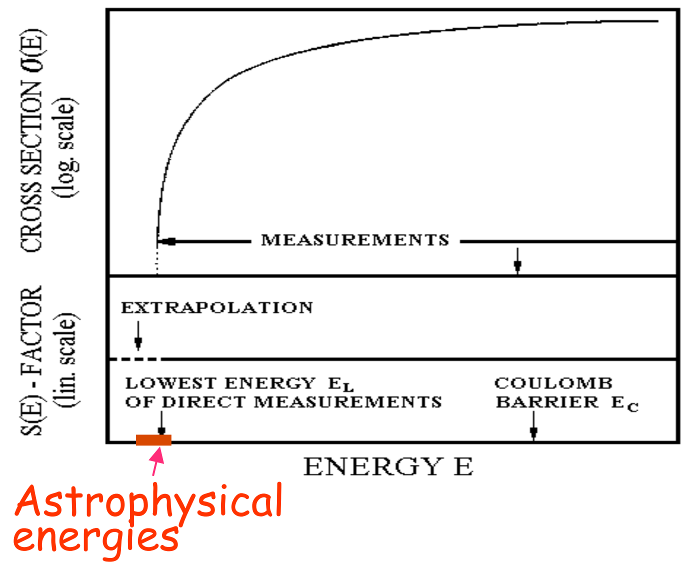
$\Rightarrow$ no access to the low energy region

Extrapolation from the 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 σ(E)



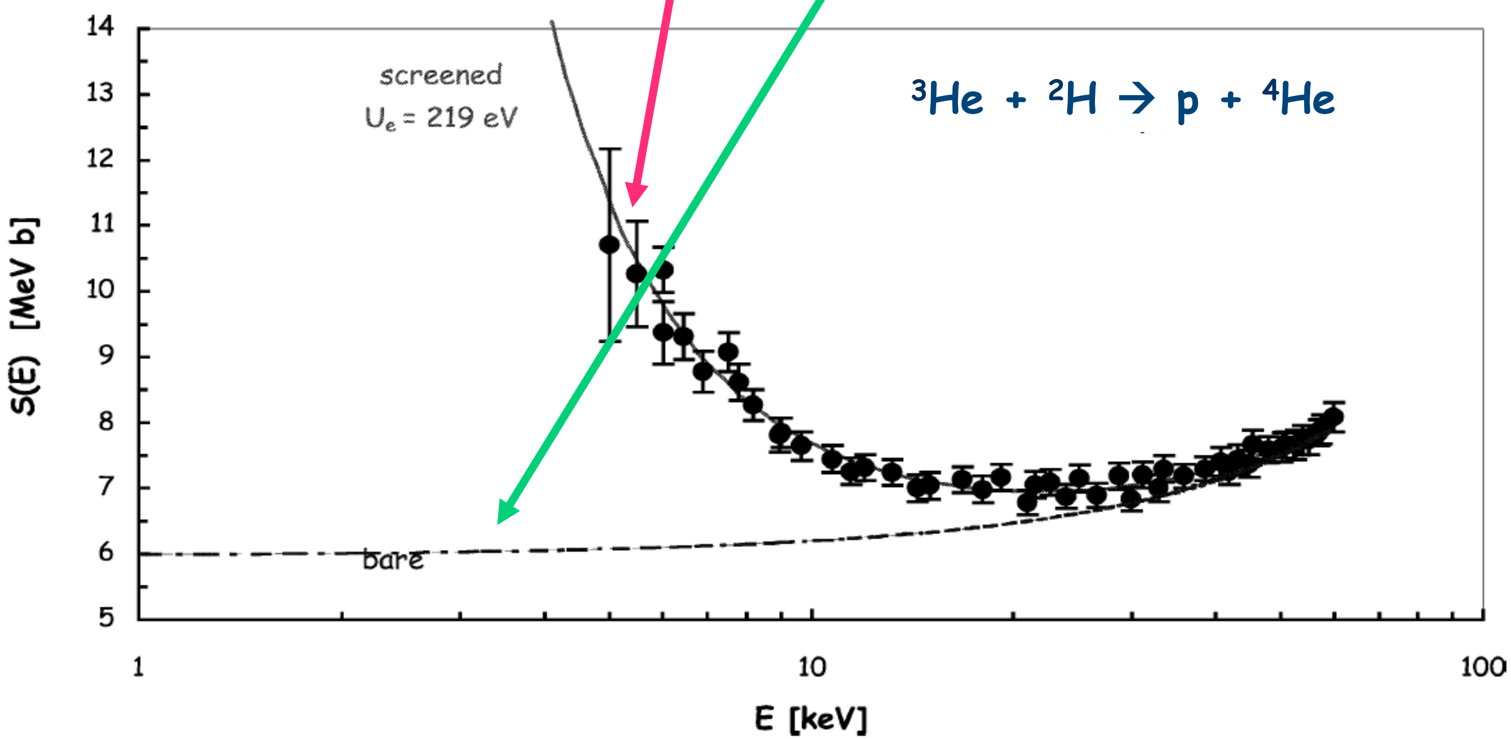
...but large uncertainties in the extrapolation

→ experimental improvements/solutions to measure at low energies

… from measurements at astrophysical energies we discover the importance of → → → → Electron Screening

S(E) enhancement experimentally found due to the Electron Screening

$$S(E)_s = S(E)_b \exp(\pi\eta U_e/E)$$



$S(E)_b$ needed to assess the reaction rate, BUT no way to measure $S(E)_b$ directly

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.

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

-> -> -> INDIRECT METHODS

❖ **Coulomb dissociation**

…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)**

… 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)**

…to determine the S(E) factor of a charged particle reaction **A+x→c+C** selecting the Quasi Free contribution of an appropriate **A+a(x+s)→ c+C+s** transfer reaction.

Trojan Horse Method

Basic principle: astrophysically relevant two-body σ from quasi- free contribution of an appropriate three-body reaction

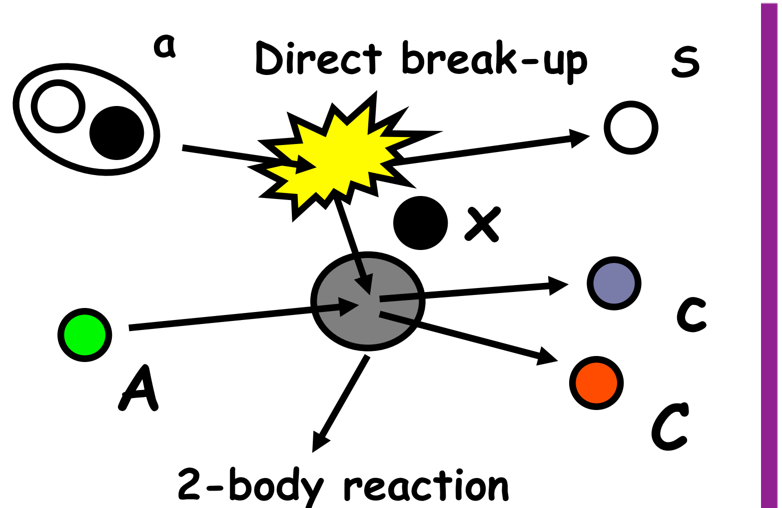
$$A + a \rightarrow c + C + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow c + C$$

a: $x \oplus s$ clusters

Quasi-free mechanism

✓ only x - A interaction

✓ s = spectator (p_s~0)



$E_A > E_{Coul} \Rightarrow$ NO Coulomb suppression

NO electron screening

$E_{q.f.} = E_{Ax} - B_{x\text{-}s}$ ± intercluster motion

plays a key role in compensating for the beam energy

$E_{q.f.} \approx 0$!!!

Theoretical approaches to the THM

$$A + a \to c + C + s \;\rightarrow\rightarrow\rightarrow\; A + x \to c + C$$

PWIA hypotheses:

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

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

MPWBA formalism

(S. Typel and H. Wolter, Few-Body Syst. 29 (2000) 75)

- distortions introduced in the c+C channel, but plane waves for the three-body entrance/exit channel

- off-energy-shell effects corresponding to the suppression of the Coulomb barrier are included

but **<u>No absolute value of the cross section</u>**

KF kinematical factors

$|\phi|^2$ **momentum distribution of** ***s*** **inside** ***a***

$d\sigma^N/d\Omega$ **Nuclear cross section for the** $A+x \to C+c$ **reaction**

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

Theoretical approaches to the THM

R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

The THM simple factorization can be deduced from the general formula in the case of resonant reactions

Amplitude of the TH reaction

$$M^{\mathrm{PWA(prior)}}(P, \mathbf{k}_{aA}) = (2\pi)^2 \sqrt{\frac{1}{\mu_{bB} k_{bB}}} \varphi_a(\mathbf{p}_{sx})$$
$$\times \sum_{J_F M_F j' l l' m_{j'} m_l m_{l'} M_n} i^{l+l'} \langle j m_j l m_l | J_F M_F \rangle \langle j' m_{j'} l' m_{l'} | J_F M_F \rangle$$
$$\times \langle J_x M_x J_A M_A | j' m_{j'} \rangle \langle J_s M_s J_x M_x | J_a M_a \rangle \, \mathrm{e}^{-\mathrm{i}\delta_{bBl}^{hs}} Y_{l m_l}(-\hat{\mathbf{k}}_{bB})$$
$$\times \sum_{\nu,\tau=1}^{N} [\Gamma_{\nu bBjlJ_F}(E_{bB})]^{1/2} [\mathbf{A}^{-1}]_{\nu\tau} Y^{*}_{l' m_{l'}}(\hat{\mathbf{p}}_{xA})$$
$$\times \sqrt{\frac{R_{xA}}{\mu_{xA}}} [\Gamma_{\nu xAl'j'J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA}, R_{xA}) (j_{l'}(p_{xA} R_{xA})$$
$$\times [(B_{xAl'}(k_{xA}, R_{xA}) - 1) - D_{xAl'}(p_{xA}, R_{xA})]$$
$$+ 2 Z_x Z_A e^2 \mu_{xA} \int_{R_{xA}}^{\infty} \mathrm{d}r_{xA} \frac{O_{l'}(k_{xA}, r_{xA})}{O_{l'}(k_{xA}, R_{xA})} j_{l'}(p_{xA} r_{xA})).$$

This accounts for:

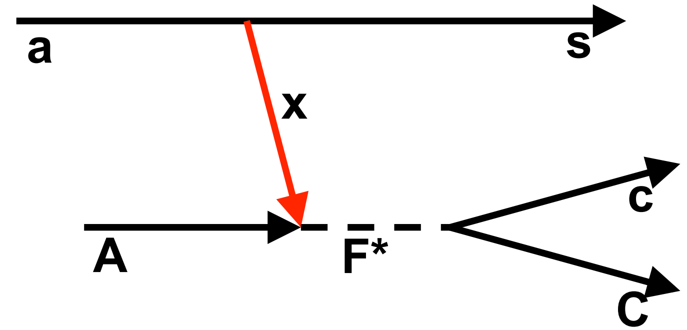
- HOES effects
- Normalization (very useful for RIBS)

Moreover:
Possible generalization to CDCC & DWBA

However → More complicated!

...for resonant reactions

The $A + a(x+s) \to F^*(c + C) + s$ 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

When transfer to a bound F state, M^2 is proportional to the ANC of the populated F state

Advantages:
- possibility to measure down to zero energy
- No electron screening
- HOES reduced widths are the same entering the OES S(E) factor (New!)

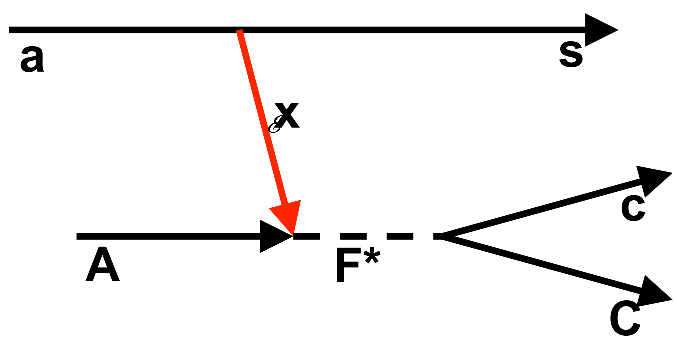
... effects of final state Coulomb interaction on the two-body cross section

From recent update of the theory within the formalism of the three-body Coulomb asymptotic states (CAS) (A.M. Mukhamedzhanov and A.S. Kadyrov FBS 2019)

$$\frac{d^3\sigma}{d\Omega_{\mathbf{k}_{sF(f)}}\, d\Omega_{\mathbf{k}_{bB(f)}}\, dE_{sF(f)}} = \sigma_0 \frac{\Gamma_{bB}}{[E_{0(bB)} - E_{bB(f)}]^2 + \Gamma^2/4} \frac{\pi\zeta}{\mathrm{sh}\zeta}\, e^{2\zeta \arctan\frac{2\mathscr{E}}{\Gamma}}$$

$\mathscr{E} = E_{0(bB)} - E_{bB(f)}$

Crucial role of $\zeta = \eta_{cs} + \eta_{Cs} - \eta_{R(F^*s)}$



Coulomb renormalization factor:
Coulomb effects on the resonance line shape plus energy dependence of the cross section.

The conclusions are:

The simultaneous inclusion of the Coulomb effects in the intermediate and final state decreases the effect of the final-state Coulomb interactions on the triple differential cross section.

In particular if one of the Coulomb parameters in the final state, for example η_{bs}, is zero or very small then the cumulative effect of the Coulomb interactions in the intermediate and final state is negligible.

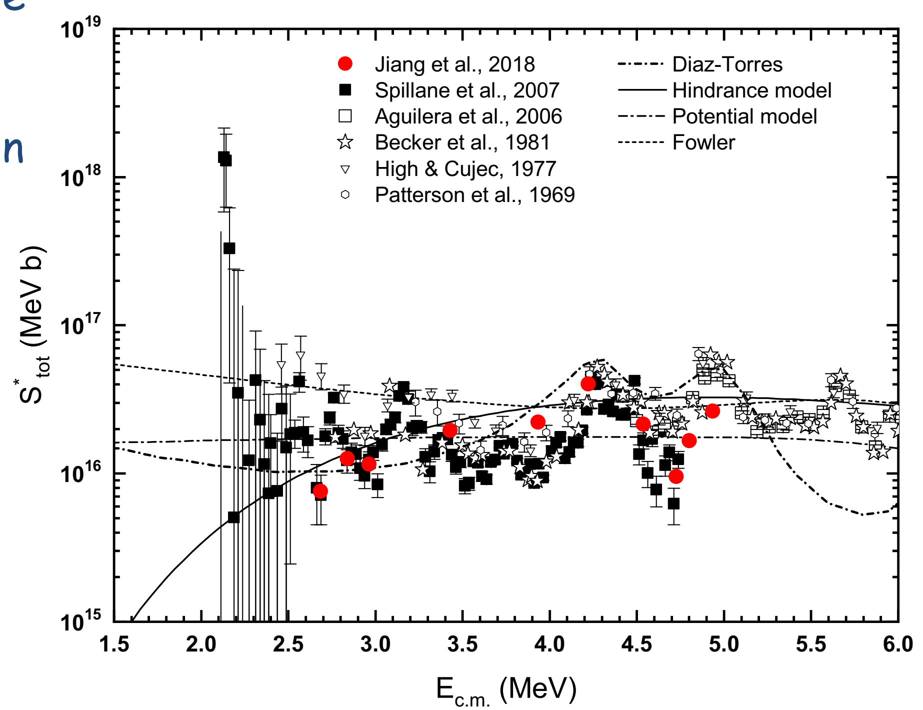
	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	
1	$^{7}Li(p, \alpha)^{4}He$	$^{2}H(^{7}Li, \alpha\ \alpha)n$	19-22	15.122	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC,1999, Lattuada *et al.* ApJ, 2001
2	$^{7}Li(p, \alpha)^{4}He$	$^{7}Li(^{3}He, \alpha\ \alpha)d$	33	11.853	CYCLOTRON, Rez, Praha	Tumino *et al.* EPJ, 2006
3	$^{6}Li(p, \alpha)^{3}He$	$^{2}H(^{6}Li, \alpha\ ^{3}He)n$	14,25	1.795	TANDEM 13 MV LNS-INFN, Catania	Tumino *et al.* PRC, 2003
4	$^{9}Be(p, \alpha)^{6}Li$	$^{2}H(^{9}Be, \alpha\ ^{6}Li)n$	22	-0.099	TANDEM CIAE, Beijing TANDEM 13 MV LNS-INFN, Catania	Wen *et al.* PRC, 2008, Wen et al. JPG 2011
5	$^{11}B(p, \alpha)^{8}Be$	$^{2}H(^{11}B, \alpha\ ^{8}Be)n$	27	6.36	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC, 2004, Lamia *et al.* JPG, 2011
6	$^{15}N(p, \alpha)^{12}C$	$^{2}H(^{15}N, \alpha\ ^{12}C)n$	60	2.74	CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRC, 2008
7	$^{18}O(p, \alpha)^{15}N$	$^{2}H(^{18}O, \alpha\ ^{15}N)n$	54	1.76	(CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRL 2008,
8	$^{19}F(p, \alpha)^{16}O$	$^{2}H(^{19}F, \alpha\ ^{16}O)n$	50,55	8.11	TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* ApJ Lett., 2011 Indelicato et al. ApJ 2017
9	$^{17}O(p, \alpha)^{14}N$	$^{2}H(^{17}O, \alpha^{14}N)n$	45	-1.032	TANDEM 13 MV LNS-INFN, Catania TANDEM 11 MV Notre Dame	Sergi et al. PRC (R), 2010 Sergi et al PRC 2016

	Binary reaction	Indirect reaction	E_{lab}	Q_3	Accelerator	Ref.
10	$^{18}F(p,\alpha)^{15}O$	$^{2}H(^{18}F,\alpha^{15}O)n$	48	0.65	CYCLOTRON CNS-RIKEN, Tokyo	Cherubini et al. PRC 2015 Pizzone et al. EPJ 2016
11	$^{10}B(p,\alpha)^{7}Be$	$^{2}H(^{10}B,\alpha^{7}Be)n$	27	-1.078	TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. PRC 2014 Spitaleri et al. PRC 2017
12	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	5 4.8	20.9	TANDEM Demoscritos,Atene TANDEM, IRB, Zagreb	Cherubini *et al.* ApJ, 1996 Spitaleri *et al* .PRC, 2001
13	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	6	20.9	CYCLOTRON Rez, Praha	Pizzone et al. PRC, 2011
14	$^{3}He(d,\alpha)^{1}H$	$^{6}Li(^{3}He,p^{4}He)^{4}He$	5,6	16.878	DINAMITRON, Bochum	La Cognata *et al.* 2005
15	$^{2}H(d,p)^{3}H$	$^{2}H(^{6}Li,p^{3}He)^{4}He$	14	2.59	DINAMITRON, Bochum	Rinollo *et al.* EPJ 2005
16	$^{2}H(d,p)^{3}H$	$^{2}H(^{3}He,p^{3}H)^{1}H$	18	-1.46	CYCLOTRON, Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
17	$^{2}H(d,n)^{3}He$	$^{2}H(^{3}He,n^{3}He)^{1}H$	18	-2.224	CYCLOTRON Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
18	$^{9}Be(p,d)^{8}Be$	$^{9}Be(d,d^{8}Be)n$	18	-1.66	TANDEM 13 MV CIAE, Beijing	Qungang Wen et al.2016
19	$^{6}Li(n,a)^{3}H$	$^{2}H(^{6}Li,t\,\alpha)^{1}H$	14	2.224	TANDEM 13 MV LNS-INFN, Catania	Tumino et al.,EPJ A 2005 Gulino et al., JPG 2010

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
20	$^{17}O(n,a)^{14}C$	$^{17}O(n, a^{14}C)^{1}H$	43.5	-0.40 7	TANDEM 11 MV Notre Dame TANDEM 13 MV LNS-INFN, Catania	Gulino et al. PRC(R) 2013
21	$^{13}C(a,n)^{16}O$	$^{13}C(^{6}Li, a\ n)^{16}O$	7.82	3.85	TANDEM FSU, Tallaassee, Florida, USA	La Cognata et al. PRL 2013 La Cognata et al ApJ 2013
22	$^{12}C(^{12}C,a)^{20}Ne$ $^{12}C(^{12}C,p)^{23}Na$	$^{12}C(^{14}N,a^{20}Ne)^{2}H$ $^{12}C(^{14}N,p^{23}Na)^{2}H$	30	-5.65 -8.03	TANDEM 13 MV LNS-INFN, Catania	Tumino et al. Nature 2018
23	$^{12}C(a,a)^{12}C$	$^{13}C(^{6}Li, a\ n)^{16}O$	20	0	TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. EPJ 2000
24	$^{1}H(p,p)^{1}H$	$^{2}H(p,pp)n$	5,6	2,224	CYCLOTRON ATOMKI,Debrecen TANDEM IRB, Zagreb TANDEM 13 MV LNS-INFN, Catania TANDEM 5 MV Napoli University	Tumino et al. PRL 2007 Tumino et al. PRC 2008
25 0	$^{19}F(a,p)^{22}Ne$	$^{6}Li(^{19}F,p^{22}Ne)^{2}H$	6	1.2	IRB, Zagreb, TANDEM	Pizzone et al. ApJ 2017 D'Agata et al ApJ 2018
25 0	$^{7}Be(n,a)^{4}He$	$^{2}H(^{7}Be,aa)^{1}H$	43.5	16.7	TANDEM LNL-INFN, Catania	L. Lamia et al., to be submitted

12C+12C fusion

- Crucial phase in the nucleosynthesis of massive stars (> 8 $M_{\odot}$) at T ~ 0.6-1.2 GK
- It influences M_{up}
- Engine for superbursts from accreting neutron stars
- ignition conditions of Type Ia supernovae



From J. Zickefoose et al., Phys. Rev. C **97** (2018) 06580

Main issues:

- Cross section drops by many orders of magnitude with decreasing energy →Lack of data at the relevant low energies
- Inconsistencies among different theoretical extrapolations

1 to 3 orders of magnitude uncertainty at low energies

Our Experiment with theTHM

$^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the Trojan Horse Method applied to the $^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$ and $^{12}C(^{14}N,p^{23}Na)^{2}H$ three-body processes

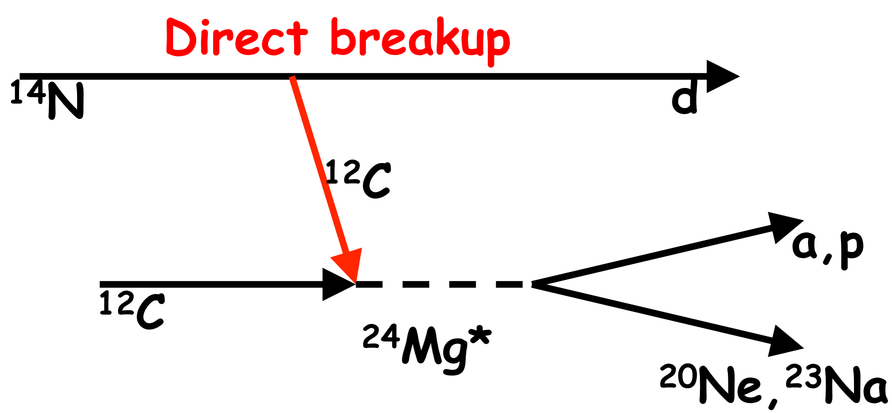
^{2}H from the ^{14}N as spectator s

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 barrier in the entrance channel

NO electron screening

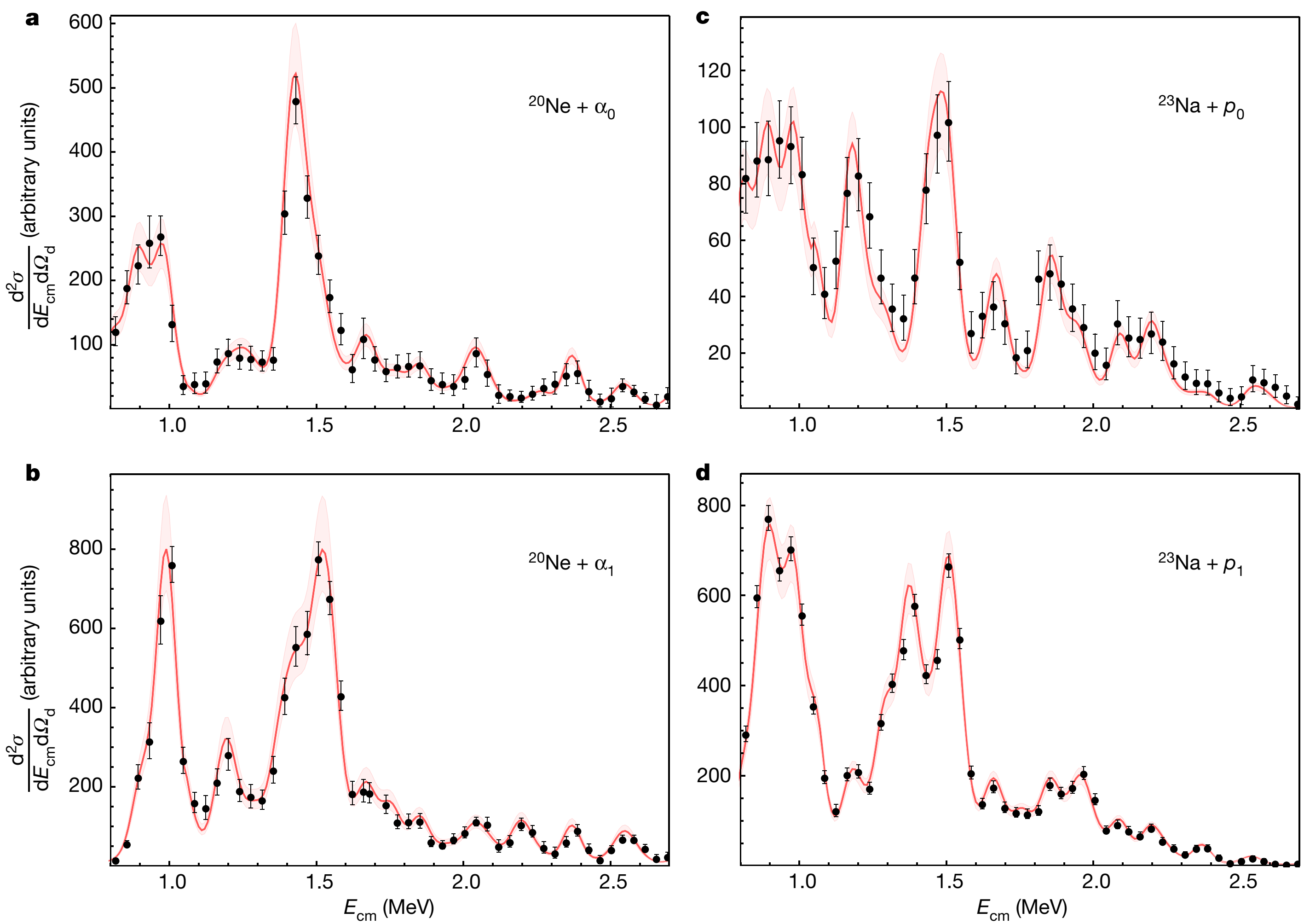
$$E_{QF} = E_{14N}\,\frac{m_{^{12}C}}{m_{^{14}N}}\cdot\frac{m_{^{12}C}}{m_{^{12}C}+m_{^{12}C}} - 10.27\ \text{MeV}$$

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

12C+12C with theTHM

Measured $^{12}C(^{12}C,\alpha_{0,1})^{20}Ne$ and $^{12}C(^{12}C,p_{0,1})^{23}Na$ HOES cross-sections

obtained after Q-value selection plus PWIA tests



Red lines and bands: modified 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

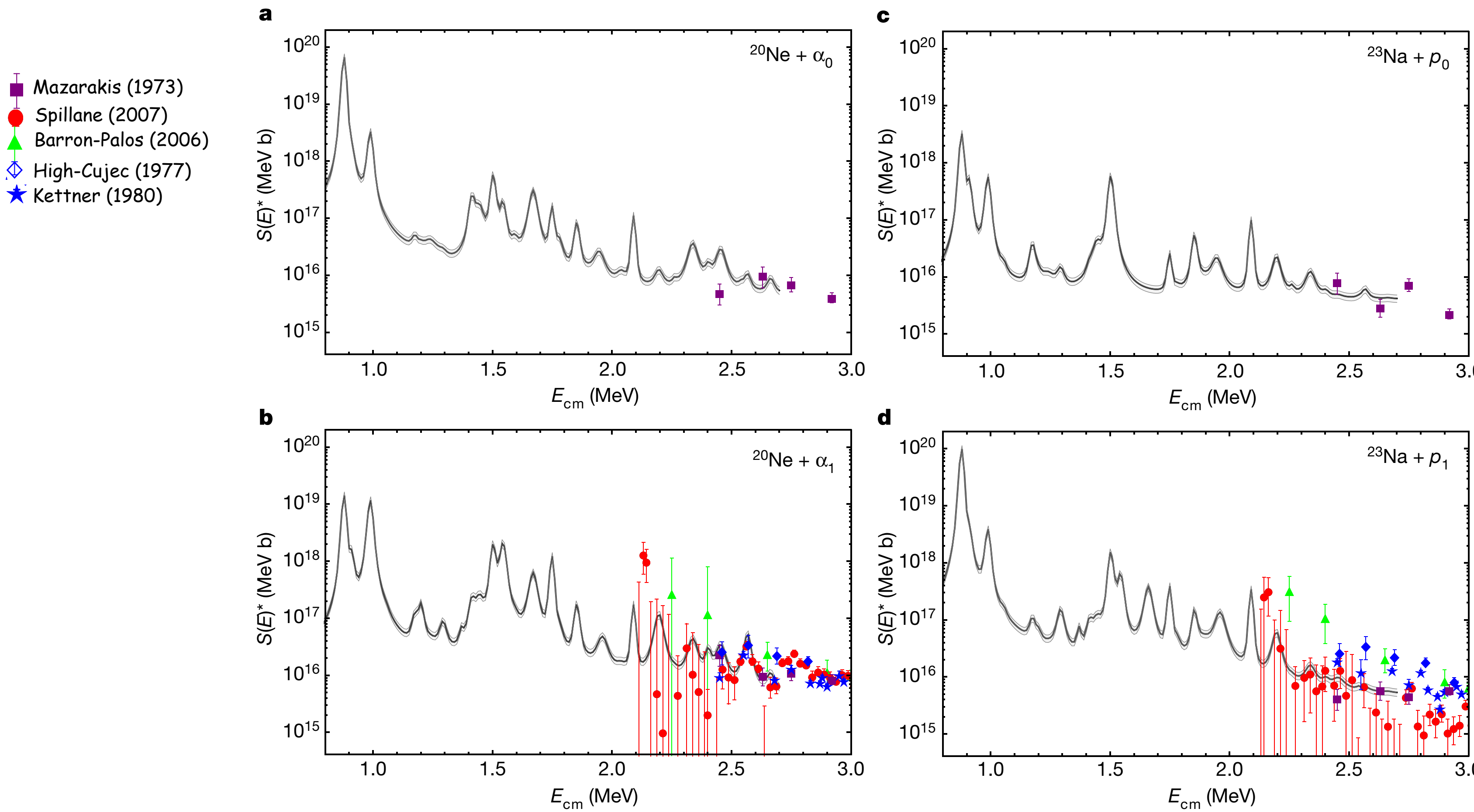
A. Tumino et al., Nature 557, 687 (2018)

S(E)* factors

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

Normalization to direct data done in the E_{cm} window 2.50–2.63 MeV of the ^{20}Ne + α_1: all data sets available included, less sensitivity to flawed ones

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



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

nature
International journal of science

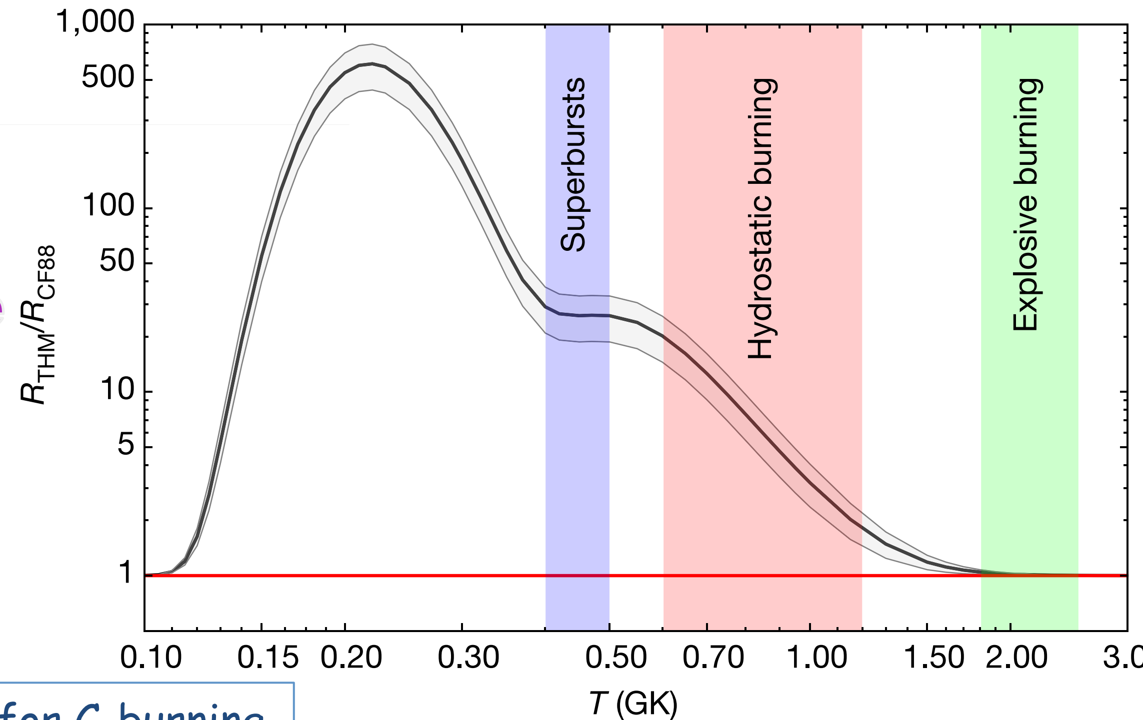
Letter | Published: 23 May 2018

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

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

Some implications from the new 12C+12C rate

- Impacts of the New Carbon Fusion Cross Sections on Type Ia Supernovae (K. Mori et al. MNRAS 2018)

The resonances found in the $^{12}C+^{12}C$ cross section result in a decrease of the carbon burning ignition temperature in the progenitors, with a reduction of contribution of the DD scenario to the SNe Ia rate.

- On the mass of supernova progenitors: the role of the $^{12}C+^{12}C$ reaction (O. Straniero et al. 2019 Springer Procs.)

New stellar models with mass between 7 and 10 $M_{\odot}$
upper bound for the mass of the progenitors of CO white dwarfs (Mup) reduced from 8 to 7.5 $M_{\odot}$

lower bound for the mass of the progenitors of normal type II supernovae ($M\star$) a bit less than 10 $M_{\odot}$

Small changes but very important for stellar models.

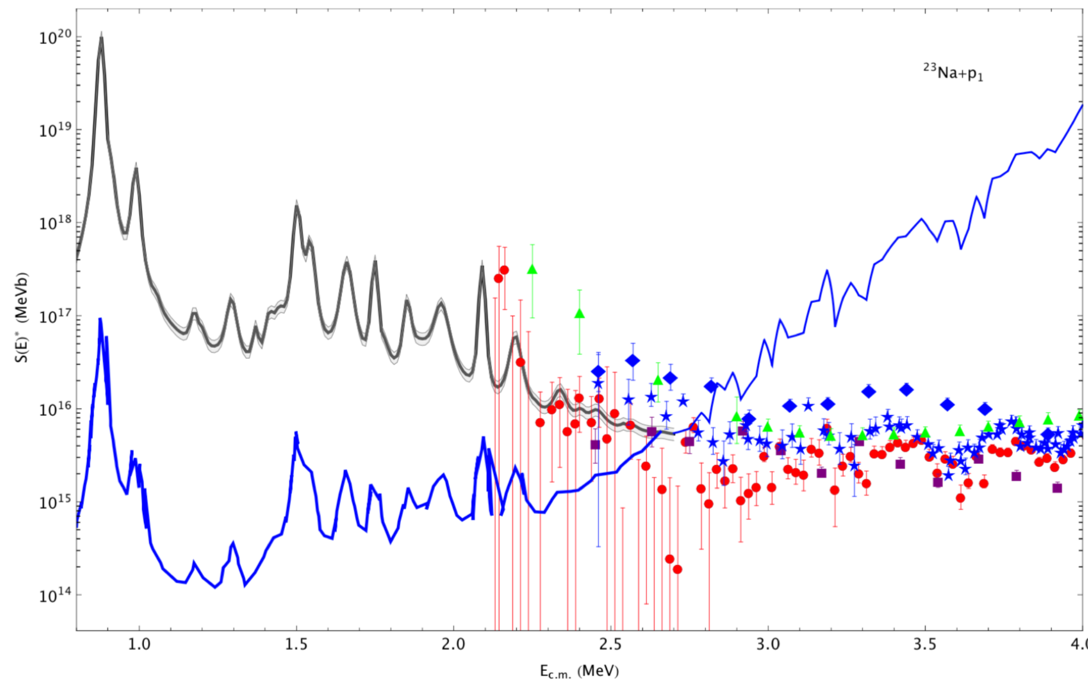
Still a lot of applications to do …

- From nuclear side: try to find the missing low-lying states of the $^{12}C+^{12}C$ molecular rotational band

In arXiv you can find a REJECTED comment on this work, pointing out that the S(E)* factor is overestimated as Coulomb interaction is not properly accounted for:

arXiv:submit/2328427 [nucl-th] 13 Jul 2018

From the ratio S*_theo/S*_exp at low energy we can deduce the trend of the correction factor, essentially an exponential which gives no agreement with direct data



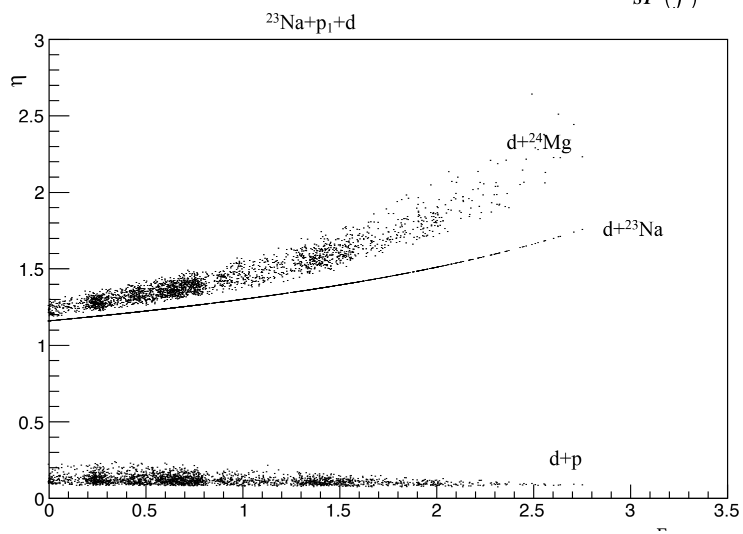
The drop can be due to an incomplete inclusion of Coulomb effects (only those from intermediate channel are in)

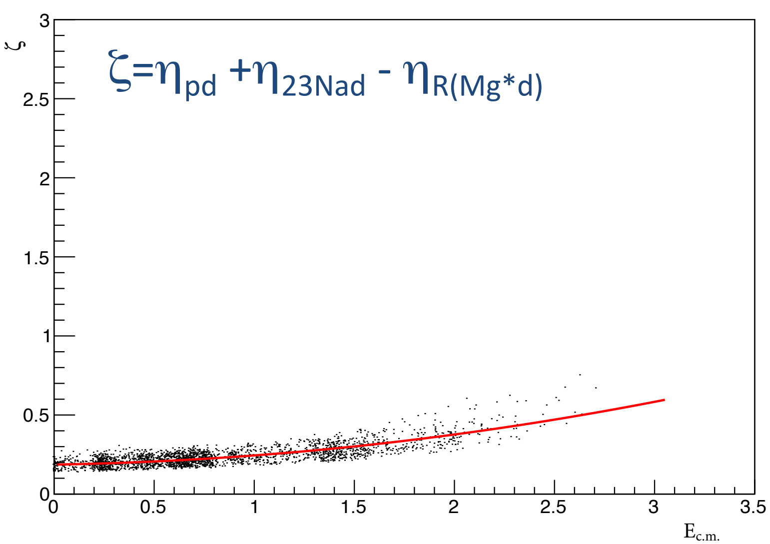
With a full account of intermediate and final state Coulomb effects, the drop disappears.

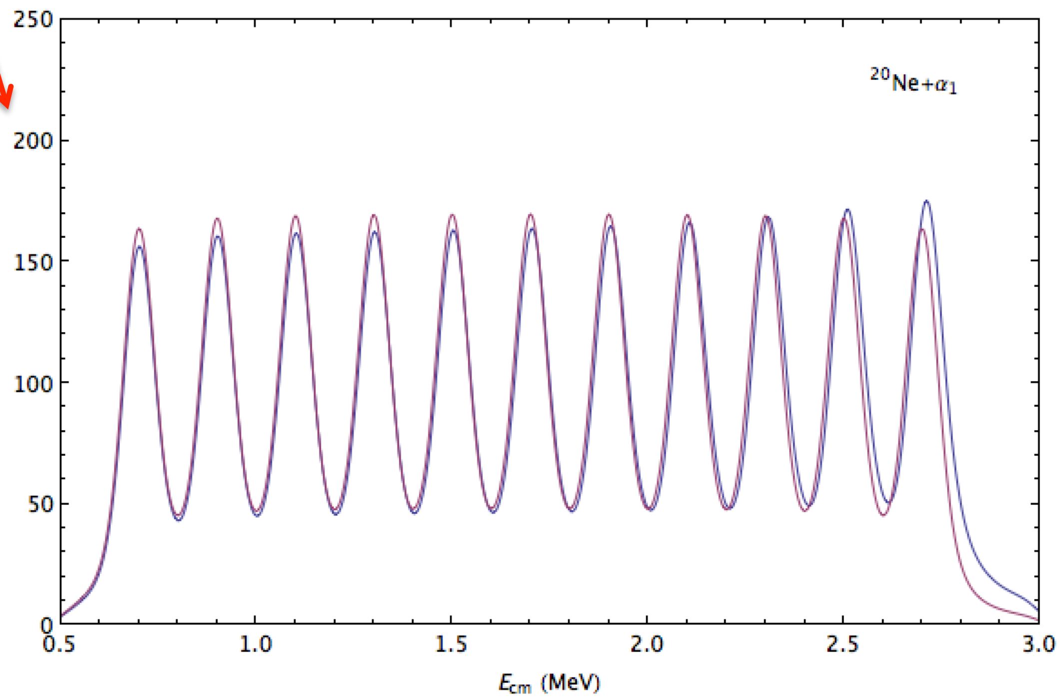
… indeed including the Coulomb renormalization parameter

Breit-Wigner approximation with η and ζ from experiment

$$\frac{d^3\sigma}{d\Omega_{\mathbf{k}_{sF(f)}}\, d\Omega_{\mathbf{k}_{bB(f)}}\, dE_{sF(f)}} = \sigma_0 \frac{\Gamma_{bB}}{[E_{0(bB)} - E_{bB(f)}]^2 + \Gamma^2/4} \frac{\pi\zeta}{\mathrm{sh}\zeta} e^{2\zeta \arctan \frac{2\mathscr{E}}{\Gamma}}$$

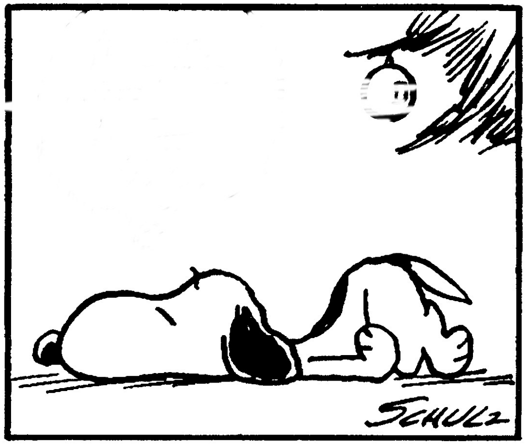






Red line: no Coulomb
Blue line: with Coulomb
No change within experimental errors

Conclusions



THM (this holds for indirect in general) measurements are unique tools to investigate reactions on energy ranges difficult to study otherwise

still great potential for future applications (also beyond astrophysical applications)

However, when possible, a joint work with direct and indirect measurements is the best choice to ensure accurate normalization and reaction rates for astrophysical applications

Thank you for your attention!

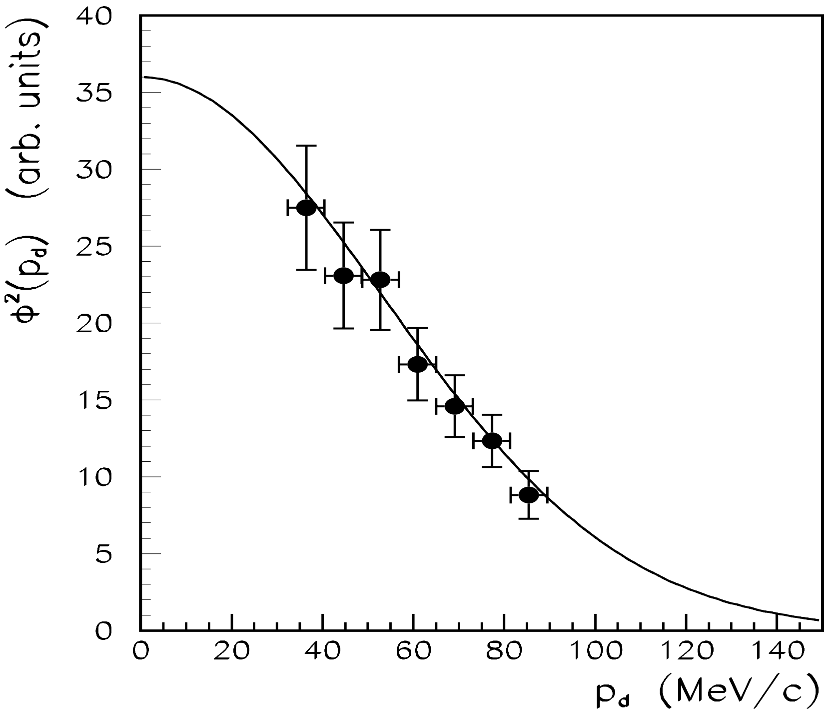
Selection of the quasi-free mechanism

Comparison between the experimental momentum distribution and the theoretical one

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

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:

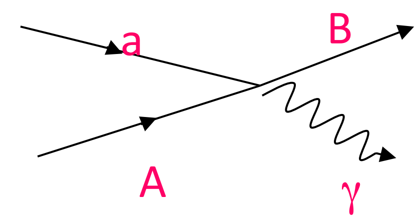
- $p_d < (2\mu_{d12C}B_{d12C})^{1/2}$=181 MeV/c → Proved that the shape of the momentum distribution is insensitive to the theoretical framework used for its derivation (agreement between PWA and DWBA)

- 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)

Asymptotic Normalization Coefficients: few hints

At low relative energies the S(0) for a direct capture reaction a+A → B+γ

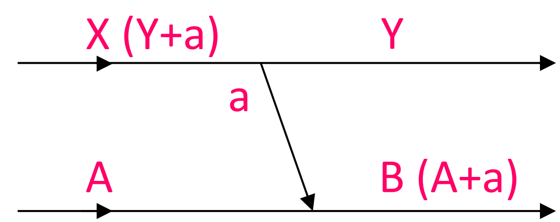
$$S(0)_{DC} \propto (C^{B}_{aA})^2$$



C^B_{aA} is the so called ANC that specifies the tail of the B overlap function in the a+A channel

For a peripheral transfer reaction X+A → Y+B into a bound state of B,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} \propto (C^{B}_{aA})^2 \cdot (C^{X}_{Ya})^2 \left(\frac{d\tilde{\sigma}}{d\Omega}\right)_{DW}$$



reduced DWBA cross section
insensitive to the bound
state potential parameters

The ANC C^B_{aA} can be obtained normalising the calculated angular distribution to the experimental one. What we need: precise optical potentials and one additional ANC (from elastic scattering angular distributions)