ENSAR2-NUSPRASEN Workshop, HIL-Warsaw, 22-24 January 2018

Resonant Reactions with the Trojan Horse Method

Aurora Tumino

INFN Istituto Nazionale di Fisica Nucleare

Universitas Studiorum Hennae · Libera Università Kore Enna

Outline

Basic features of the Trojan Horse Method

The Trojan Horse Method for resonant reactions

Physics Case: The $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions

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

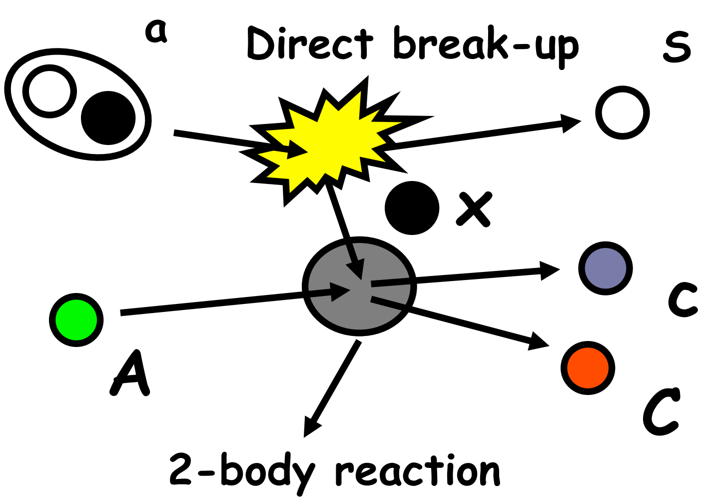
Quasi-free mechanism

✓ only x - A interaction

✓ s = spectator (p_s~0)

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

NO electron screening



$$E_{q.f.} = E_{ax} = m_x / (m_x + m_A) E_A - B_{x-s} \quad (\pm \text{ intercluster motion})$$

↓ plays a key role in compensating for the beam energy → $E_{q.f.} \approx 0$!!!

Theoretical approach to the THM

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

PWIA hypotheses:

- A does not interact simultaneously with x and s

- The presence of s does not influence the A-x interaction

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

KF kinematical factors

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

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

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

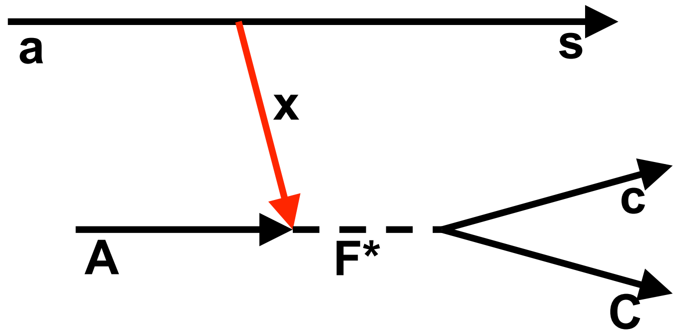
$d\sigma^{off}/d\Omega \rightarrow d\sigma/d\Omega$ (on shell)
the penetration factor P_l has to be introduced:

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

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

...for resonant reactions

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

Advantages:

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

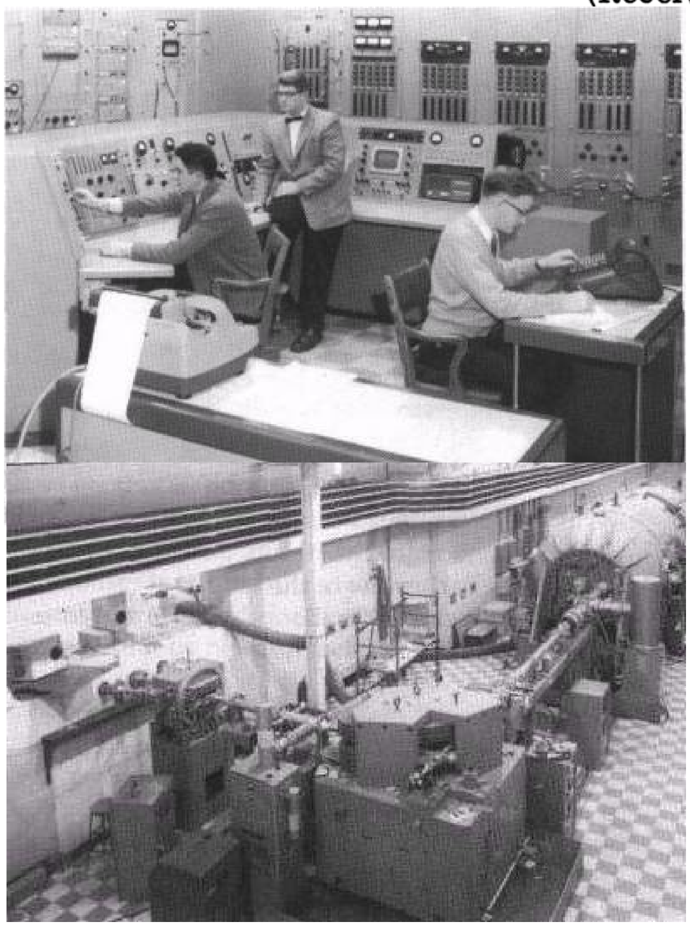
	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	
1	$^{7}Li(p, \alpha)^{4}He$	$^{2}H(^{7}Li, \alpha\ \alpha)n$	19-22	15.122	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC,1999, Lattuada *et al.* ApJ, 2001
2	$^{7}Li(p, \alpha)^{4}He$	$^{7}Li(^{3}He, \alpha\ \alpha)d$	33	11.853	CYCLOTRON, 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

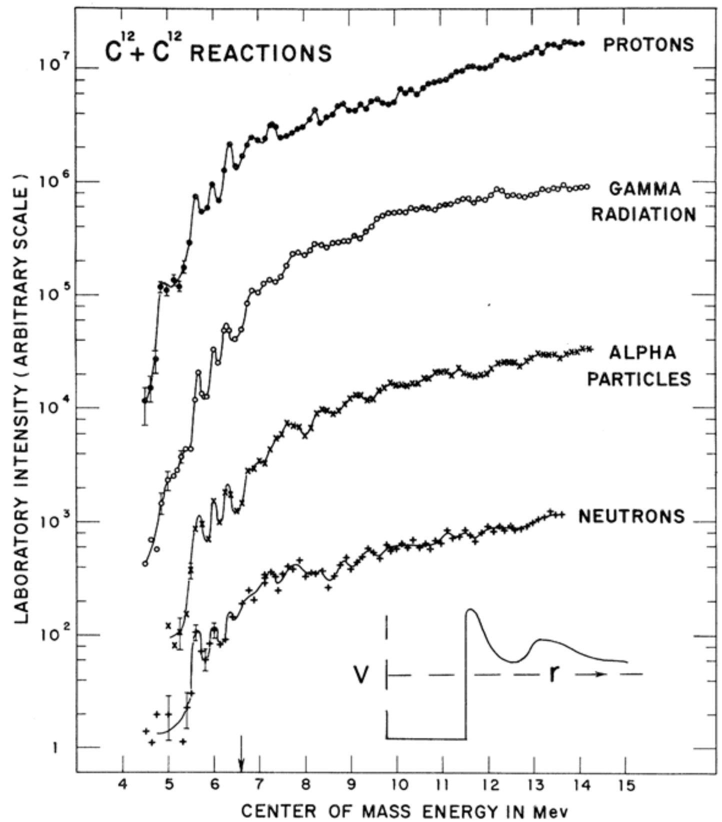
	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
20	$^{17}O(n,a)^{14}C$	$^{17}O(n, a^{14}C)^{1}H$	43.5	-0.40 7	TANDEM 11 MV Notre Dame TANDEM 13 MV LNS-INFN, Catania	Gulino et al. PRC(R) 2013
21	$^{13}C(a,n)^{16}O$	$^{13}C(^{6}Li, a\ n)^{16}O$	7.82	3.85	TANDEM FSU, Tallaassee, Florida, USA	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. submitted
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	$^{19}F(a,p)^{22}Ne$	$^{6}Li(^{19}F,p^{22}Ne)^{2}H$	6	1.2	IRB, Zagreb, TANDEM	Pizzone et al. ApJ 2017 D'Agata et al in prep.
25	$^{7}Be(n,a)^{4}He$	$^{2}H(^{7}Be,aa)^{1}H$	43.5	16.7	TANDEM LNL-INFN	Under analysis

RESONANCES IN C^{12} ON CARBON REACTIONS

E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)



The world's first tandem accelerator
Installed at Chalk River in 1959



Molecular resonances in the $^{12}C+^{12}C$ fusion reaction

12C+12C fusion

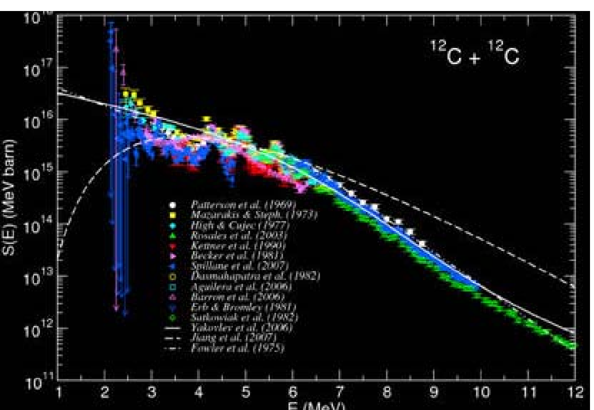
Great interest in a wide range of stellar burning scenarios in carbon-rich environments such as late evolutionary stages of stars with more than 8 $M_\odot$
superbursts from accreting neutron stars
Sne Ia

Carbon burning temperature from 0.5 to 1.2 GK → E_{cm} from 1 to 2 MeV

Principal reactions:

$^{12}C(^{12}C,\alpha)^{20}Ne$	+ 4.617 MeV	} The most frequent results of the interaction
$^{12}C(^{12}C,p)^{23}Na$	+ 2.241 MeV	
$^{12}C(^{12}C,n)^{23}Mg$	- 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)
K. U. Kettner *et al.*, Phys. Rev. Lett. 38, 337 (1977)
H.W. Becker et al., Z. Phys. A 303, 305 (1981)
L. Barron-Palos et al., Nucl. Phys. A 779, 318 (2006)
E.F. Aguleira et al.,Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. Lett. 98, 122501 (2007)
B. Bucher et al., Phys. Rev. Lett. 114, 251102 (2015)
C.L. Jiang et al., Phys. Rev. C 97, 012801(R) (2018)

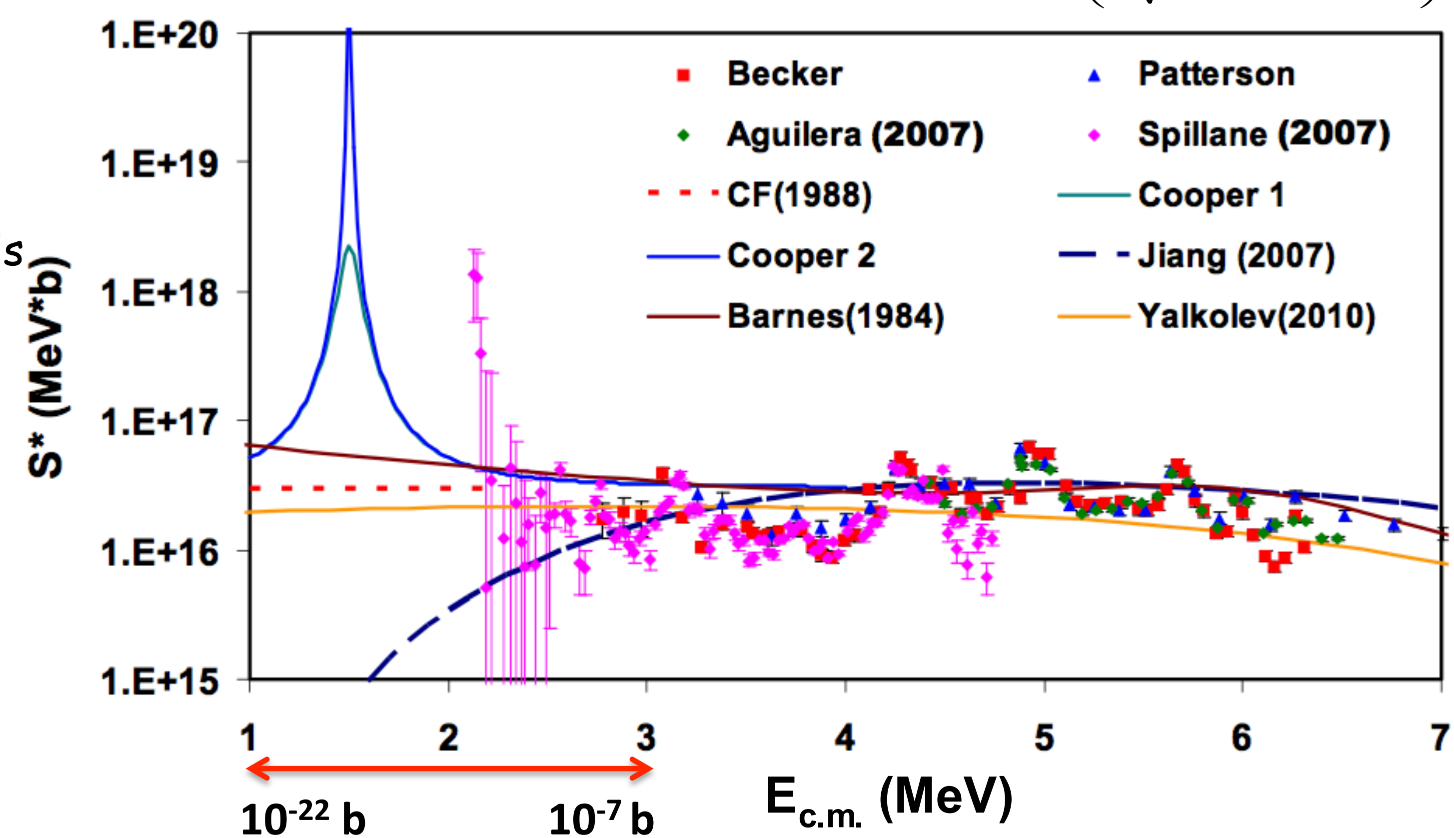
C-burning: Status of Art

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

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

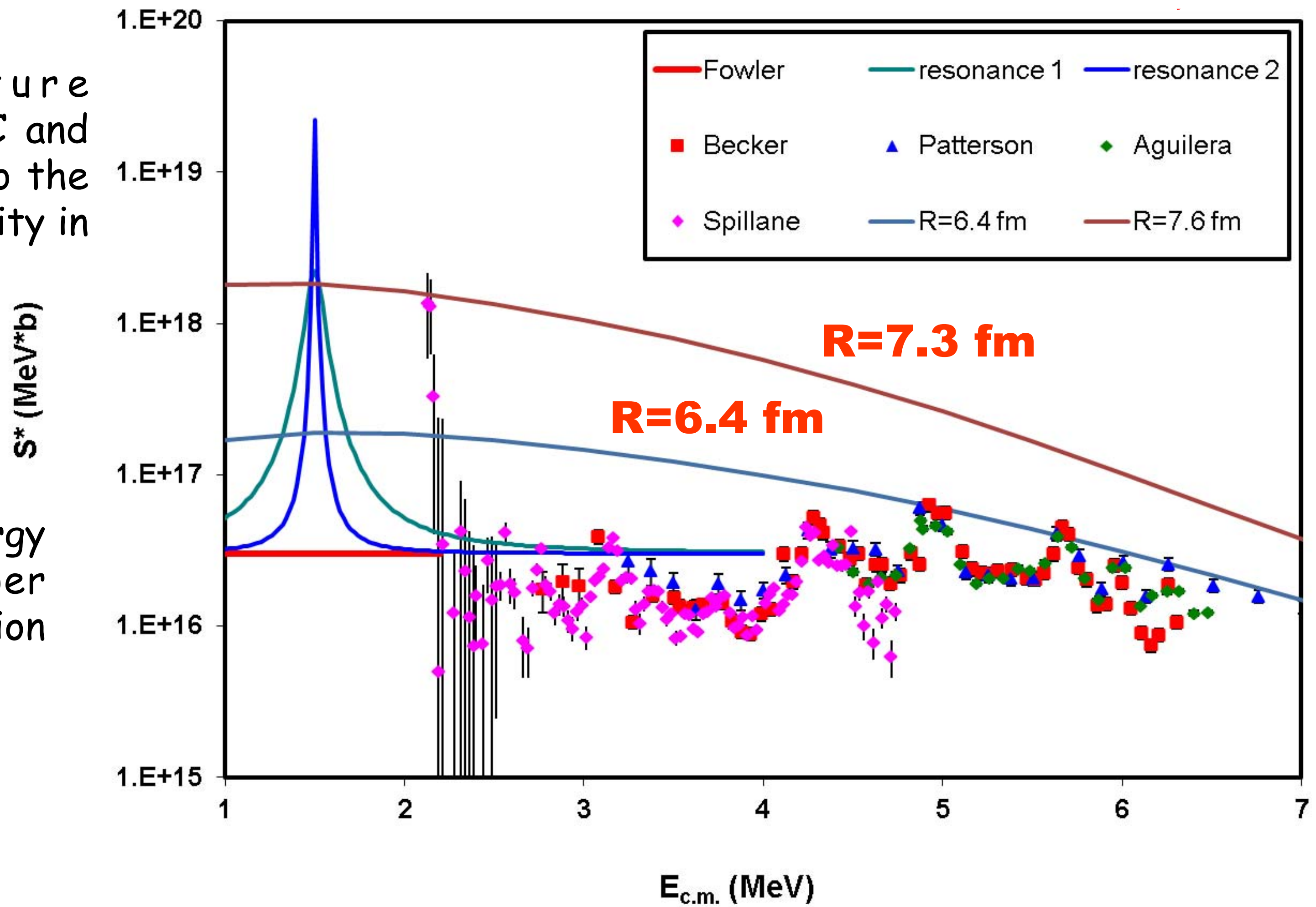


C-burning: Status of Art

By comparing the cross sections for the three carbon isotope systems, $^{12}C+^{12}C$, $^{12}C+^{13}C$, and $^{13}C+^{13}C$, it is found that the cross sections for $^{12}C+^{13}C$ and $^{13}C+^{13}C$ provide an upper limit for the fusion cross section of $^{12}C+^{12}C$ over a wide energy range (M. Notani et al. PRC 85 (2012) 014607)

Resonant structure smeared in the $^{12}C+^{13}C$ and $^{13}C+^{13}C$ systems, due to the much higher level density in their compound nuclei.

With the lowest energy point different upper limit (change in fusion barrier parameters)



No definite conclusion!

→Thus, further measurements extending down to at least 1 MeV would be extremely important.

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

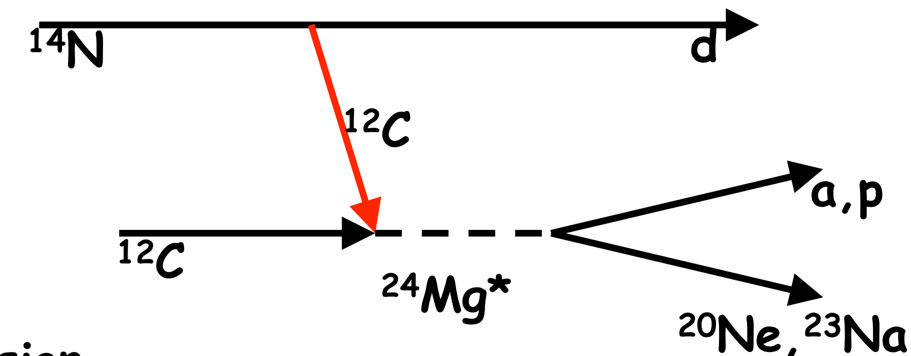
^{2}H from the ^{14}N as spectator s

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 suppression

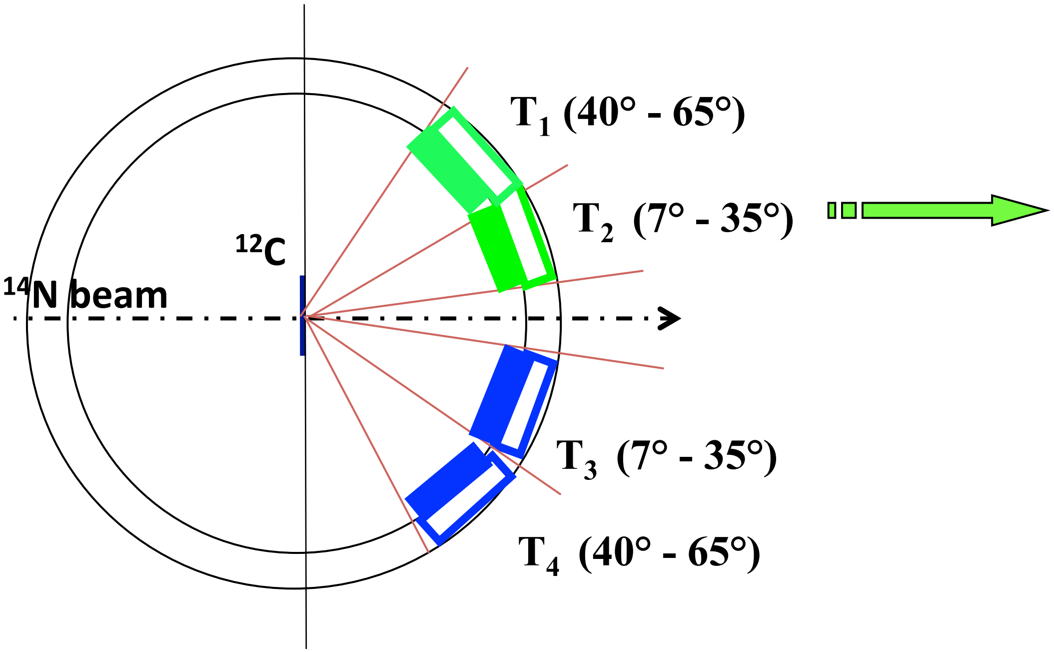
NO electron screening

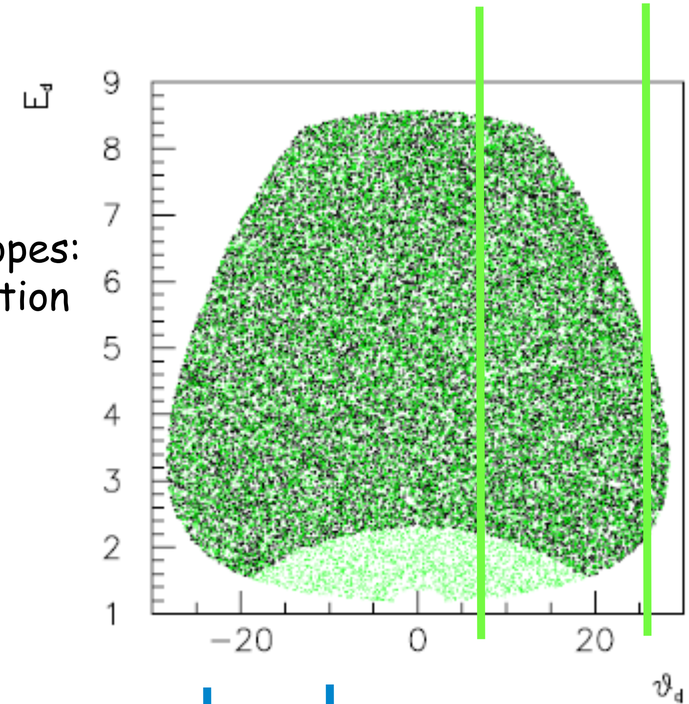
$$E_{QF} = E_{14N}\,\frac{m_{^{12}C}}{m_{^{14}N}}\cdot\frac{m_{^{12}C}}{m_{^{12}C}+m_{^{12}C}} - 10.27\ \text{MeV}$$

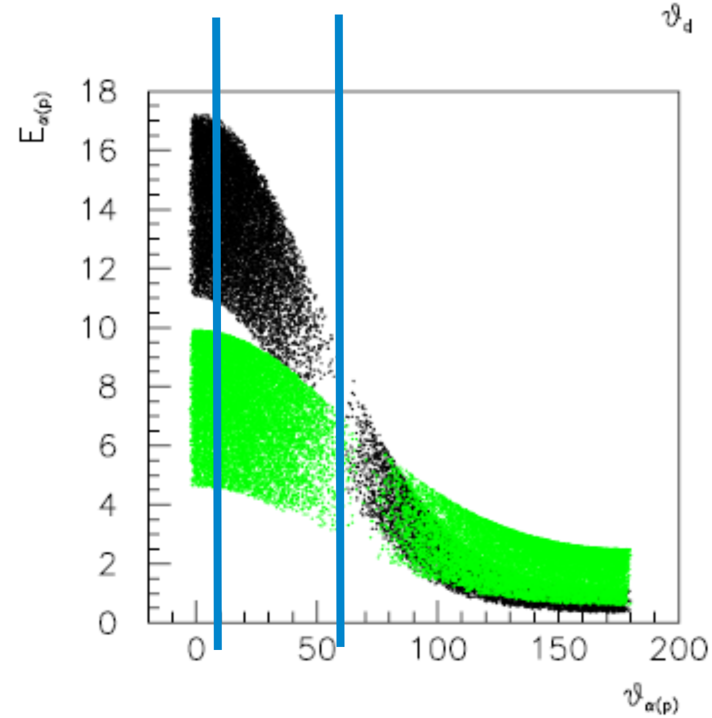
The 14N+12C experiment at LNS

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



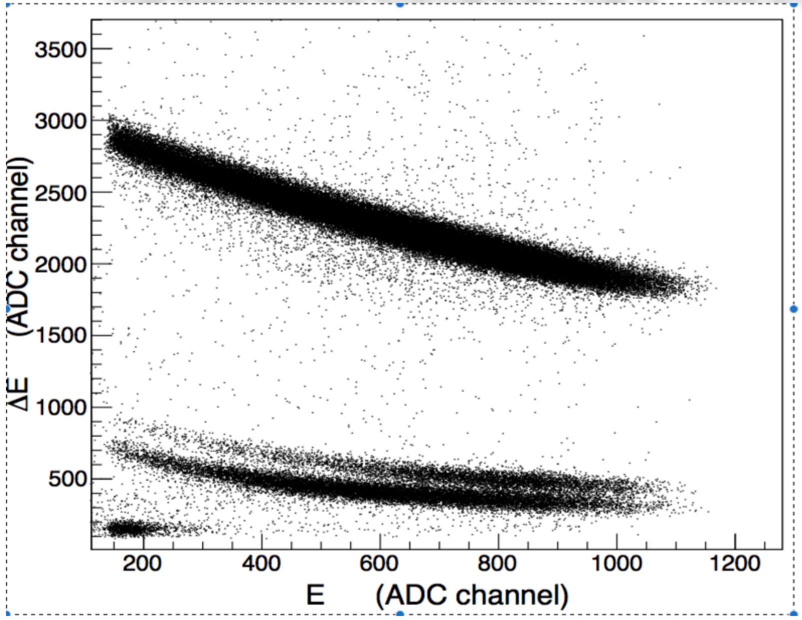


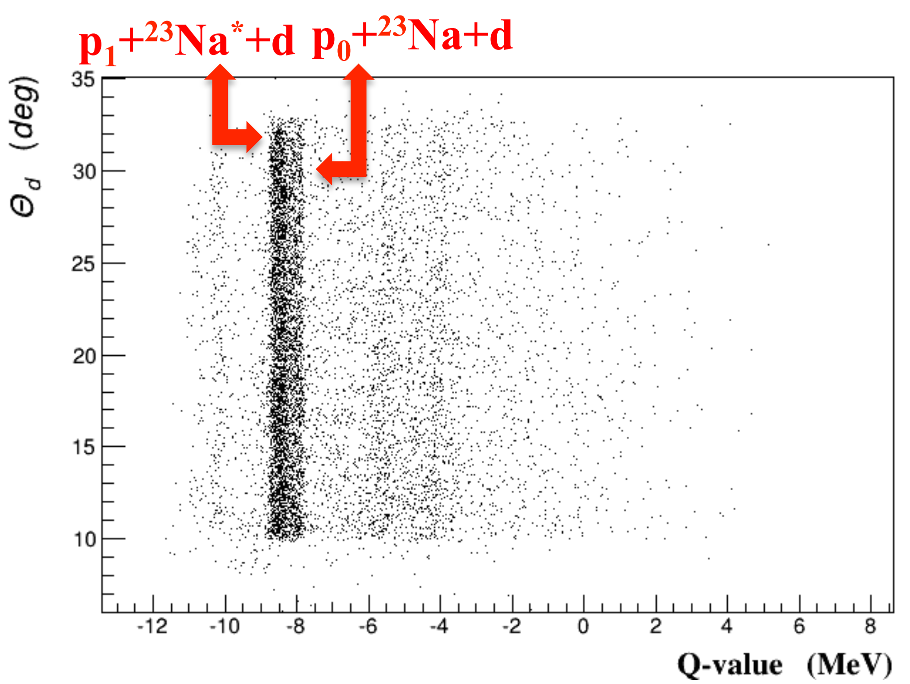


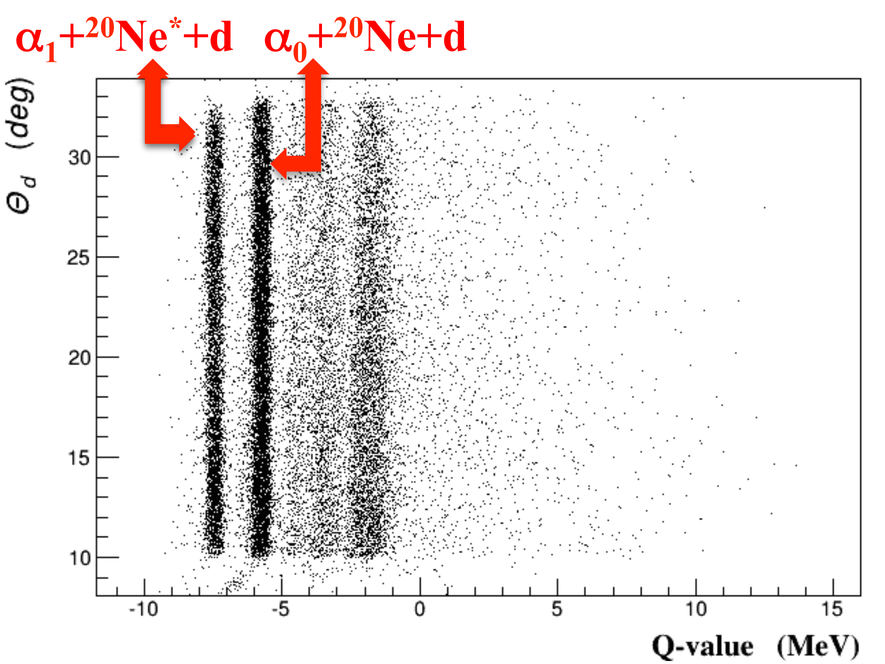
^{20}Ne+α+d and ^{23}Na+p+d reaction channels reconstructed when detecting the ejectile of the two-body reactions (either α (black dots) or p (green dots)) in coincidence with the spectator d particle.

No detection of ^{20}Ne or ^{23}Na quite low energy → too high detection threshold

Selection of the 3-body channels



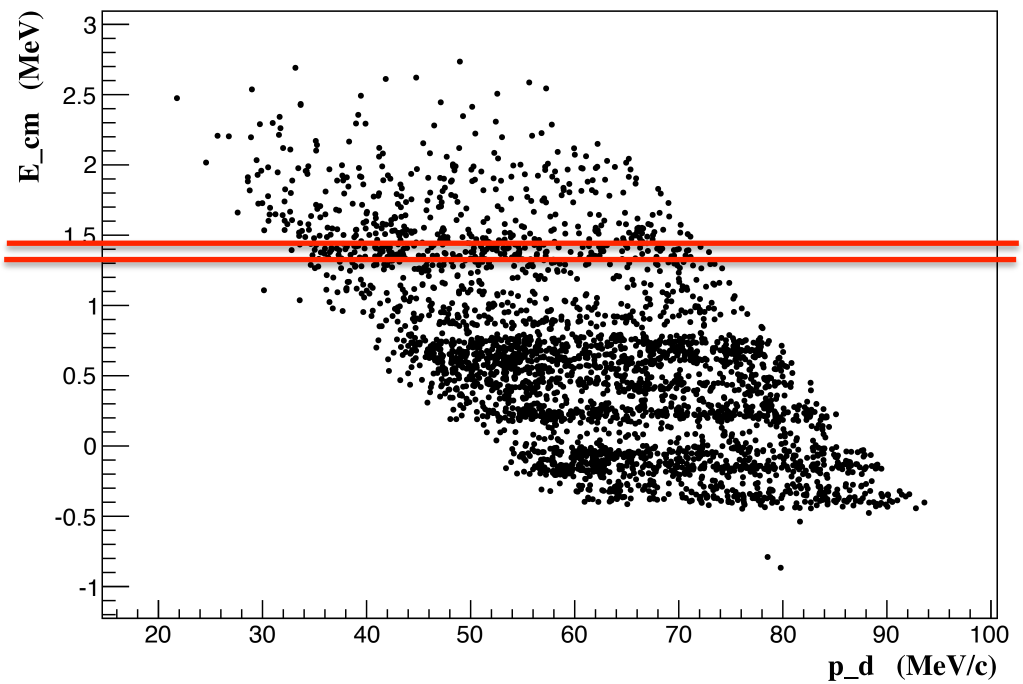




Selection of the quasi-free mechanism

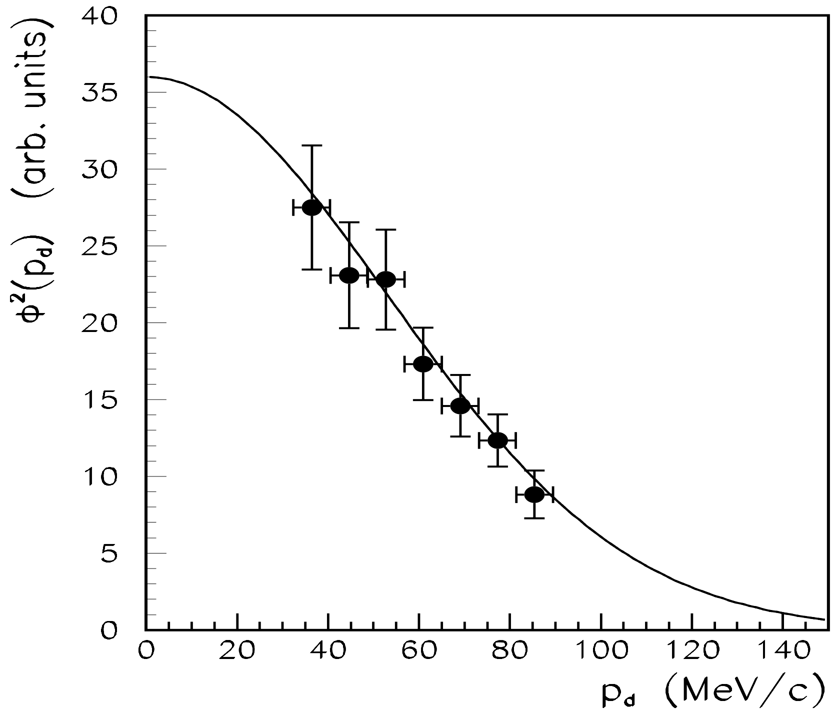
Comparison between the experimental momentum distribution and the theoretical one

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



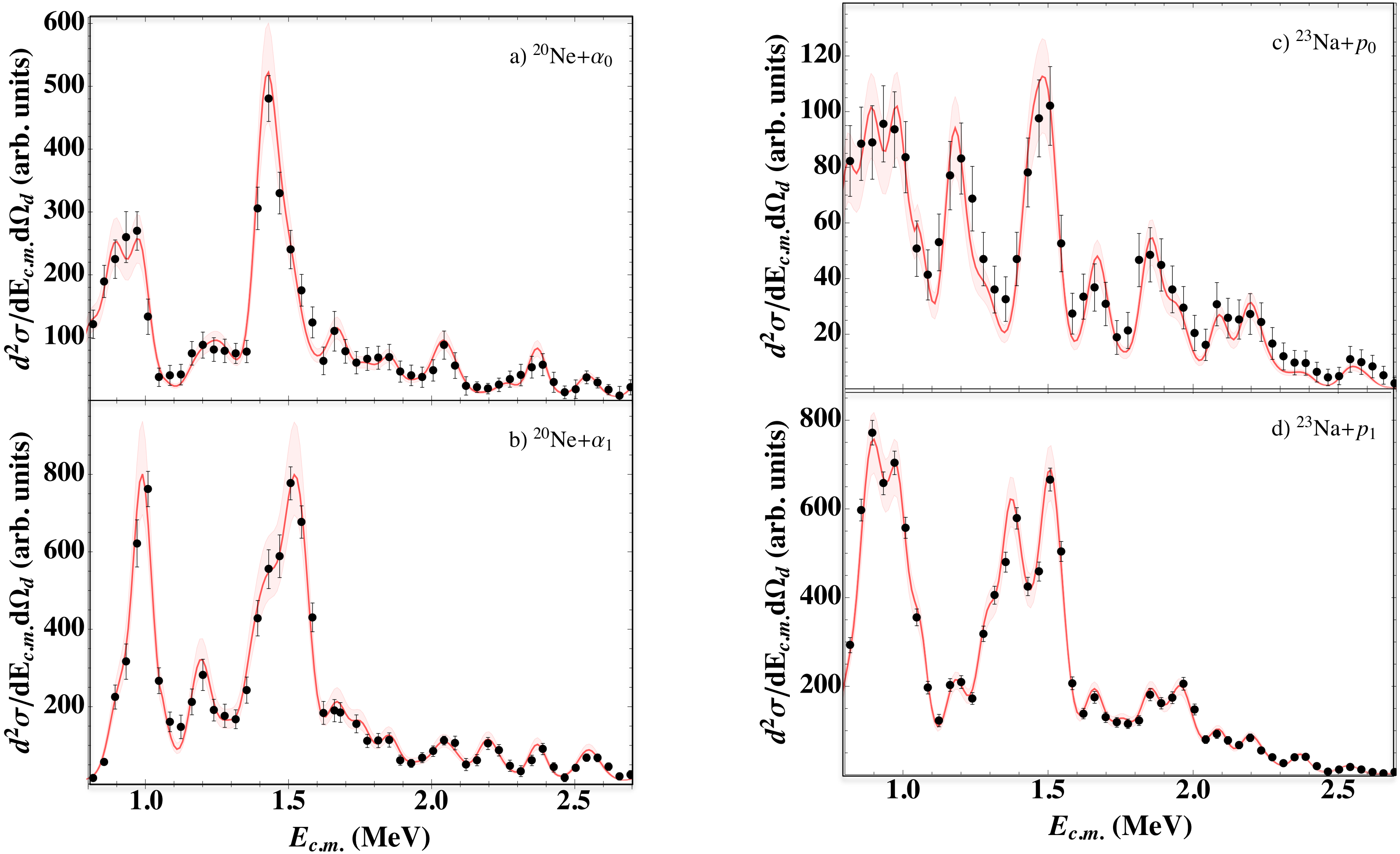
Momentum distribution of d inside ^{14}N from the Wood-Saxon ^{12}C-d bound state potential with standard geometrical parameters

r_0=1.25 fm, a=0.65 fm and V_0=54.427 MeV



Extraction of the two-body cross section

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



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

Reduced widths for known levels are fixed to reproduce their total and partial widths as in Abegg & Davis, PRC 1991

Conclusions

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

Fields of interest: astrophysics, applied physics, nuclear structure, fundamental interactions

However, guidance by direct data and normalization to them is necessary not to incur in systematic errors

→ A synergic application of direct and indirect approaches is the best guarantee of accurate reaction rates for astrophysical applications

THE ASFIN GROUP

C. Spitaleri, S. Cherubini, 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!

Comparison between two-body cross sections in the astrophysical region

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

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

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

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

$^{12}C+^{12}C \rightarrow \alpha_0+^{20}Ne$
$^{12}C+^{12}C \rightarrow \alpha_1+^{20}Ne^*$
$^{12}C+^{12}C \rightarrow p_0+^{23}Na$
$^{12}C+^{12}C \rightarrow p_1+^{23}Na^*$

Reduced widths for known levels are fixed to reproduce their total and partial widths as in Abegg & Davis, PRC 1991

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.