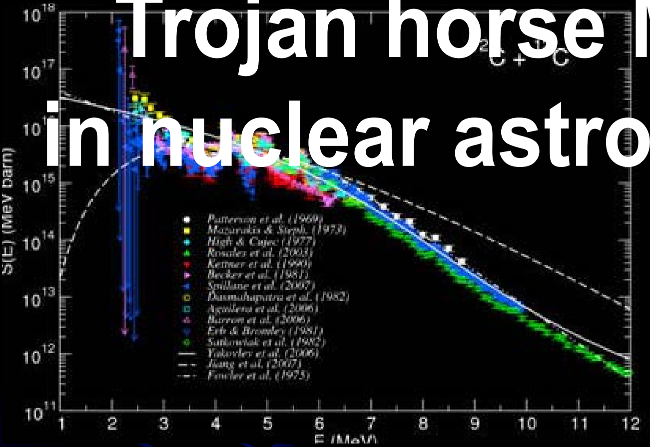
ENSAR2-NUSPRASEN Worpshop
ISOLDE - CERN, 6 December 2016

Trojan horse Method for resonant reactions in nuclear astrophysics including recent results



Aurora Tumino

Outlook

Basic features of the Trojan Horse Method

The Trojan Horse Method for resonant reactions

Recent results
two physics cases: the $^{18}F(p,\alpha)^{15}O$ reaction (unstable beam)
the $^{12}C(^{12}C,\alpha)^{20}Ne/^{23}Na$ reaction

Trojan Horse Method

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

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

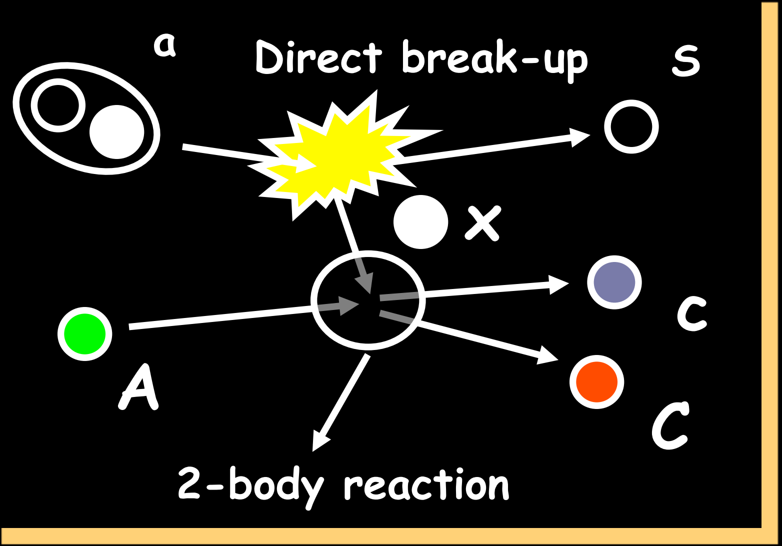
a: $x \oplus s$ clusters

Quasi-free mechanism

- ✓ only x - A interaction
- ✓ s = spectator ($p_s \sim 0$)

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

<u>NO electron screening</u>



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

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

Theoretical approaches to the THM

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

PWA hypotheses:

-A does not interact simultaneously with x and s
- The presence of s does not influence the A-x interaction

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

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

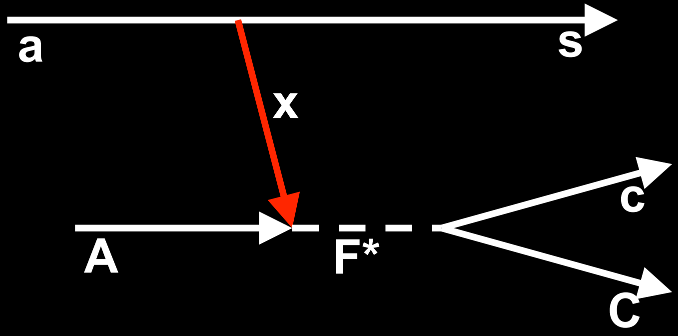
$|\phi|^2$ momentum distribution of *s* inside *a*

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

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

The Trojan horse method 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 and in particular the strenght

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

	Binary reaction	**Indirect reaction**	**E_{lab}**	**Q**	**Accelerator**	
1	^{7}Li(p, α)^{4}He	^{2}H(^{7}Li, α α)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, α)^{4}He	^{7}Li(^{3}He, α α)d	33	11.853	CYCLOTRON, Rez, Praha	**Tumino *et al.* EPJ, 2006**
3	^{6}Li(p, α)^{3}He	^{2}H(^{6}Li, α ^{3}He)n	14,25	1.795	**TANDEM 13 MV** LNS-INFN, Catania	**Tumino *et al.* PRC, 2003**
4	^{9}Be(p, α)^{6}Li	^{2}H(^{9}Be, α ^{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, α)^{8}Be	^{2}H(^{11}B, α ^{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, α)^{12}C	^{2}H(^{15}N, α ^{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, α)^{15}N	^{2}H(^{18}O, α ^{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, α)^{16}O	^{2}H(^{19}F, α ^{16}O)n	50	8.11	**TANDEM 13 MV** LNS-INFN, Catania	**La Cognata *et al.* ApJ Lett., 2011)**
9	^{17}O(p, α)^{14}N	^{2}H(^{17}O, α^{14}N)n	45	-1.032	**TANDEM 13 MV** LNS-INFN, Catania **TANDEM 11 MV** Notre Dame	**Sergi et al. PRC (R), 2010**

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
10	^{18}F(p ,α)^{15}O	^{2}H(^{18}F, α^{15}O)n	48		CYCLOTRON CNS-RIKEN, Tokyo	Cherubini et al. PRC 2015
11	^{10}B(p, α)^{7}Be	^{2}H(^{10}B, α^{7}Be)n	27		TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. PRC 2014
12	^{6}Li(d,α)^{4}He	^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He	5 4.8	22.372	TANDEM Demoscritos, Atene TANDEM, IRB, Zagreb	Cherubini *et al.* ApJ, 1996 Spitaleri *et al* .PRC, 2001
13	^{6}Li(d,α)^{4}He	^{6}Li(^{6}Li,$\alpha\alpha$)^{4}He			CYCLOTRON Rez, Praha	Pizzone et al. PRC, 2011
14	^{3}He(d,α)^{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			TANDEM 13 MV CIAE, Beijing	Preliminary results
19	^{6}Li(n,a)^{3}H	^{2}H(^{6}Li, t α)^{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	-0.407	TANDEM 11 MV Notre Dame TANDEM 13 MV LNS-INFN, Catania	Gulino et al. PRC(R) 2013
21	$^{13}C(a,n)^{16}O$	$^{13}C(^{6}Li, a\ n)^{16}O$			TANDEM FSU, Tallaassee, Florida, USA	La Cognata et al. PRL 2013
22	$^{12}C(^{12}C,a)^{20}Ne$ $^{12}C(^{12}C,p)^{23}Na$	$^{12}C(^{14}N,a^{20}Ne)^{2}H$ $^{12}C(^{14}N,p^{23}Na)^{2}H$			TANDEM 13 MV LNS-INFN, Catania	Preliminary results
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	$n(^{7}Be,a)^{4}He$	$^{2}H(^{7}Be,aa)^{1}H$			TANDEM LNL-INFN	Under analysis

Recent Results: the $^{18}F(p,\alpha)^{15}O$ Reaction

Its knowledge is crucial to understand nova explosion phenomena.
The γ-ray emission following the nova explosion is dominated by the 511 keV energy line, coming from the annihilation of positrons produced by the decay of radioactive nuclei. Among them, ^{18}F is the most important source.

Abundance determined by production vs. destruction rate → dominated by $^{18}F(p,\alpha)^{15}O$ reaction

astrophysical energy range: 100 – 400 keV

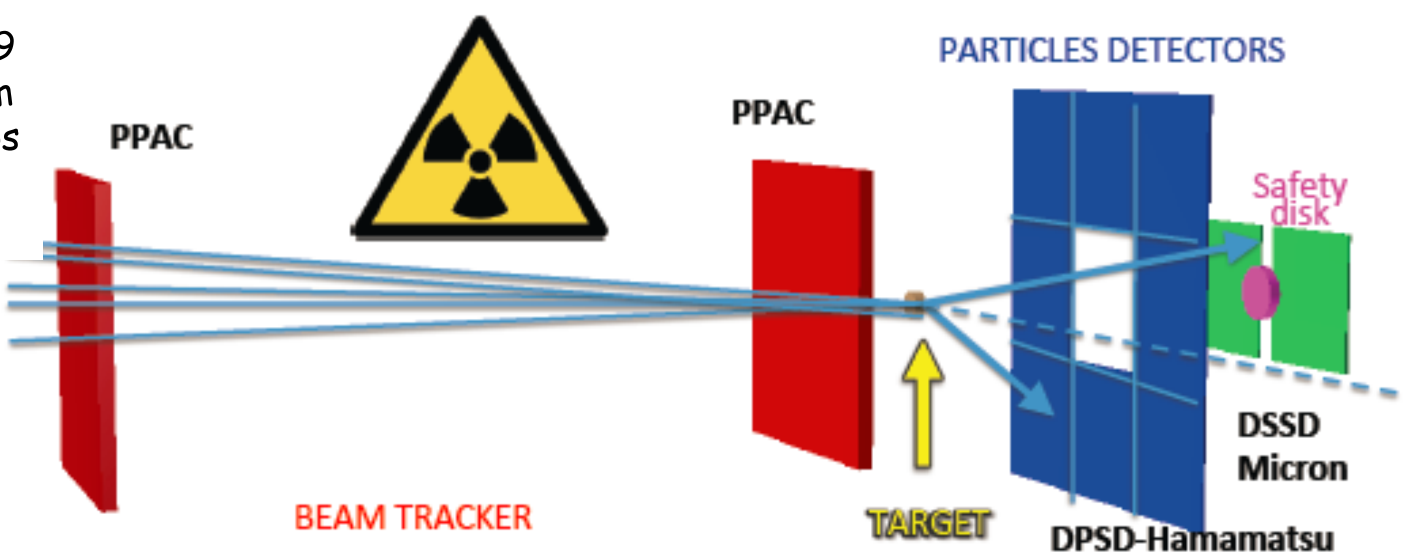
cross section dominated by the contribution of states in the ^{19}Ne compound nucleus around the $^{18}F+p$ threshold: still poor knowledge of some resonance parameters.

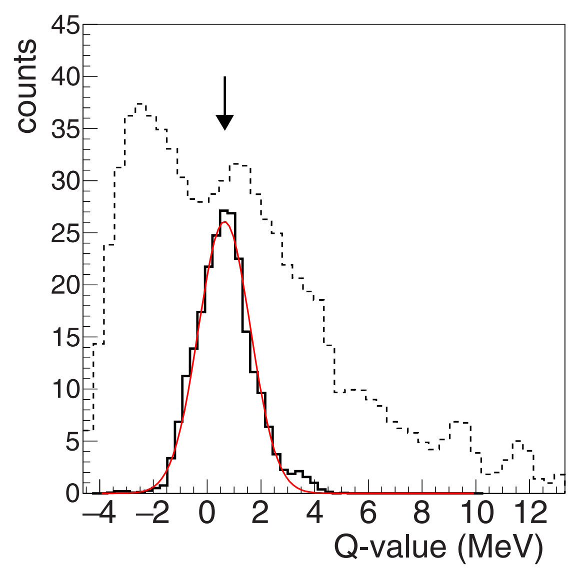
The ^{18}F(p,α)^{16}O experiment

three body reaction ^{2}H(^{18}F,α^{15}O)n

Experiments performed @ CRIB – CNS – RIKEN and
@ Cyclotron Laboratory, TAMU using a ^{18}F RIB → first THM experiments with RIBs

E_beam peaked at 47.9 MeV (FWHM 1.9 MeV), maximum beam intensity of 2×10^{6} pps and purity better than 98%.





Experimental Q-value spectrum without conditions (dashed line)
Q-value spectrum with particle selection (black solid histogram)

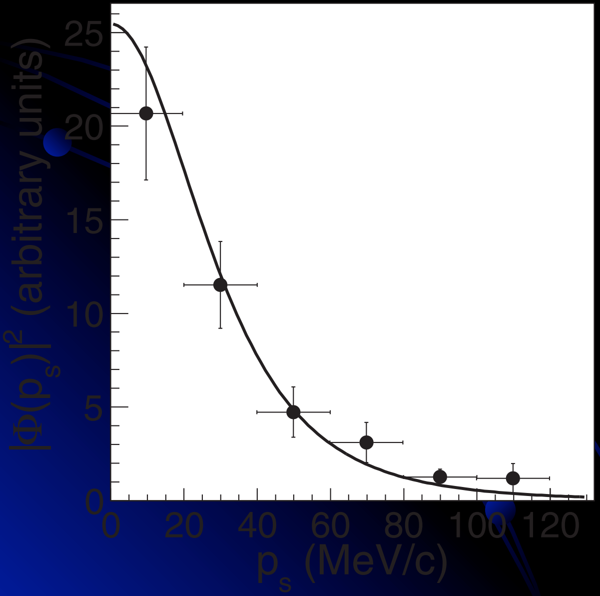
Single peak, centered at the value 0.668 MeV, very close to the theoretical Q value (0.658 MeV)
The arrow represents the theoretical Q value and the red line is a Gaussian fit with μ = 0.668 MeV and σ = 0.322 MeV

S. Cherubini et al. PRC 92 (2015) 015805
R.G. Pizzone et al. EpJ A (2016)

Selection of the Quasi-Free Mechanism

Comparison between the experimental momentum distribution and the theoretical one

$$|\Phi(\overrightarrow{p_p})|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_{15O}\, d\Omega_\alpha\, dE_\alpha}}{(KF)\left(\dfrac{d\sigma_{p18F}}{d\Omega}\right)^N}$$

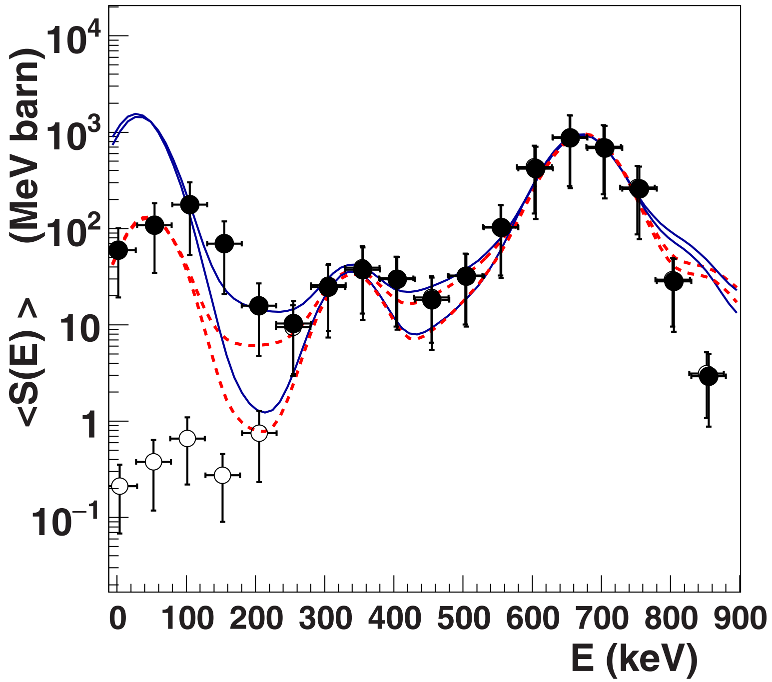


Solid circles: measured momentum distribution of the neutron inside deuteron using the $^2H(^{18}F,\alpha^{15}O)n$ reaction

Solid line: theoretical momentum distribution, given by the squared Hulthén function in momentum space

→ Good agreement implies that the reaction mechanism is QF and the THM equations can be applied to deduce the cross section of the $^{18}F(p,\alpha)^{15}O$ reaction from the one of the $^2H(^{18}F,\alpha^{15}O)n$ reaction

Recent Results: the ^{18}F(p,α)^{16}O Reaction



The ^{18}F(p,α)^{15}O astrophysical S factor from the present experiment.

Solid circles: THM experimental data with the assumption of $J^{\pi} = 3/2^{+}$ for the resonance at E=6460 keV (upper limit)

Open circles: ^{18}F(p,α)^{15}O astrophysical S factor corresponding to the assumption of $J^{\pi} = 5/2^{-}$ (lower limit)

Blue solid and red dashed lines: calculations reported and discussed in Beer et al. PRC 83 (2011) 042801 smeared to the present experimental resolution (σ = 53 keV). The difference is given by the alternative interference pattern adopted in the calculations.

Each pair of curves represents the upper and lower limit for each calculation

Around 700 keV: normalization region

Elsewhere: fair agreement with the dashed lines if $J^{\pi} = 3/2^{+}$ is assumed

C-burning: Status of Art

Results from $^{14}N + ^{12}C$ experiments for C-burning

importance: evolution of massive stars

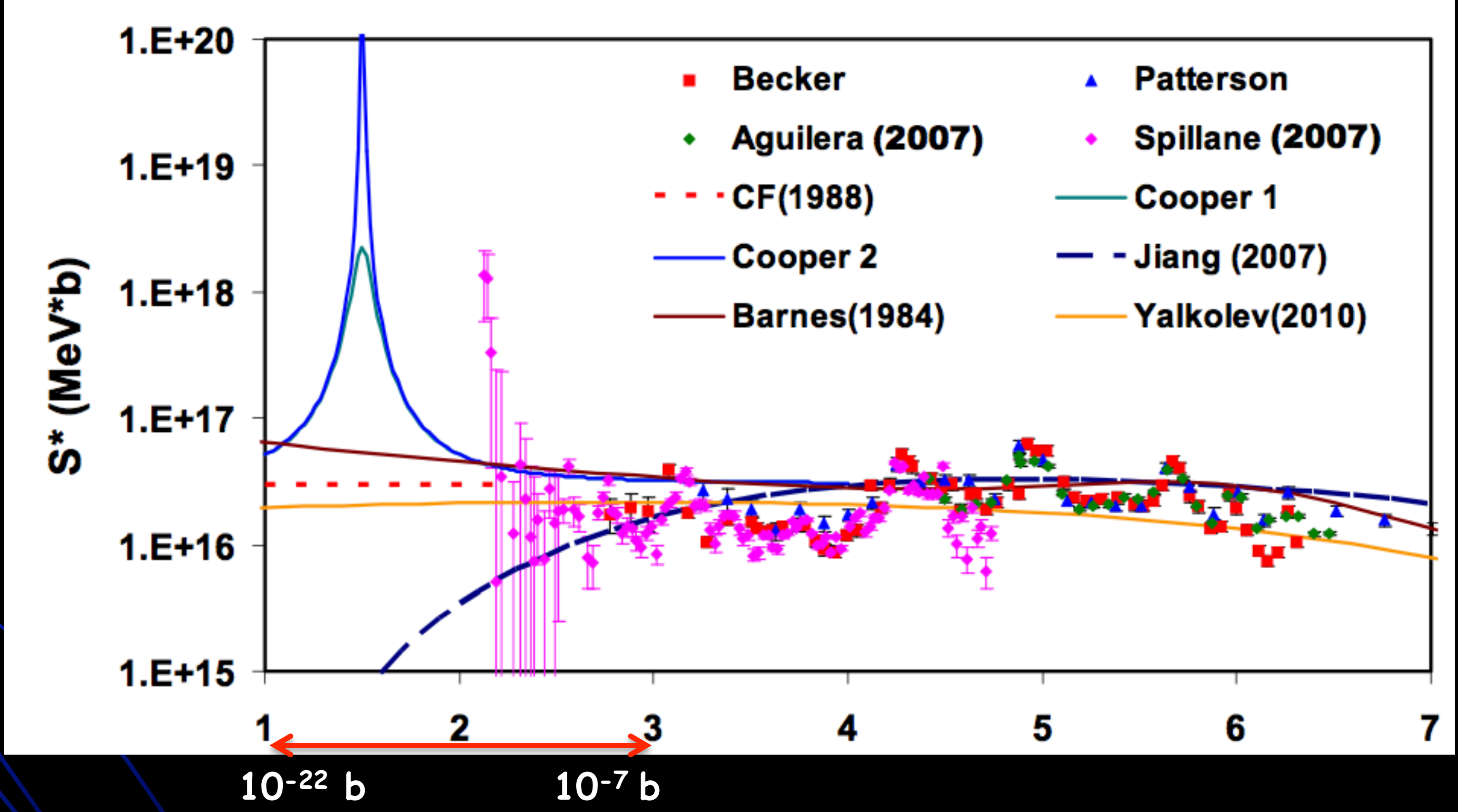
astrophysical energy: 1 – 3 MeV

minimum measured E: 2.1 MeV (by γ-ray +part. spectroscopy)

$^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$

$^{12}C + ^{12}C \rightarrow p + ^{23}Na$

extrapolations differ by 3 orders of magnitude complicated by the presence of resonant structures even in the low-energy part of the excitation function



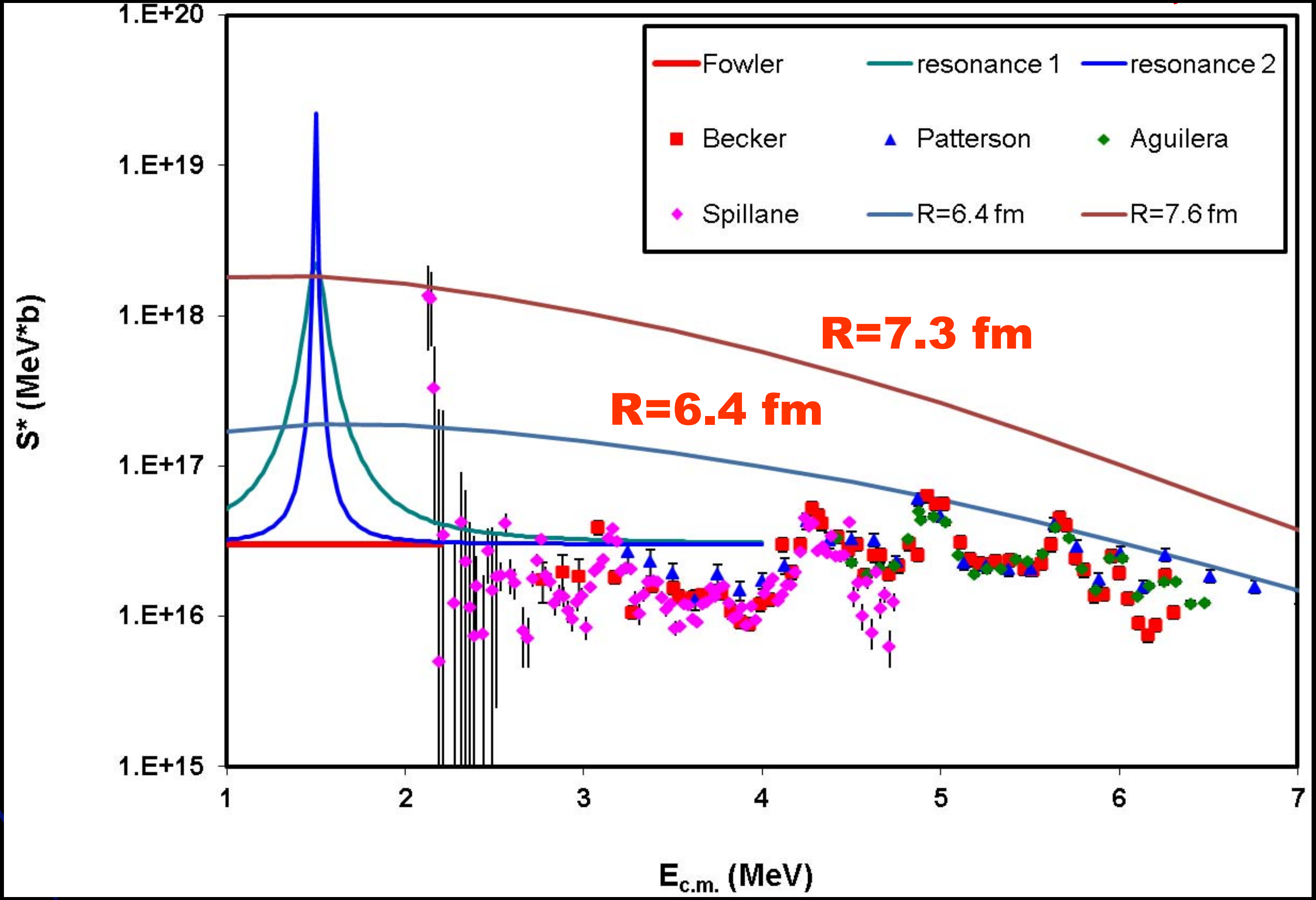
large uncertainties in astrophysical models of stellar evolution and nucleosynthesis

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

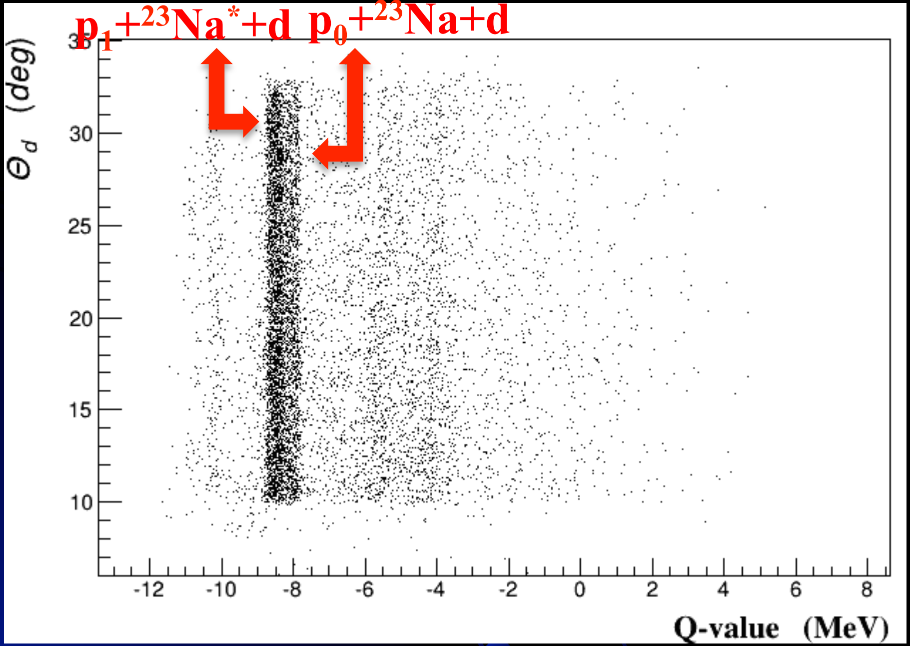
Our Experiment with theTHM

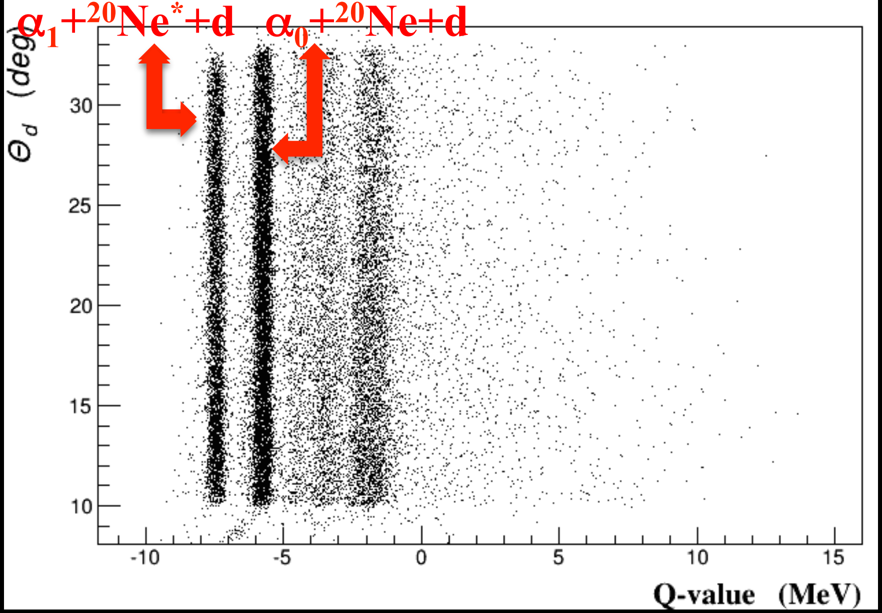
$^{12}C(^{12}C,\alpha)^{20}Ne$ and **$^{12}C(^{12}C,p)^{23}Na$** reactions via the Trojan Horse Method applied to the **$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$** and **$^{12}C(^{14}N,p^{23}Na)^{2}H$** three-body processes

^{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)

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

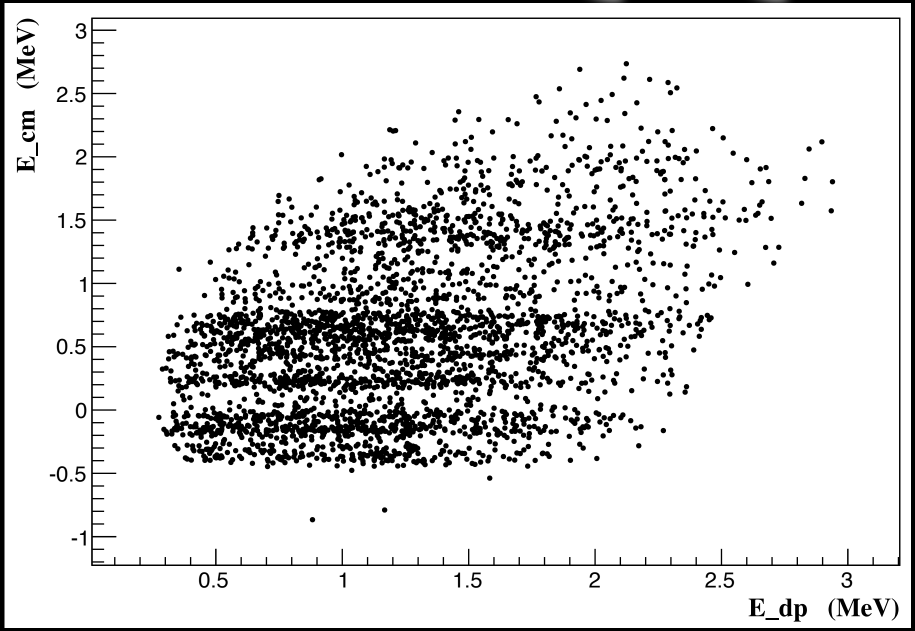




m_{14N}

A. Tumino et al. "12th International Conference on Nucleus-Nucleus Collisions 2015", Conference Proceedings Vol.109, SIF, 2016

Investigating the reaction mechanism

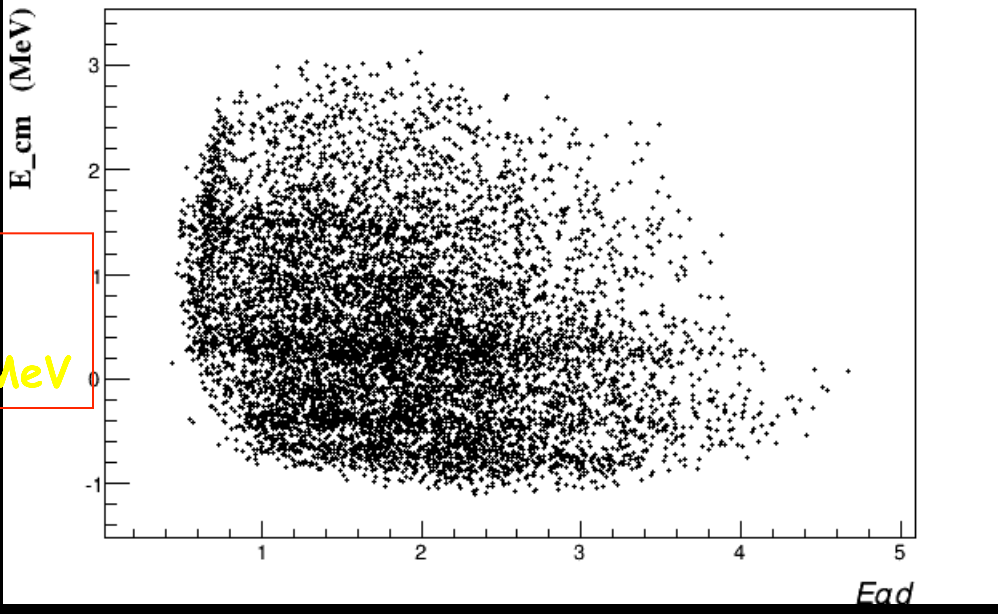


$^{14}N+^{12}C\rightarrow p_1+^{23}Na^*+d$

$E_{cm}=E_{(23Na-p)}-2.221-0.440$ MeV

E_cm=0 corresponds to $E^*(^{24}Mg)=13.933$ MeV

$^{14}N+^{12}C\rightarrow \alpha_0+^{20}Ne+a$



$E_{cm}=E_{(20Ne-a)}-4.617$ MeV

E_cm=0 corresponds to $E^*(^{24}Mg)=13.933$ MeV

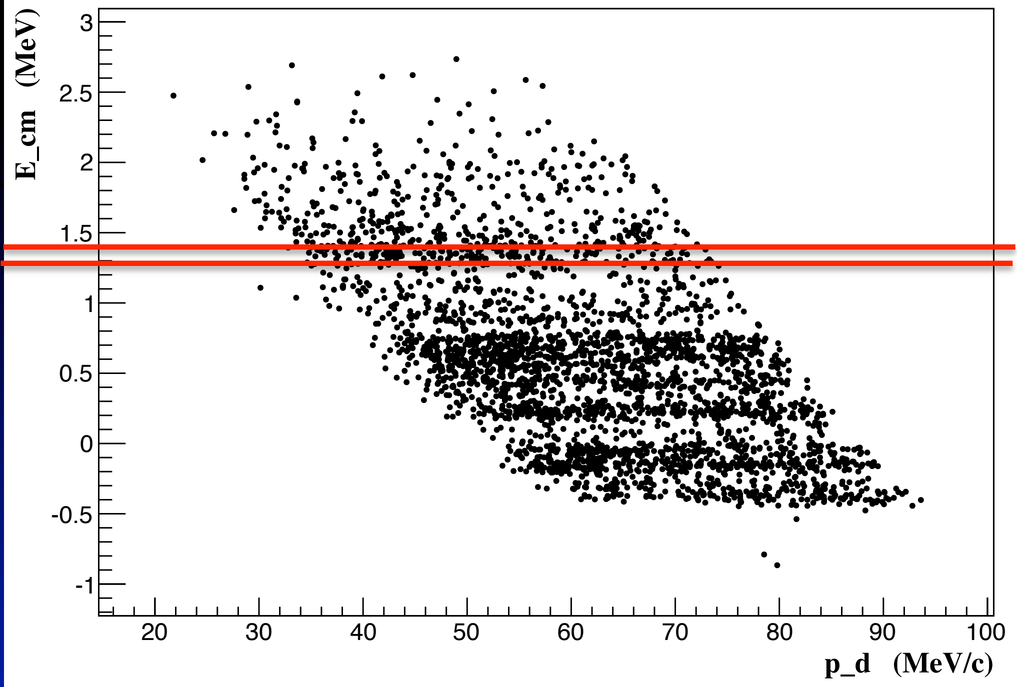
Selection of the quasi-free mechanism

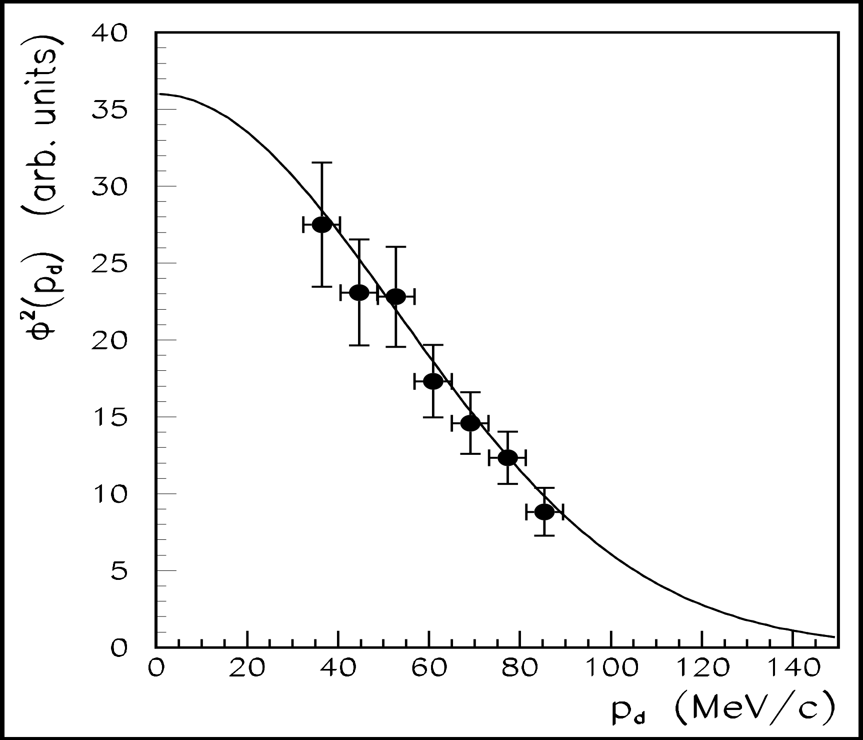
Comparison between the experimental momentum distribution and the theoretical one

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

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

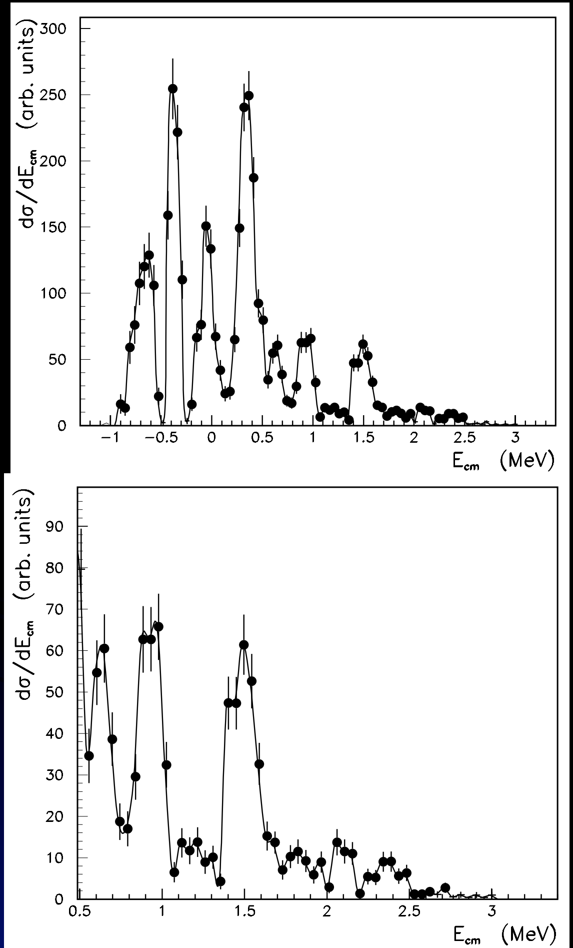
r_0=1.25 fm, a=0.65 fm and V_0=54.427 MeV



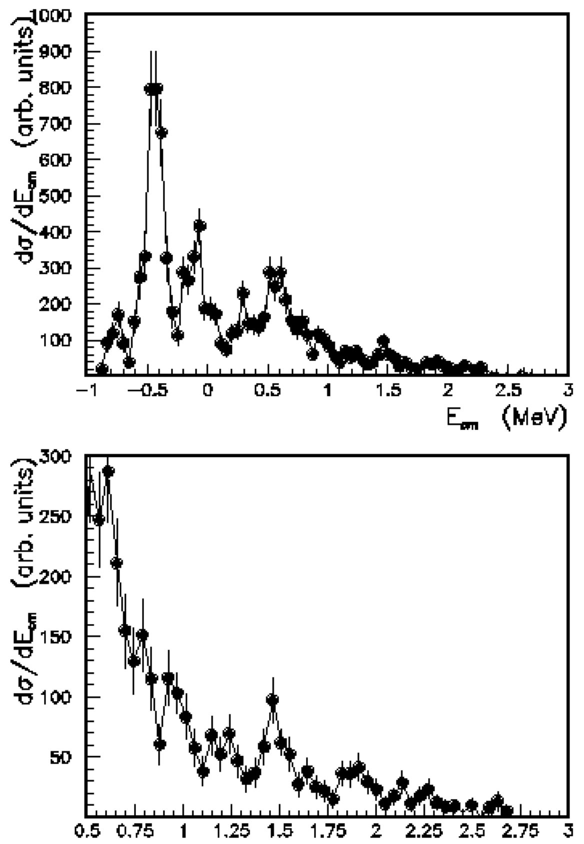


Extraction of the two-body cross section

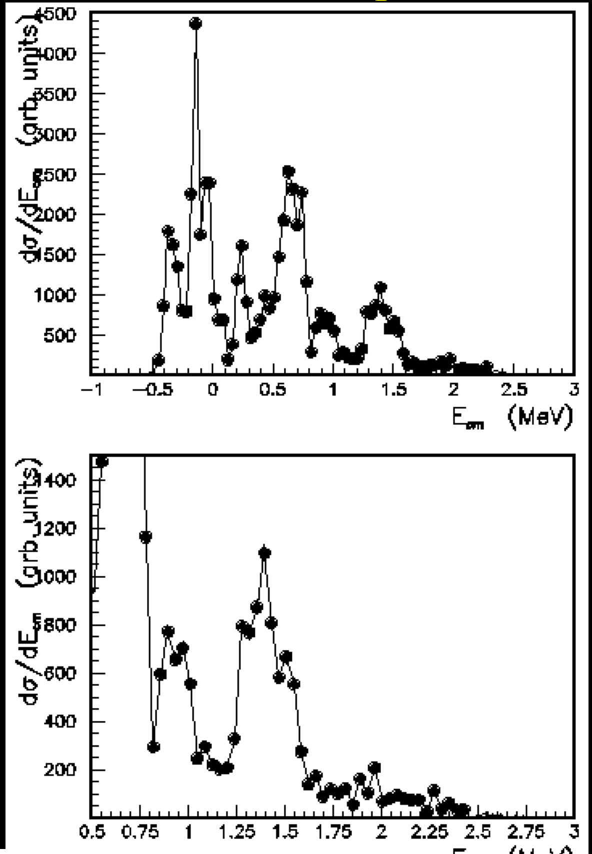
$^{12}C+^{12}C \rightarrow \alpha_0+^{20}Ne$



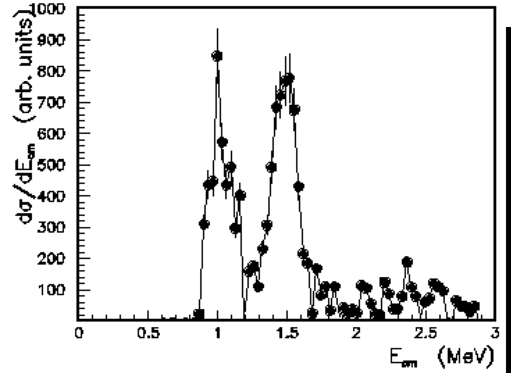
$^{12}C+^{12}C \rightarrow p_0+^{23}Na$



$^{12}C+^{12}C \rightarrow p_1+^{23}Na^*$



$^{12}C+^{12}C \rightarrow \alpha_1+^{20}Ne^*$



Comparison between two-body cross sections in the astrophysical region

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

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

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

$D_i(E_{xA})$ = 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.

Some near future with RIBS

Big Bang Nucleosynthesis and Light Element Depletion:

^{7}Be(n,a)^{4}He and ^{7}Be(n,p)^{7}Li

Insights of the massive star forming conditions (mainly from explosive phase) as well as of the astrophysical context of the Solar System formation

^{26}Al(n,p)^{26}Mg and ^{26}Al(n,a)^{23}Na reactions

Other nuclei of interest: ^{22}Na (Novae)
^{22}Mg and ^{26}Si in the ap-process in X-ray bursts

Notice: Standard approaches cannot be used to measure short-lived RIBs + n reactions → need of **indirect methods** such as THM, ANC, surrogate reactions …

The collaboration

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