CRITICAL STABILITY WORKSHOP
Erice, October 9-15, 2011

New advances in the Trojan Horse Method as an indirect approach to Nuclear Astrophysics

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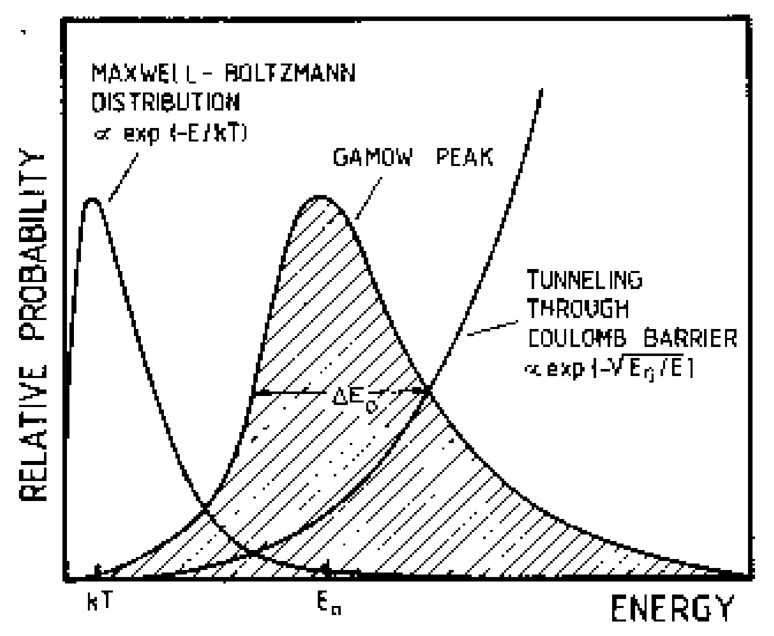
The Trojan Horse Method

Indirect technique to measure charged particle 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.

Why we need indirect techniques?

Charged particle cross section measurements at astrophysical energies

σ ~picobarn ⇒ Low signal-to-noise ratio due to the Coulomb barrier between the interacting nuclei

Extrapolation from the higher energies by using the

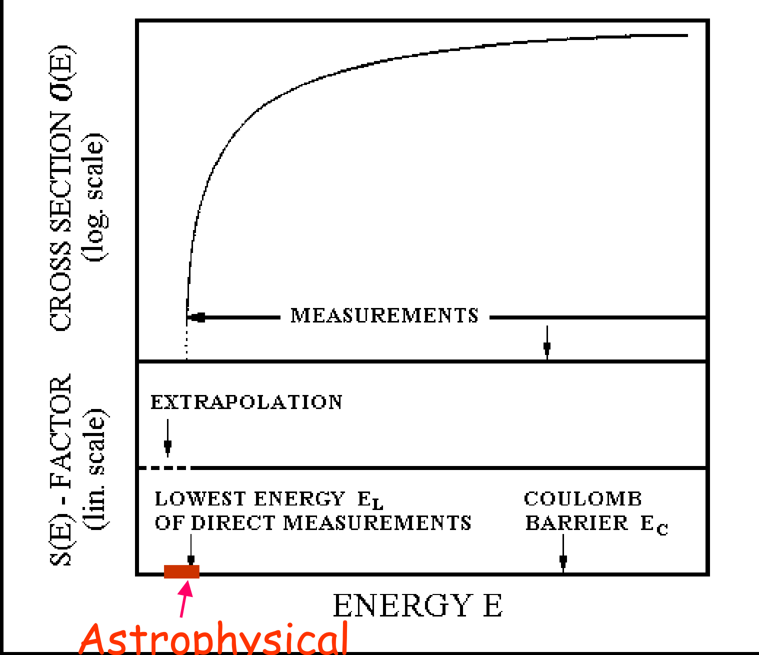
ASTROPHYSICAL FACTOR

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

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**



Astrophysical energies

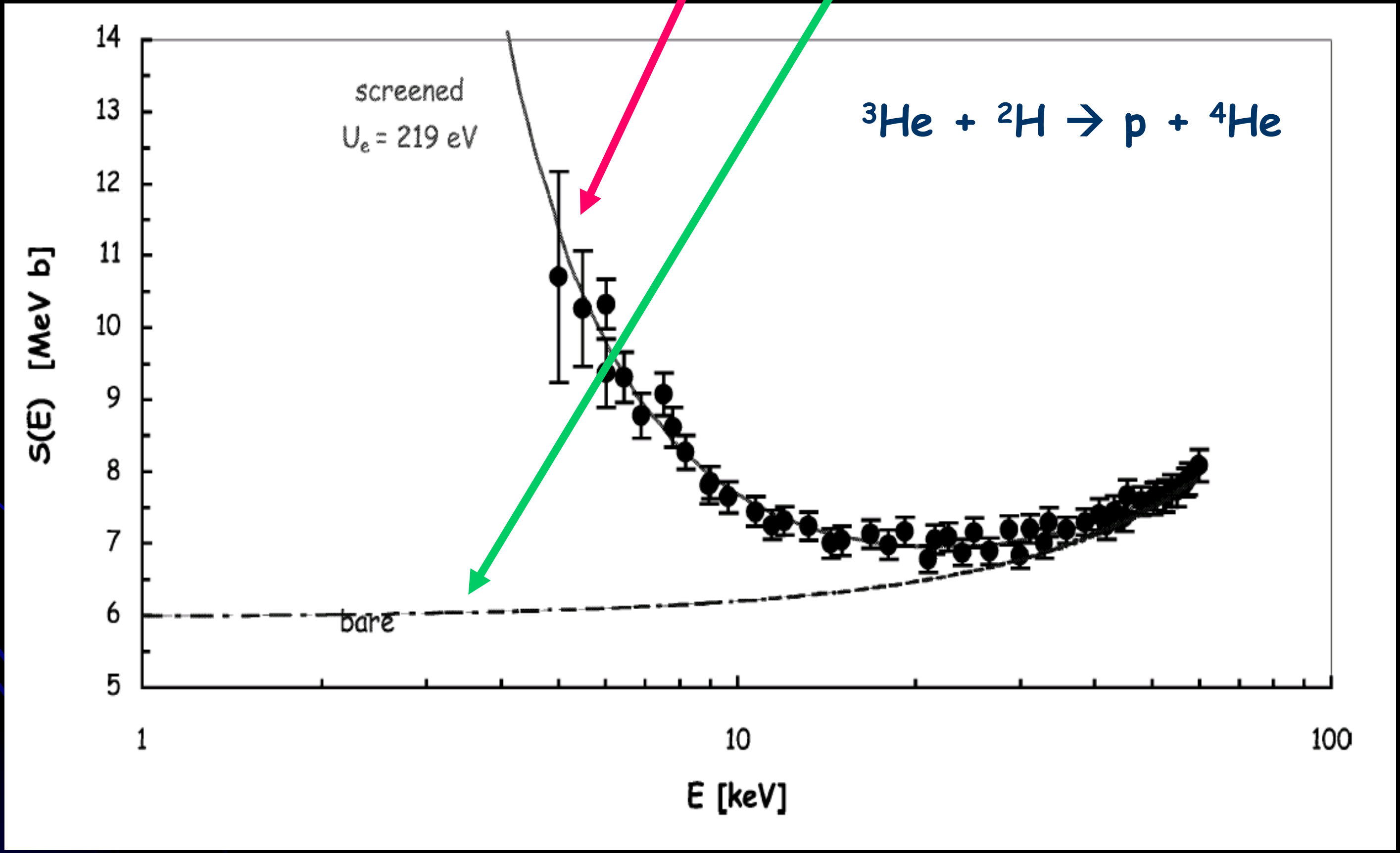
- **> to increase the number of detected particles**
- **> to reduce the background**

…but… further problem at astrophysical energies → → → →

Electron Screening

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

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



Electron Screening

In astrophysical plasma:

- the screening, due to free electrons in plasma, can be different → we need $S(E)_b$ to evaluate reaction rates

→

A theorical approach to extract the electron screening potential U_e in the laboratory is needed

→

Experimental studies of reactions involving light nuclides have shown that the **observed** exponential enhancement of the cross section at low energies were in all cases significantly larger

(about a factor of 2)

than it could be accounted for from available atomic-physics model, i.e. the adiabatic limit **$(U_e)_{ad}$**

Although we try to improve experimental techniques to measure at very low energy → →

$S_b(E)$-factor extracted from extrapolation of higher energy data

… new methods are necessary

- to measure cross sections at never reached energies
- to get independent information on U_e

-> -> -> INDIRECT METHODS

❖ **Asymptotic Normalization Coefficients (ANC)**

…to extract direct capture cross sections using peripheral transfer reactions

❖ **Coulomb dissociation**

…to study radiative capture reactions

❖ **Trojan Horse Method (THM)**

…to extract charged particle reaction cross sections using the quasi-free mechanism…

Trojan Horse Method

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

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

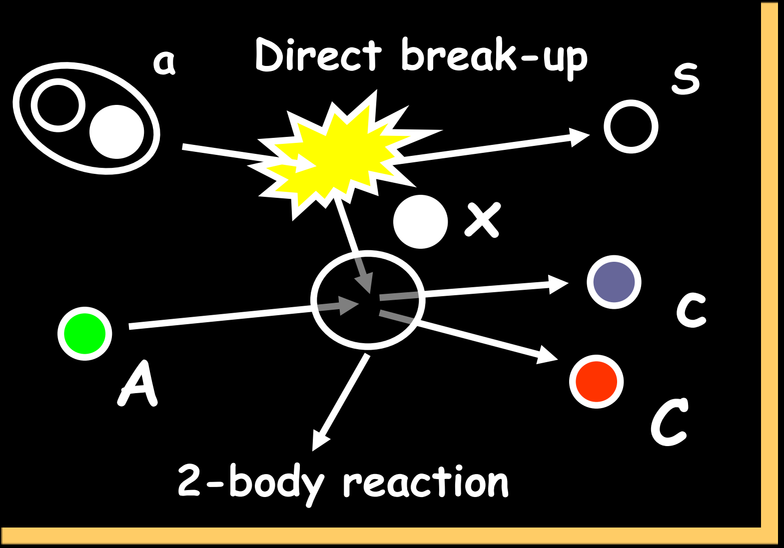
a: $x \oplus s$ clusters

Quasi-free mechanism

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

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

<u>NO electron screening</u>



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

↓

plays a key role in compensating for the beam energy

→ $E_{q.f.} \approx 0$!!!

Theoretical approaches to the THM

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

PWIA hypotheses:

-A does not interact simultaneously with x and s

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

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

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*

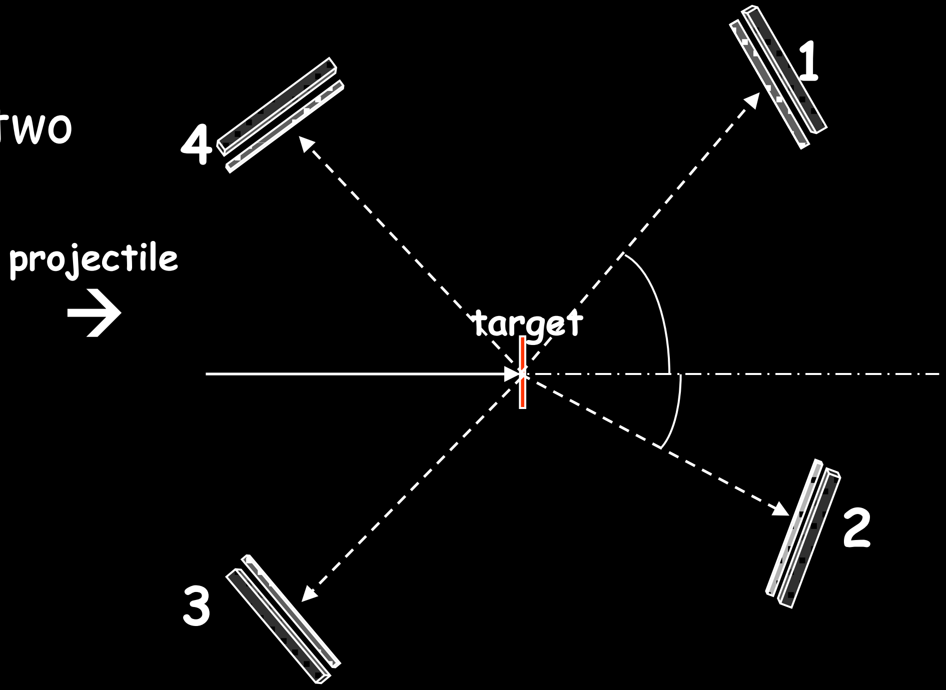
$d\sigma^N/d\Omega$ Nuclear cross section for the A+x→C+c reaction

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

Typical experimental set-up

Very simple, consisting of few telescopes

Trigger: coincidence detection of two particles



Telescopes:

▭ ΔE-detector: Silicon detectors (10 to 30 μm thick) or Ionization Chambers

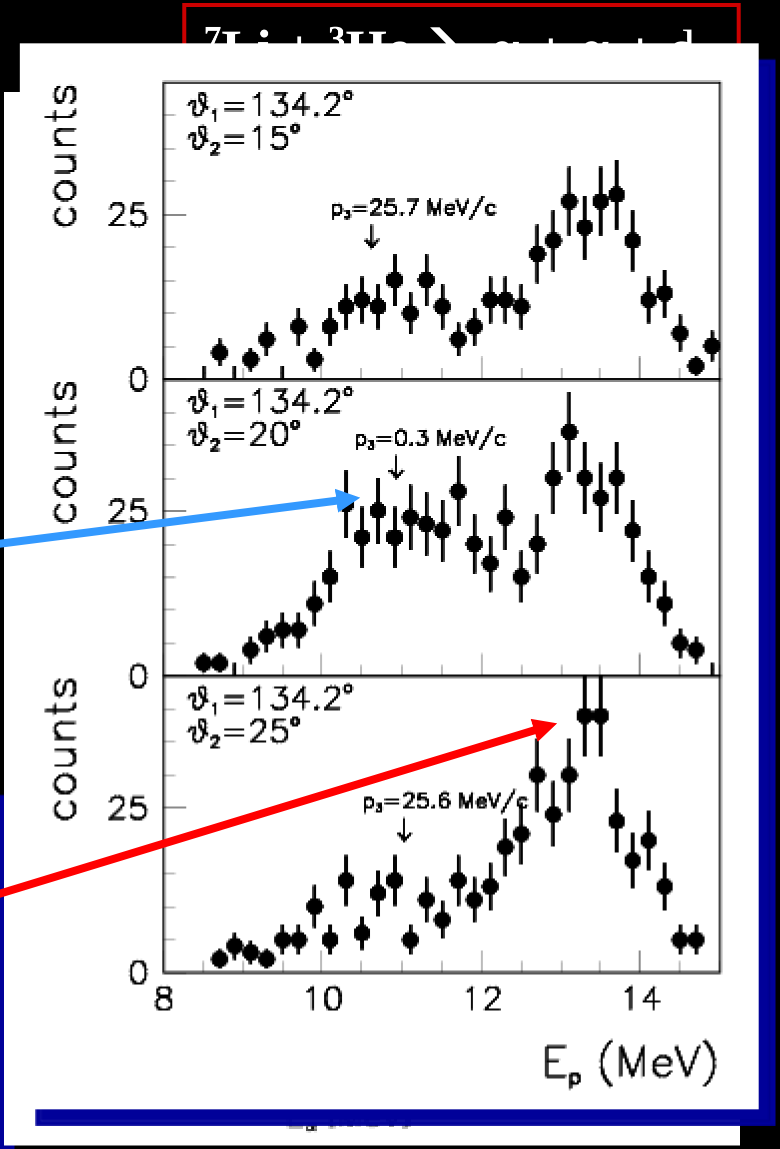
▭ E-detector: Position sensitive detector (500 to 1000 μm thick)

Selection of quasi-free contribution

Angular correlation analysis

coincidence spectra projected onto an E axis for a fixed θ_1 and different θ_2

events corresponding to a quasi-free mechanism show an enhancement of the yield for p_3 approaching zero (QF angles).



Example for the ^{3}He + ^{6}Li → α + p + α: ^{4}He-d relative motion within ^{6}Li in s-wave

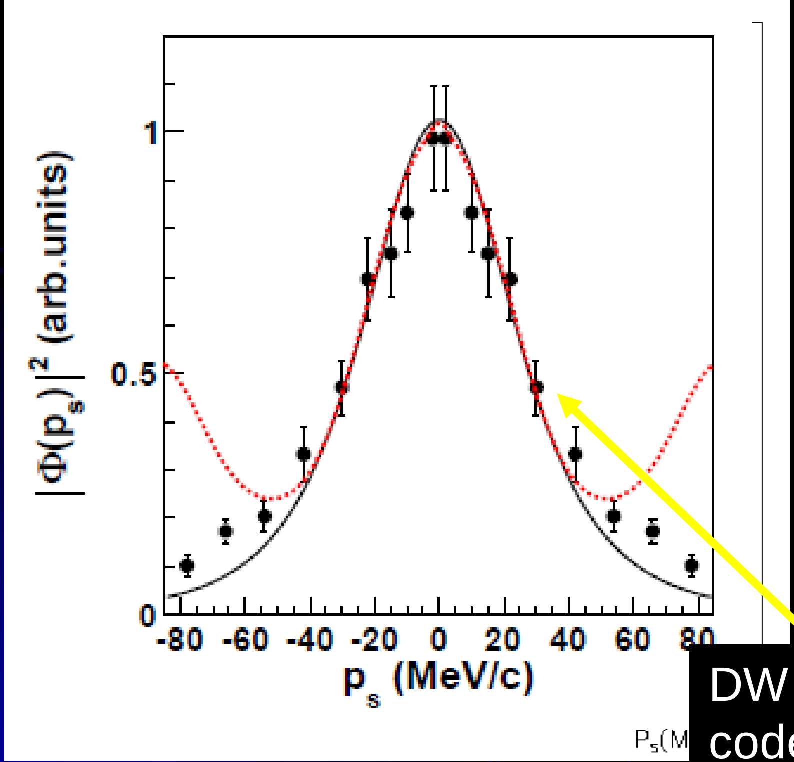
Large background contribution: sequential decay through the ^{8}Be first excited state (already seen in a previous experiment (Zadro et al. (1987))

Selection of quasi-free contribution

Momentum Distribution

An observable which turns out to be very sensitive to the reaction mechanism is the shape of the experimental momentum distribution

$^{18}O + p \rightarrow \alpha_o + {}^{15}N$



DWBA distribution with FRESCO code **(M.L. Sergi et al PRC (R) (2010))**

The extracted experimental momentum distribution is compared with the theoretical one. For p-n system it is given by the Hulthén wave function in momentum space:

$$G^2(p_s)=N\left[\frac{1}{a^2+p_s^2}-\frac{1}{b^2+p_s^2}\right]^2$$

N: normalization parameter

$a = 0.2317\ \mathrm{fm}^{-1}$

$b = 1.202\ \mathrm{fm}^{-1}$

Extraction of the 2-body cross section

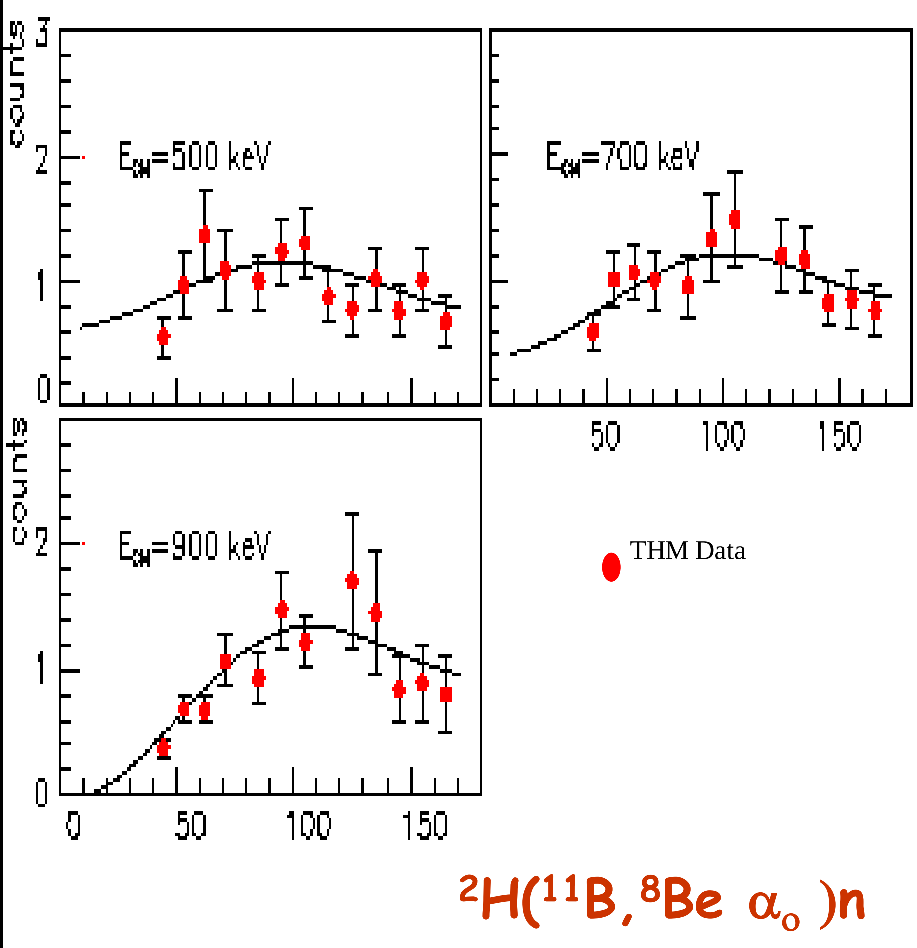
Monte Carlo simulation of the three-body cross section under the assumptions:

- PWIA/DWBA approach

- Quasi-free contribution is the only reaction mechanism

- a p_s window of 20 MeV/c is considered

$$\sigma_{bare}(E)=\frac{\text{Coincidence yield}}{KF\ |\phi(p_s)|^2\ P_0^{-1}}$$



$^2H(^{11}B,^8Be\ \alpha_o)n$

Spitaleri et al, PRC 69, 55806 (2004)

The indirect THM cross section $\sigma_{bare}(E)$ is normalized to the direct data at high energies, where the electron screening is negligible

Table XI.1. Two-Body reactions studied via Trojan Horse Method.

	Reaction	Indirect reaction	E_{inc} (MeV)	Q_2 (MeV)	THM-Nucl. Cluster-x
1	$^{7}\mathrm{Li}(p,\alpha)^{4}\mathrm{He}$	$^{2}\mathrm{H}(^{7}\mathrm{Li},\alpha\ \alpha)n$	19-22	15.122	^{2}H (p)
2	$^{7}\mathrm{Li}(p,\alpha)^{4}\mathrm{He}$	$^{7}\mathrm{Li}(^{3}\mathrm{He},\alpha\ \alpha)^{2}H$	33	11.853	^{3}He (p)
3	$^{6}\mathrm{Li}(p,\alpha)^{3}\mathrm{He}$	$^{2}\mathrm{H}(^{6}\mathrm{Li},a\ ^{3}\mathrm{He})n$	14,25	1.795	^{2}H (p)
4	$^{6}\mathrm{Li}(d,\alpha)^{4}\mathrm{He}$	$^{6}\mathrm{Li}(^{3}\mathrm{He},\alpha\ \alpha)^{1}\mathrm{H}$	17.5	16.879	^{3}He (d)
5	$^{6}\mathrm{Li}(d,\alpha)^{4}\mathrm{He}$	$^{6}\mathrm{Li}(^{6}\mathrm{Li},\alpha\ \alpha)^{4}\mathrm{He}$	5	22.372	^{6}Li (d)
6	$^{9}\mathrm{Be}(p,\alpha)^{6}\mathrm{Li}$	$^{2}\mathrm{H}(^{10}\mathrm{Be},\alpha\ ^{6}\mathrm{Li})n$	22.35	-0.099	^{2}H (p)
7	$^{10}\mathrm{B}(p,\alpha)^{7}\mathrm{Be}$	$^{2}\mathrm{H}(^{10}\mathrm{B},\alpha\ ^{7}\mathrm{Be})n$	24.4	-1.079	^{2}H (p)
7	$^{11}\mathrm{B}(p,\alpha)^{8}\mathrm{Be}$	$^{2}\mathrm{H}(^{11}\mathrm{B},\alpha\ ^{8}\mathrm{Be})n$	27	6.36	^{2}H (p)
8	$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$	$^{2}\mathrm{H}(^{15}\mathrm{N},\alpha\ ^{12}\mathrm{C})n$	60	2.74	^{2}H (p)
9	$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$	$^{2}\mathrm{H}(^{17}\mathrm{O},\alpha\ ^{14}\mathrm{N})n$	45	-1.032	^{2}H (p)
10	$^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$	$^{2}\mathrm{H}(^{18}\mathrm{O},\alpha\ ^{15}\mathrm{N})n$	54	1.76	^{2}H (p)
11	$^{3}\mathrm{He}(d,p)^{4}\mathrm{He}$	$^{6}\mathrm{Li}(^{3}\mathrm{He},p\ ^{4}\mathrm{He})^{4}\mathrm{He}$	5,6	16.879	^{6}Li (d)
12	$^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$	$^{2}\mathrm{H}(^{6}\mathrm{Li},p\ ^{3}\mathrm{He})^{4}\mathrm{He}$	14	2.59	^{6}Li (d)
13	$^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$	$^{2}\mathrm{He}(d,p\ ^{3}\mathrm{H})^{1}\mathrm{H}$	18	-1.46	^{3}He(d)
14	$^{2}\mathrm{H}(d,n)^{3}\mathrm{He}$	$^{2}\mathrm{H}(d,n\ ^{3}\mathrm{He})^{1}\mathrm{H}$	18	-2.224	^{3}He(d)
15	$^{12}\mathrm{C}(\alpha,\alpha)^{12}\mathrm{C}$	$^{6}\mathrm{Li}(^{12}\mathrm{C},\alpha\ ^{12}\mathrm{C})^{2}\mathrm{H}$	20,16	0	^{6}Li (α)
16	$^{6}\mathrm{Li}(n,t)^{4}\mathrm{He}$	$^{2}\mathrm{H}(^{6}\mathrm{Li},t\ \alpha)^{1}\mathrm{H}$	14	2.224	^{2}H (n)
17	$^{1}\mathrm{H}(p,p)^{1}\mathrm{H}$	$^{2}\mathrm{H}(p,p\ p)n$	5,6	2.224	^{2}H(p)
18	$^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$	$^{19}\mathrm{F}(p,\alpha\ ^{16}\mathrm{O})n$	50	8.11	^{2}H (p)

Reactions recently studied

$^6Li + d \rightarrow \alpha + \alpha$ via $^6Li + ^6Li \rightarrow \alpha + \alpha + \alpha$

S_0 = 16.9 MeV b

U_e (ad)	U_e (THM) ^6Li+d	U_e (Dir) ^6Li+d
186 eV	340 ± 50 eV	330 ± 120 eV

$^7Li+p \rightarrow \alpha+\alpha$ via $^7Li+d \rightarrow \alpha+\alpha+n$

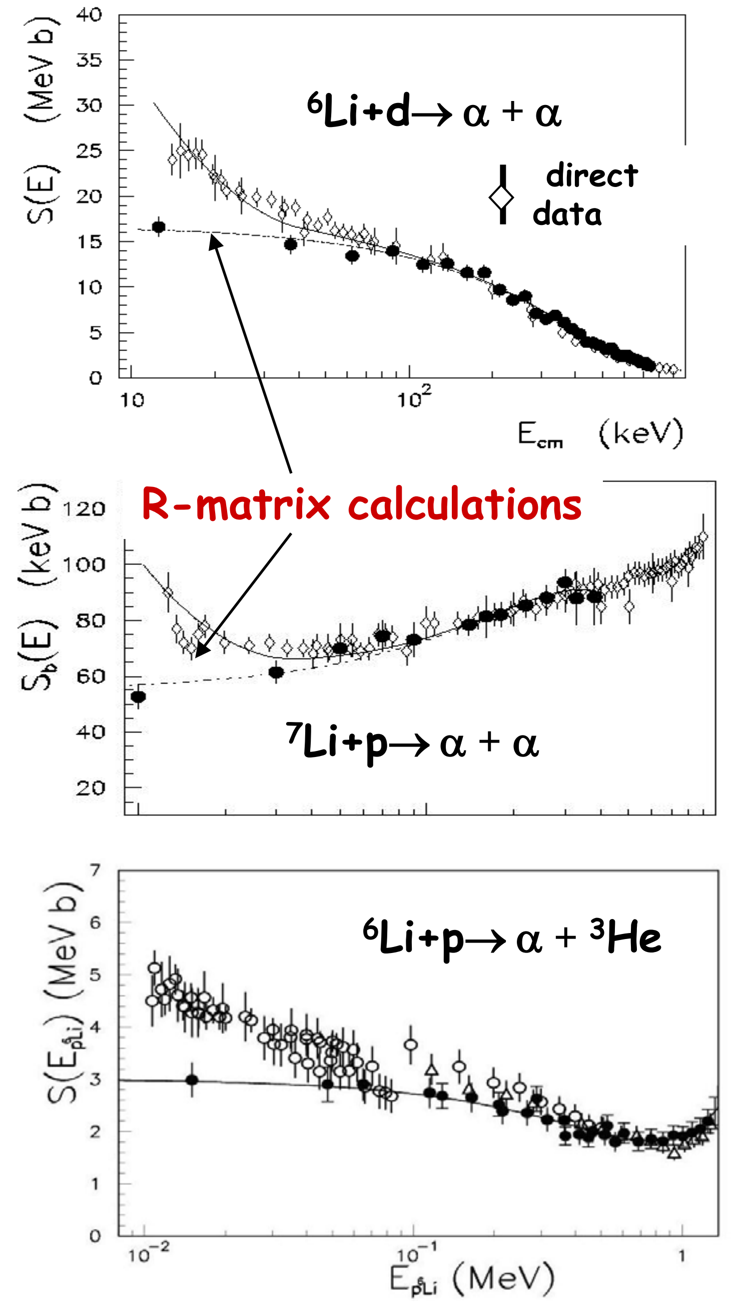
S_0 = 55 ± 3 keV b

U_e (ad)	U_e (THM) ^7Li+p	U_e (Dir) ^7Li+p
186 eV	330 ± 40 eV	300 ± 160 eV

$^6Li+p \rightarrow \alpha + ^3He$ via $^6Li+d \rightarrow \alpha + ^3He+n$

S_o = 3.± 0.9 MeV b

U_e (ad)	U_e(THM) ^6Li+p	U_e(Dir) ^6Li+p
186 eV	435 ± 40 eV	440 ± 80 eV



R-matrix calculations

C. Spitaleri et al., PRC60 (1999)055802

C. Spitaleri et al., PRC63 (2001) 005801

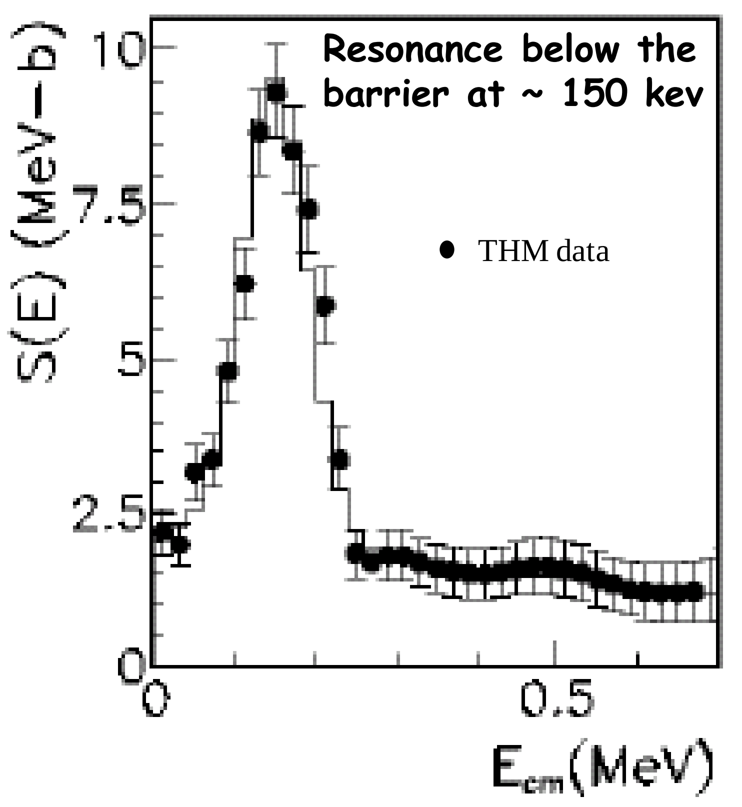
A. Tumino et al., PRC67 (2003) 065803

$^{11}B(p,\alpha_0)^8Be$: direct and indirect data

- **Astrophysical factor**

Direct reaction at astrophysical energies proceeds through an intermediate state of ^{12}C at 16.1 MeV → Very important result: resonance reproduced through the indirect approach!

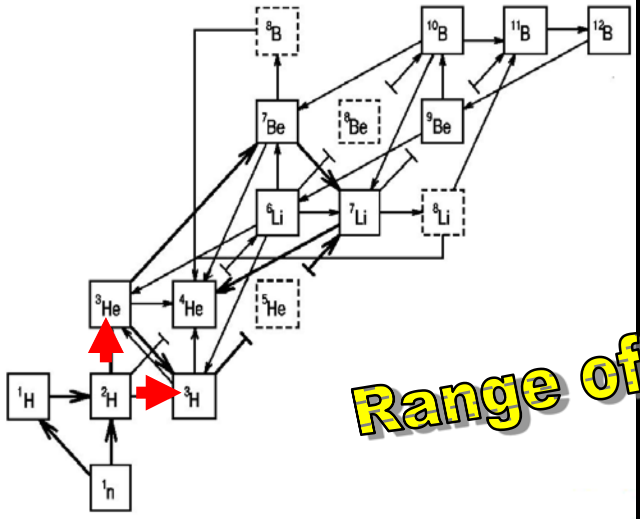
$S(0)_b = 2.2 \pm 0.3$ MeV b



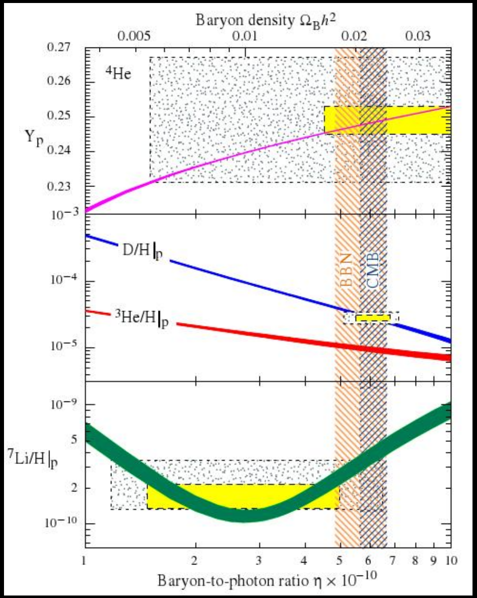
C. Spitaleri et al., PRC 69 (2004) 055806
L. Lamia et al., submitted to JPG

2H+2H reactions in the primordial nucleosynthesis

T≈10^9÷10^{11} K – 0.1÷10 MeV t ≈ 10^2÷10^3 s



Range of interest: 50-350 keV



Other contexts of interest

- In the *Pre Main Sequence* phase (PMS) of the stellar

- In the future fusion power plants: nuclear energy production with inertial confinement

Range of interest : 0-30 keV

d+d->3He+n two-body cross section

Comparison between THM data (black dots) and direct data (colored symbols)

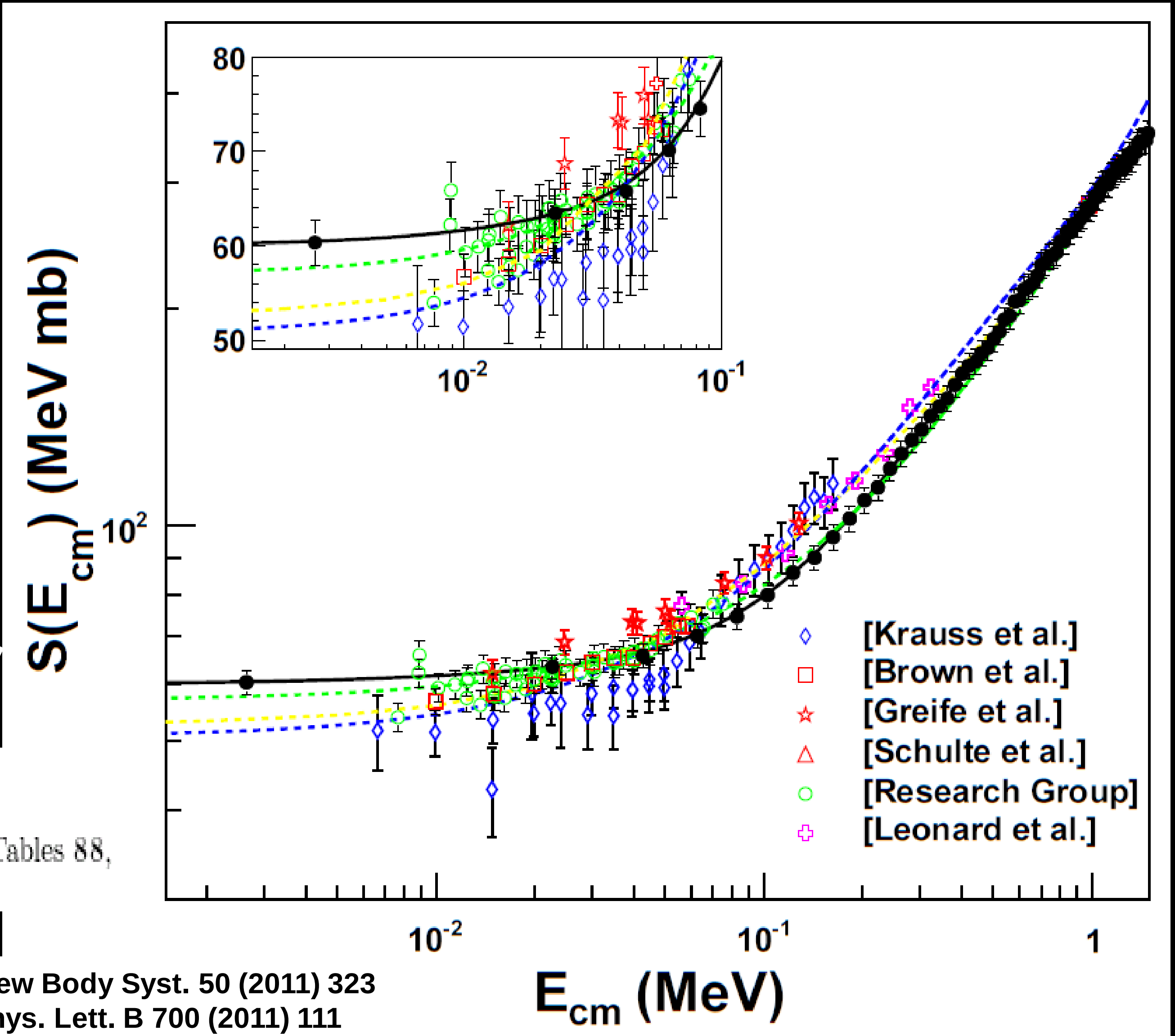
<u>Yellow line:</u> polynomial expansion reported in the NACRE compilation

<u>Blue line:</u> calculation from the Cyburt compilation

<u>Green line:</u> calculation by P. Descouvemnont et al.

C. Angulo *et al.*, Nucl. Phys. A656, 3 (1999)
R.H. Cyburt, Phys. Rev. D70, 023505 (2004)
P. Descouvemont *et al.*, At. Data Nucl. Data Tables 88, 203 (2004)

$^2H(^3He,n\ ^3He)p$



A. Tumino et al., Few Body Syst. 50 (2011) 323
A.Tumino et al., Phys. Lett. B 700 (2011) 111

d+d -> 3H+p two-body cross section

Symbols and lines with same meaning as in the previous figure

Screening potential estimate

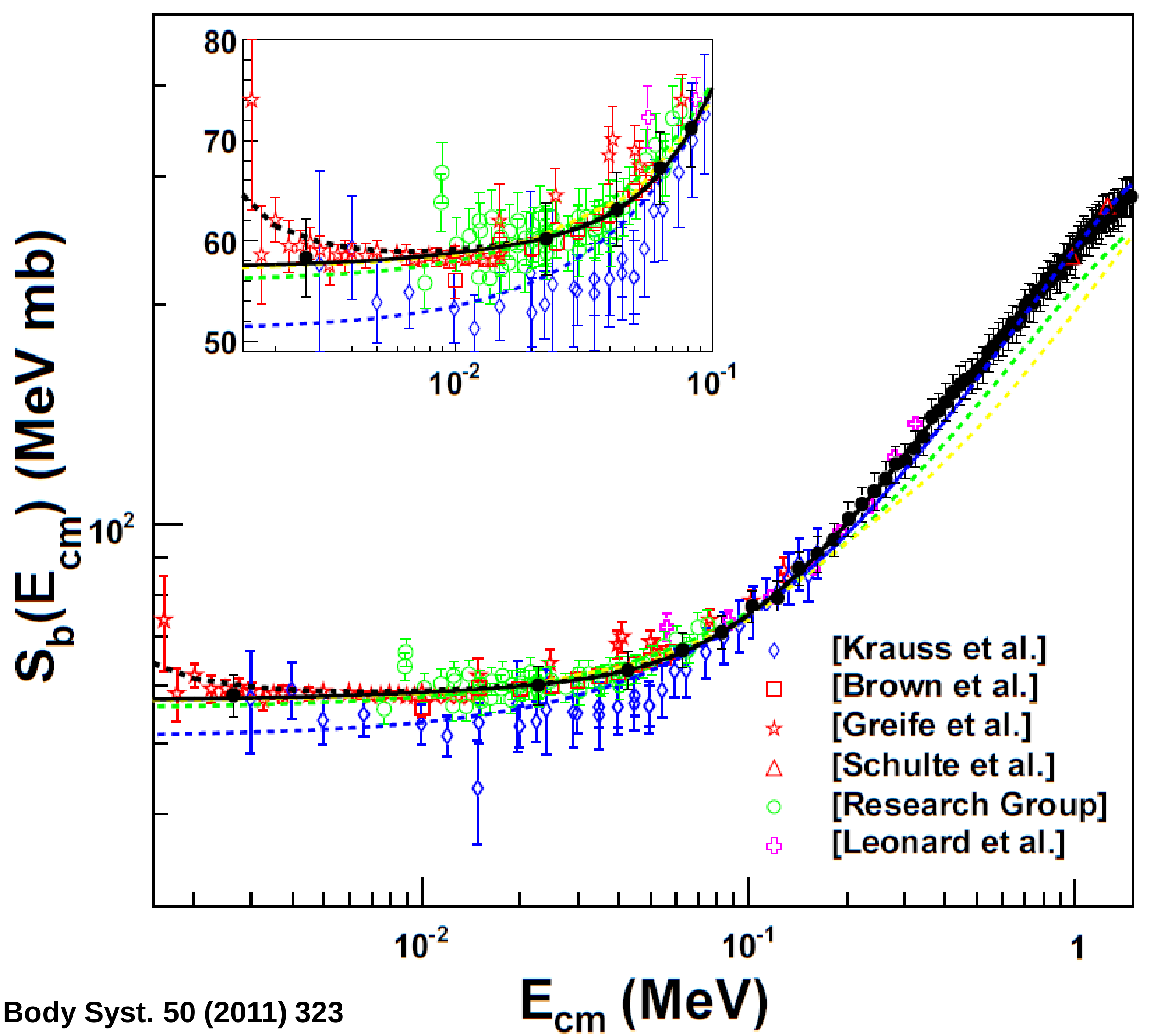
$f_{lab}(E)=\exp(U_e/E)$

(Assenbaum, H.J. et al., 1987, Z. Phys. A, 327, 461)

→U_e = 13.2±1.8 eV

In agreement with the adibatic limit

$^2H(^3He,p\ ^3H)p$



A. Tumino et al., Few Body Syst. 50 (2011) 323

A.Tumino et al., Phys. Lett. B 700 (2011) 111

Recent results for resonant reactions

$^{15}N + p \rightarrow \alpha + ^{12}C$ via $^{15}N + d \rightarrow \alpha + ^{12}C + n$ @ 60 MeV

$^{18}O + p \rightarrow \alpha + ^{15}N$ via $^{18}O + d \rightarrow \alpha + ^{15}N + n$ @ 60 MeV

…reactions belonging to the ^{19}F production/destruction path

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ [^{13}C-pocket?]
$^{13}C(\alpha,n)^{16}O$ [s-process]
$^{14}N(n,p)^{14}C$
$^{14}C(\alpha,\gamma)^{18}O$ or $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O$
$^{18}O(p,\alpha)^{15}N$ → $^{15}N(p,\alpha)^{12}C$
$^{18}O(\alpha,\gamma)^{22}Ne$
$^{15}N(\alpha,\gamma)^{19}F$ → $^{19}F(\alpha,p)^{22}Ne$

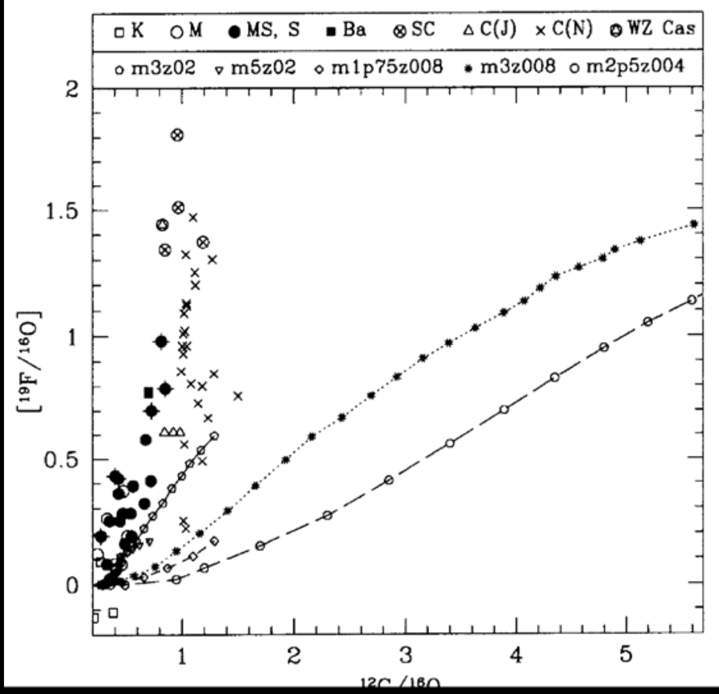
^{19}F depleting reactions

The importance of ^{19}F in astrophysics:

- ♦ its abundance observed in red giants can constrain AGB star models

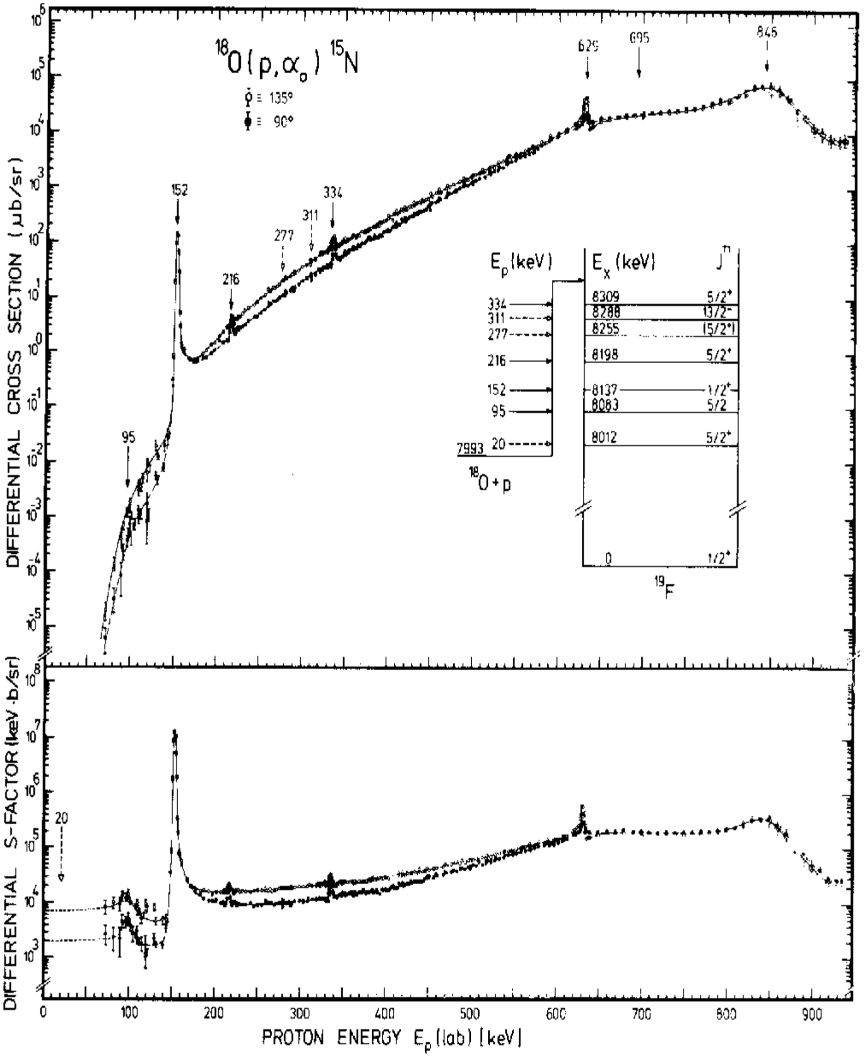
Open problem:

- ♦ fluorine abundance in red giants is enhanced by large factors with respect to the solar one



This would imply C/O values much larger than what experimental data suggest

The 18O(p,a)15N Reaction: Current Status



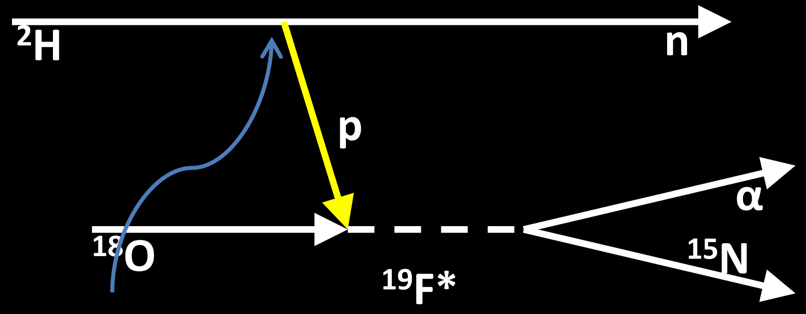
~50 resonances in the 0-7 MeV region

The main contribution to the reaction rate is given by the resonances:

1- 20 keV $J^\pi=5/2^+$
2- 144 keV $J^\pi=1/2^+$ (well established)
3- 656 keV $J^\pi=1/2^+$

The Trojan horse method for resonant reactions

In the THM the astrophysically relevant reaction, in particular $^{17,18}O(p,\alpha)^{14,15}N$, studied through an appropriate three-body process $^{2}H(^{17,18}O,\alpha^{14,15}N)n$:



The process is a transfer to the continuum where proton (p) is the transferred particle

Upper vertex: direct deuteron breakup

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the $^{18}O(p,\alpha)^{15}N$ → 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

How to extract the resonant strength?

When narrow resonances dominate the S-factor the reaction rate can be calculated by means of the resonance strength:

$$(\omega\gamma)_i = \frac{\hat{J}_i}{\hat{J}_p \hat{J}_{^{18}\mathrm{O}}} \frac{\Gamma_{(p^{18}\mathrm{O})_i}(E_{R_i})\,\Gamma_{(\alpha^{15}\mathrm{N})_i}(E_{R_i})}{\Gamma_i(E_{R_i})}$$

($^{18}O(p,\alpha)^{15}N$ case)

Where:

- **$\hat{J}=2J+1$**
- **$\Gamma_{(AB)}$ is the partial width for the A+B channel**
- **Γ_i is the total width of the i-th resonance**
- **E_{Ri} is the resonance energy**

→Area of the Breit-Wigner describing the resonance

→ no need to know the resonance shape

$$(\omega\gamma)_i = \frac{1}{2\pi}\omega_i N_i \frac{\Gamma_{(p^{18}\mathrm{O})_i}}{|M_i|^2}$$

Where:

- **$\omega_l = \hat{J}_i / \hat{J}_p\, \hat{J}_{18O}$ statistical factor**
- **N_i = THM resonance strength**
- **M_i = transfer amplitude**

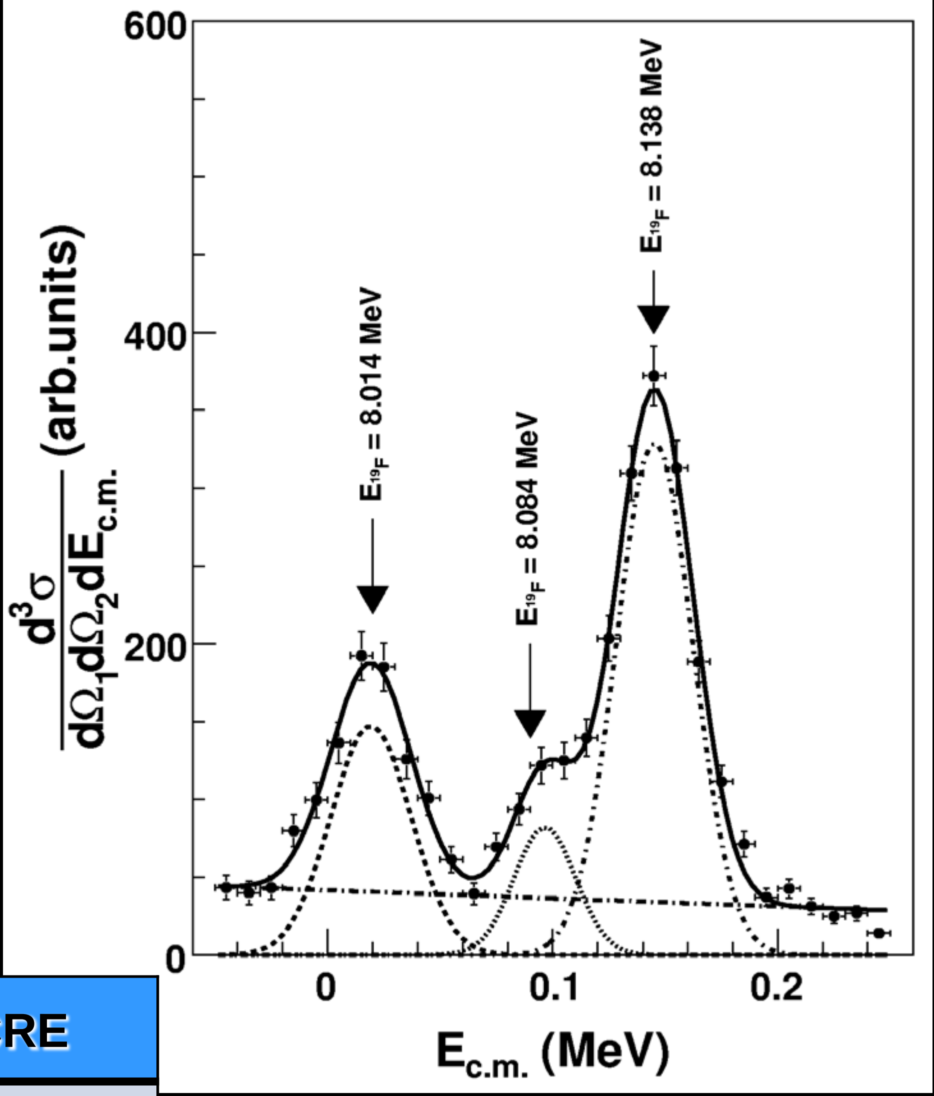
Advantages:

- **possibility to measure down to zero energy**
- **No electron screening**
- **No spectroscopic factors in the $\Gamma_{(p18O)}$ / $|M_i|^2$ ratio**

$^{18}O + p \rightarrow \alpha + {}^{15}N$ THM Results

In case of narrow resonances reaction rate depending on resonance strength:

$$(\omega\gamma)_i = \frac{\omega_i}{\omega_3}\frac{\Gamma_{p_i}(E_{R_i})}{|M_i(E_{R_i})|^2}\frac{|M_3(E_{R_3})|^2}{\Gamma_{p3}(E_{R_3})}\frac{N_i}{N_3}(\omega\gamma)_3$$



<u>Advantages</u>:

- possibility to measure down to zero energy
- No electron screening
- No spectroscopic factors in the $\Gamma_{(p18O)} / |M_i|^2$ ratio
- no need to know the absolute cross section

$\omega\gamma$ (eV)	Present work	NACRE
20 keV	$8.3^{+3.8}_{-2.6}\ 10^{-19}$	$6^{+17}_{-5}\ 10^{-19}$
90 keV	$1.8 \pm 0.3\ 10^{-7}$	$1.6 \pm 0.5\ 10^{-7}$

M. La Cognata et al. PRL 101, 152501 (2008)
M. La Cognata et al. Ap. J. 708, 796 (2010)

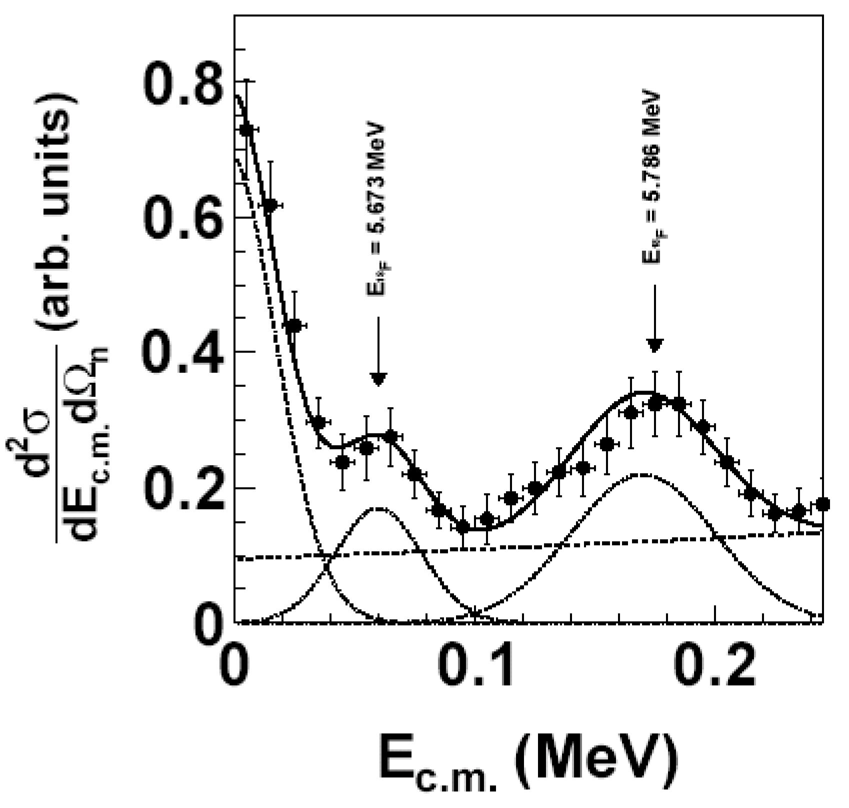
$^{17}O + p \rightarrow \alpha + {}^{14}N$: recent experiment at LNS

Importance in novae nucleosynthesis and γ astronomy

It affects the production of 18F removing ^{17}O from the production path

It influences the $^{17}O/^{16}O$ isotopic ratio, playing a crucial role to constrain extra mixing processes in AGB stars

$$(\omega\gamma)_1 = (3.66^{+0.76}_{-0.64}) \times 10^{-9} \ \text{eV}$$



THM reaction rate about 20% smaller than the most recent value reported in literature: screening effect?

M.L. Sergi et al. PRC (R) (2010)

$$f_{lab} = \frac{(\omega\gamma)_{Chafa}}{(\omega\gamma)_{THM}} = e^{\pi\eta(E_{R_i})\frac{U_e}{E_{R_i}}},$$

→ U_e = 1080 eV

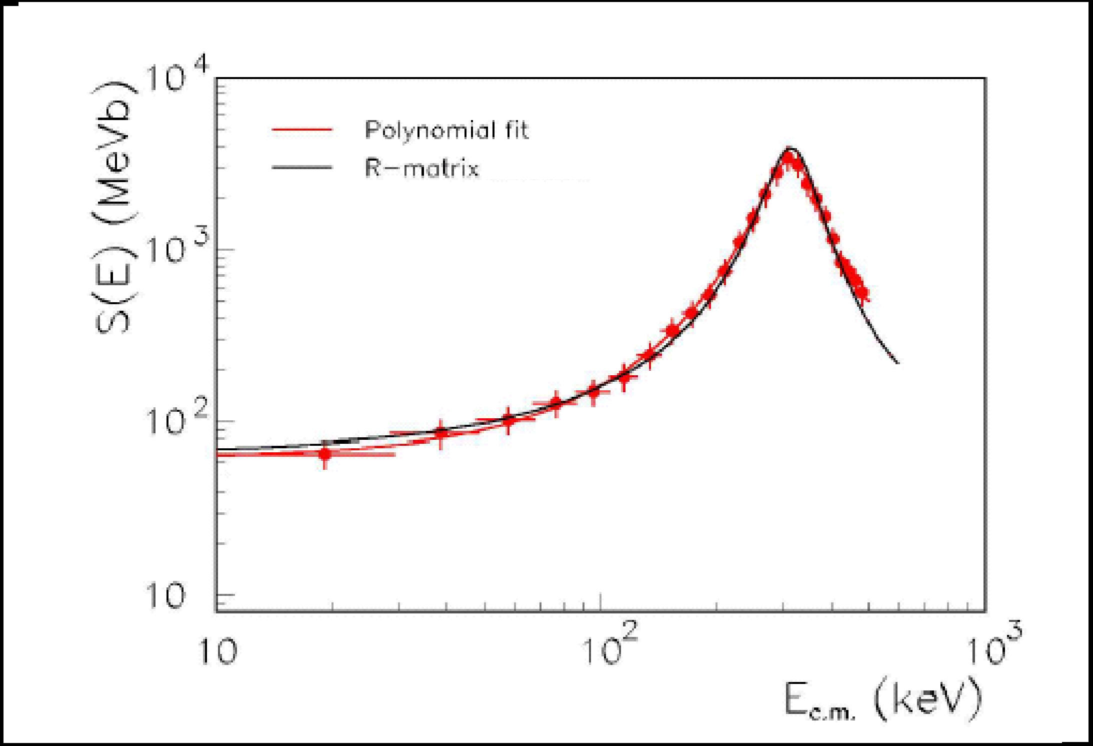
U_{AD} = 594 eV

The $^{15}N + p \rightarrow \alpha + ^{12}C$: Astrophysical S-factor

Results reported in terms of S(E) factors:

- THM data as red dots
- Direct data from NACRE as black + open dots

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the $^{15}N(p,\alpha)^{12}C$ → Modified R-Matrix is introduced instead



R-matrix calculation assuming a little destructive interference between the 300 keV, 962 keV (12.44 and 13.09 MeV states of ^{16}O) resonances and a subthreshold one (^{16}O level at E_{exc}= 9.58 MeV), all of them with $J^{\pi} = 1^{-}$

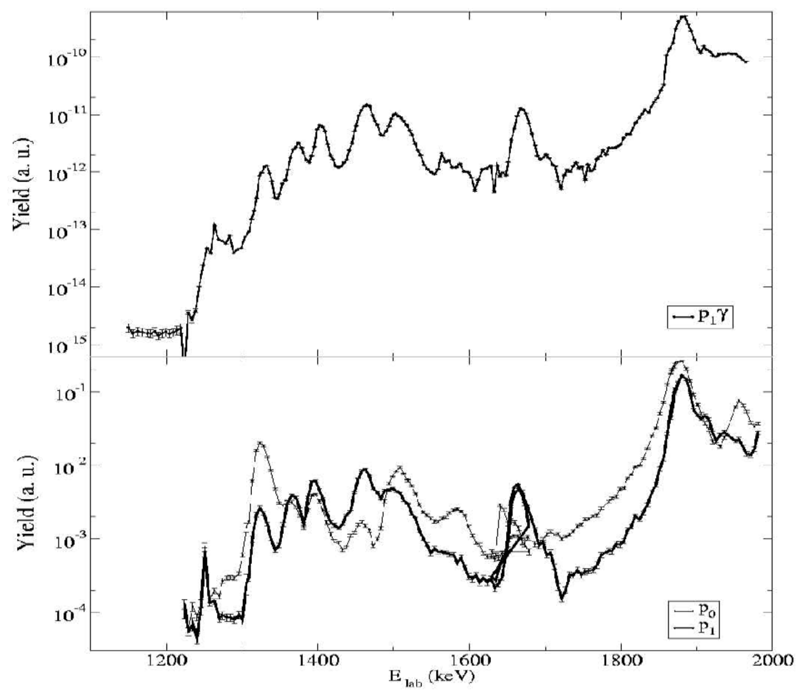
$S_{bare}(0)$=62 ± 10 MeVb

Data very well reproduced!

M. La Cognata et al. PRC 76, 065804 (2007)

Near future:

The $^{19}F(\alpha,p)^{22}Ne$ reaction



$^{19}F(\alpha,p)^{22}Ne$: main ^{19}F destruction channel AGB stars with M>2 M_o and WR stars (~30 M_o)

T → 2 10^8 K

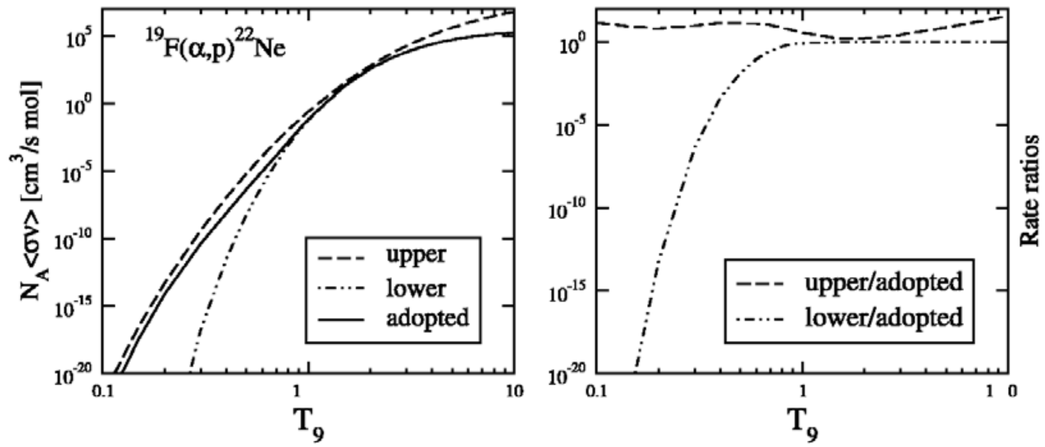
⇒ Energies of interest 300-800 keV

Most recent measurement (2006) down to 800 keV

⇒ Extrapolation impossible because of the many resonances

The rate is calculated by using simplified models

Reaction rate: uncertainty of about 14 orders of magnitude



Near future:

The ^{16}O + ^{12}C experiment

Currently a great interest in the fusion channel in the low energy region because of its critical role in studying a wide range of stellar burning scenarios in carbon-rich environments → constraints on the models

$^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$
$^{12}C + ^{12}C \rightarrow p + ^{23}Na$
$^{12}C + ^{12}C \rightarrow n + ^{23}Mg$

Carbon burning temperature from 0.8 to 1.2 GK, corresponding to center-of-mass energies E_{cm} from 1 to 3 MeV

Measured down to E_{cm} = 2.14 MeV, still at the beginning of the region of astrophysical interest.

Extrapolation from current data to the ultra-low energies is complicated by the presence of resonant structures even in the low-energy part of the excitation function

Further measurements extending down to 1 MeV would be extremely important!

December 2011: ^{14}N run at LNS

p-p scattering from THM

$$\left(\frac{d\sigma}{d\Omega}\right)_{p1p2-cm} \propto \frac{d^{3}\sigma}{dE_{p1}\,d\Omega_{p1}\,d\Omega_{p2}} \Big/ \left|\phi(p_s)\right|^{2} KF$$

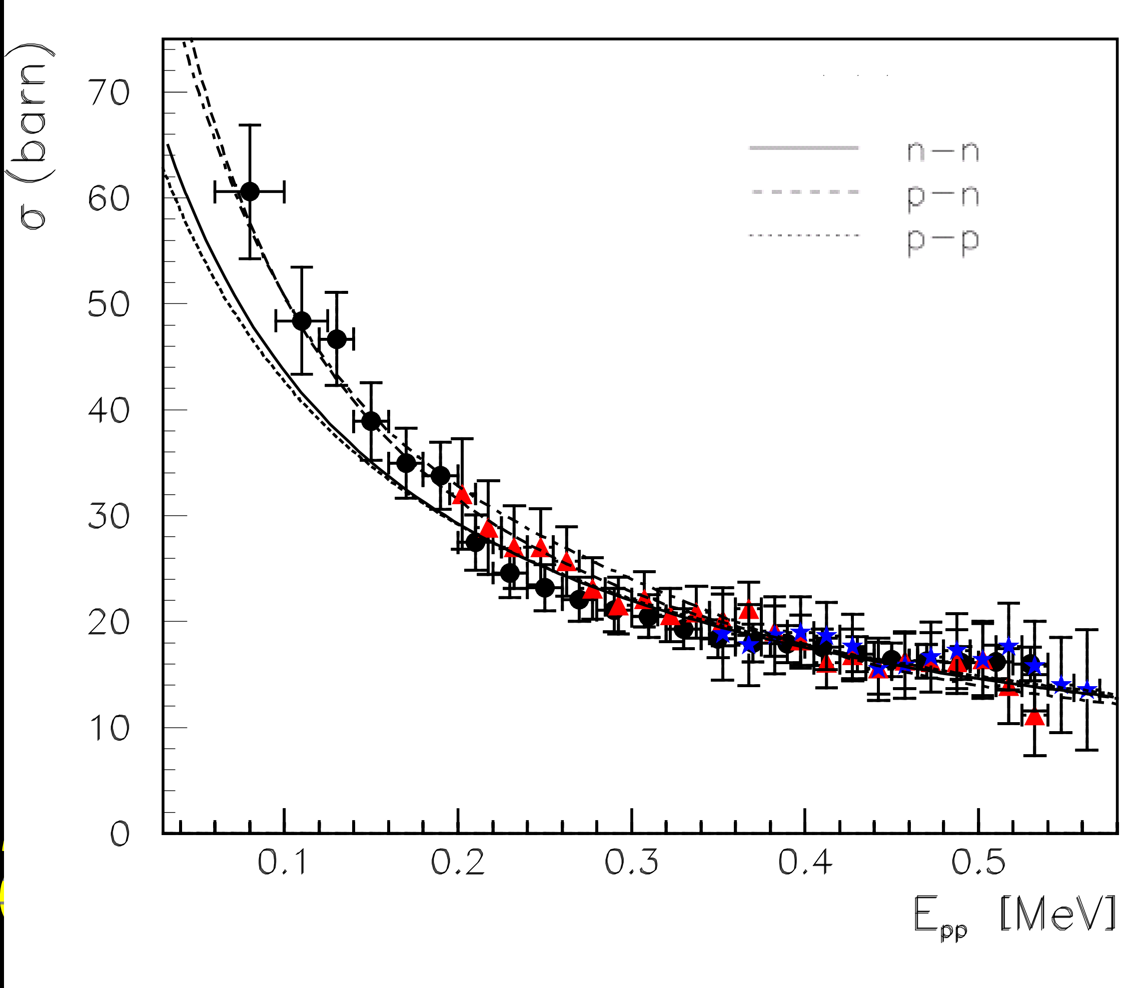
p+p elastic scattering via

p+d → p+p+n

THM p-p cross-section shows the 1/E behaviour also in the region of the expected Coulomb+nuclear interference:

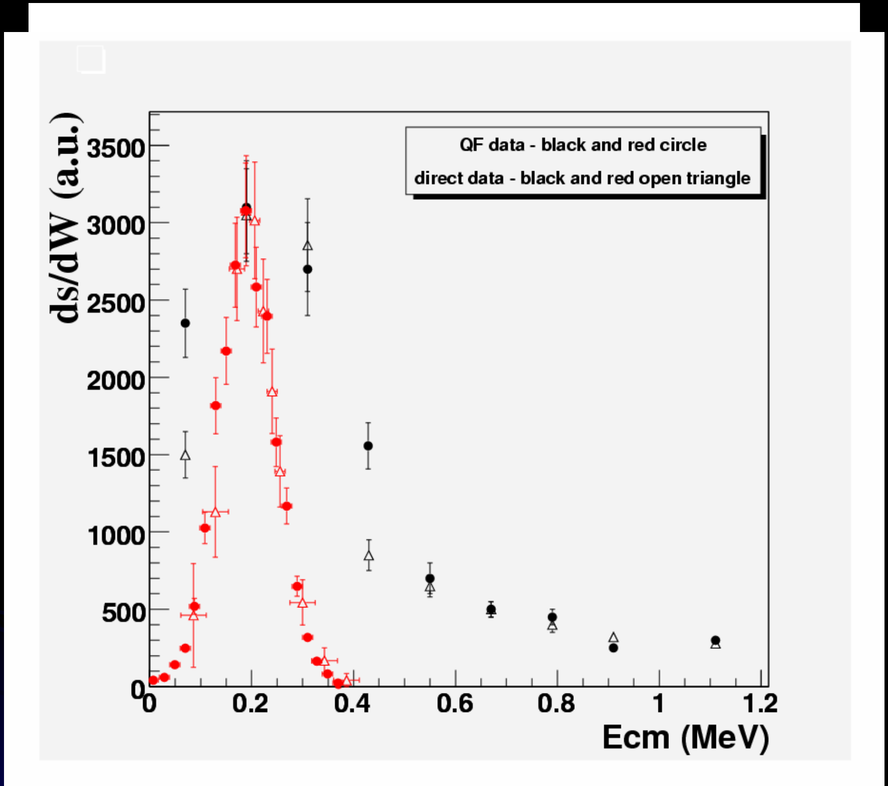
Coulomb effects appear completely suppressed

A. Tumino et al. PRL 98, 252502 (2007)
A. Tumino et al. PRC 67, 065803 (2008)



No minimum

Deuteron-Beam as a virtual Neutron-beam

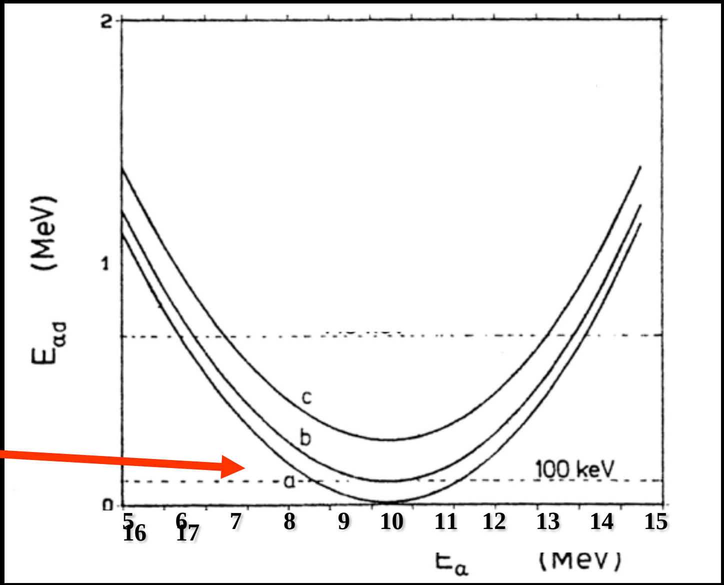


^{6}Li(n,α)^{3}H via ^{6}Li(d,α^{3}H)p reaction

E_{6Li} =14 MeV

The good agreement between THM and direct data suggests that no off-energy shell effects other than those deriving from the Coulomb barrier, when present, should be considered

New results from a recent experiment: magnifying glass effect in the resonant region…



A. Tumino et al., EPJ A (2005) 1
M. Gulino et al., JPG (2010)

The collaboration

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