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Low energy d+d fusion reactions via the Trojan Horse method

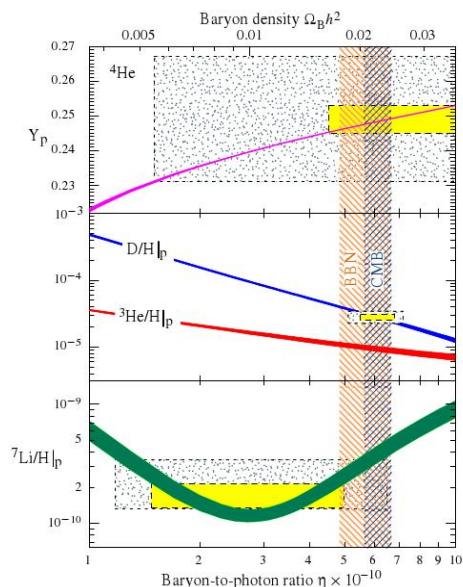
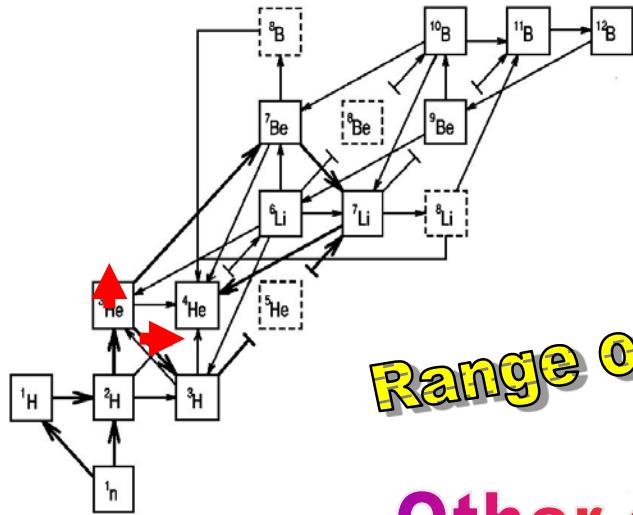
Aurora Tumino



$^2\text{H} + ^2\text{H}$ reactions in the primordial nucleosynthesis

$^2\text{H}(\text{d}, \text{p})^3\text{H}$ and $^2\text{H}(\text{d}, \text{n})^3\text{He}$

$T \approx 10^9 \div 10^{11} \text{ K} - 0.1 \div 10 \text{ MeV}$ $\tau \approx 10^2 \div 10^3 \text{ s}$



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

Status of art of the ${}^2\text{H}+{}^2\text{H}$ reactions

Prominent data sets for both ${}^2\text{H}(\text{d},\text{p}){}^3\text{H}$ and ${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$

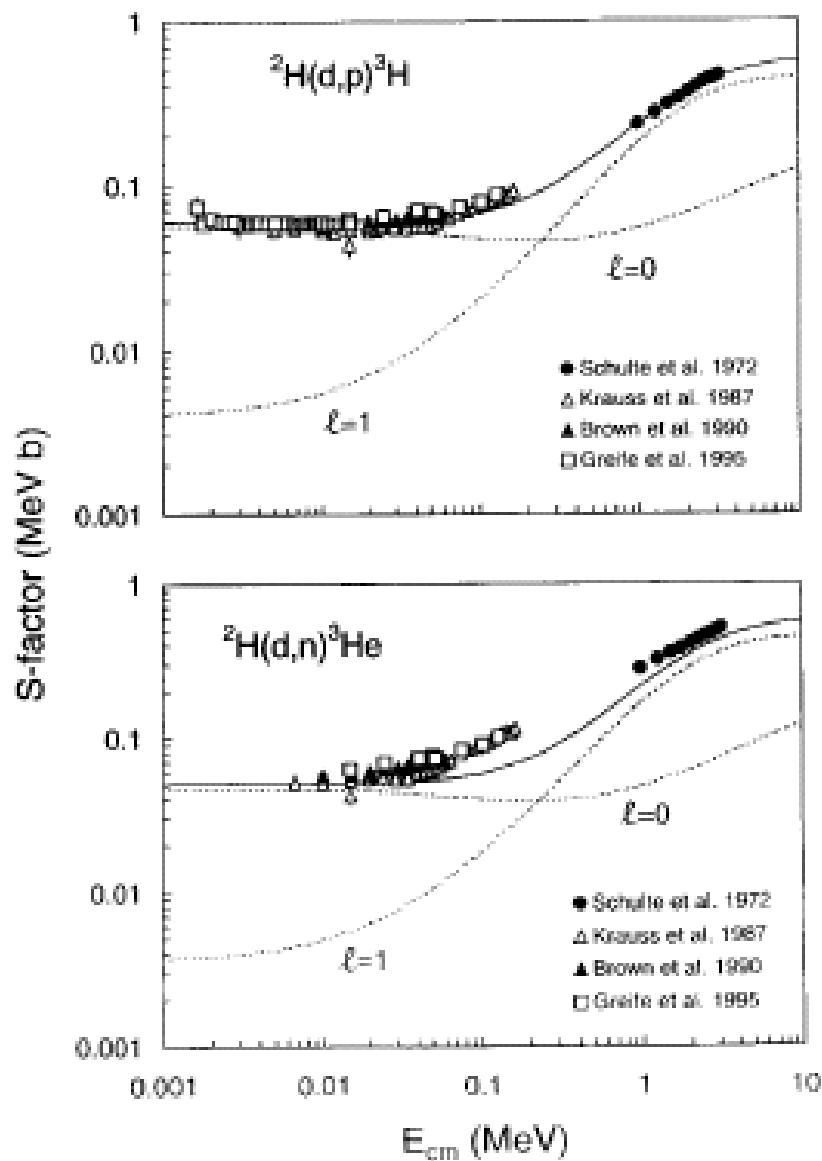
Open problems:

Missing data in the higher energy relevant BBN region: $E_{\text{cm}} = 50 - 350 \text{ keV}$

Electron screening in the ultra-low energy region below 10 keV: almost twice the adiabatic limit (14 eV)

Laboratory electron screening different from that of stellar plasma
→ Screening should be removed to assess the reaction rate correctly

→ Need to get the bare nucleus $S(E)$ factor



Trojan Horse Method

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



a: $x \oplus s$ clusters

Quasi-free mechanism

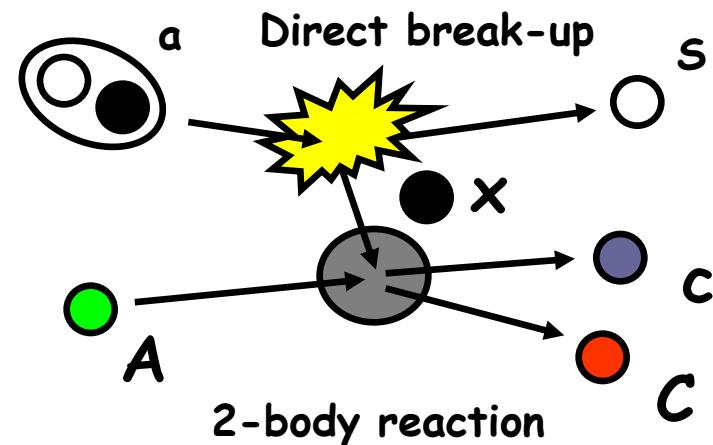
- ✓ only $x - A$ interaction
- ✓ $s = \text{spectator}$ ($E_s \sim 0$)

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

NO electron screening

$$E_{\text{q.f.}} = E_{Ax} - B_{x-s} \longrightarrow E_{\text{q.f.}} \approx 0 \quad !!!$$

plays a key role in compensating for the beam energy



In PWIA

$$\sigma_3 \propto K F |\Phi(p_s)|^2 \sigma_2$$

C. Spitaleri *et al.*, Phys. Rev. C 63, 005801 (2001)
A. Tumino *et al.*, Phys. Rev. Lett. 98, 252502 (2007)

THM experiment

$^2\text{H}(\text{d}, \text{p})^3\text{H}$ $^2\text{H}(\text{d}, \text{n})^3\text{He}$ using ^3He as TH nucleus

^3He described as d+p: lightest proton rich nucleus

d-d relative energy range: from 2 keV up to 1.5 MeV

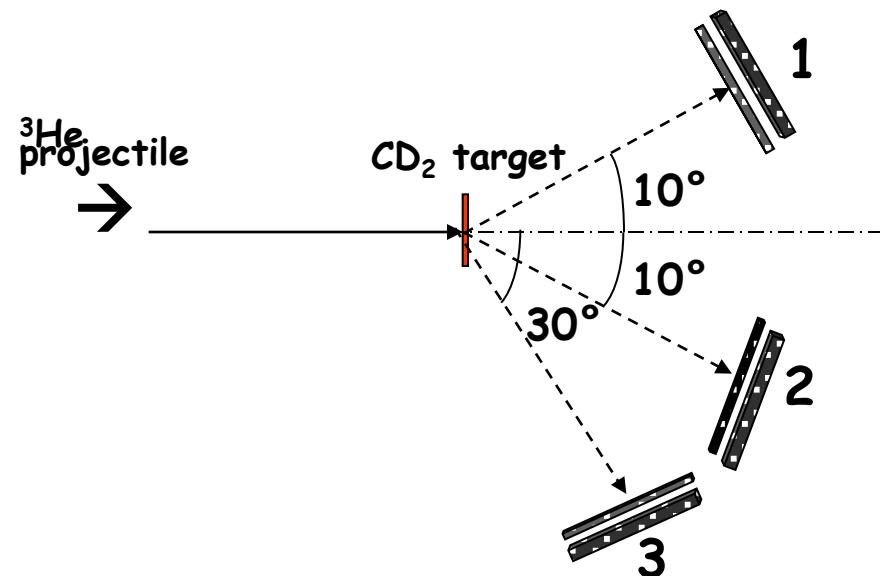
Aim:

- * Astrophysical factor throughout the relevant region and up, in order to have a wide energy range to be joint with available higher energy data (for the integral to converge at the relevant BBN temperature). This ensures an accurate calculation of the reaction rate
- * Available unscreened data below 10 keV, needed for studying fusion dynamics in plasmas

Experimental set up



Nuclear Physics Institute of Academy
of Science in Rez near Prague, Czech
Republic

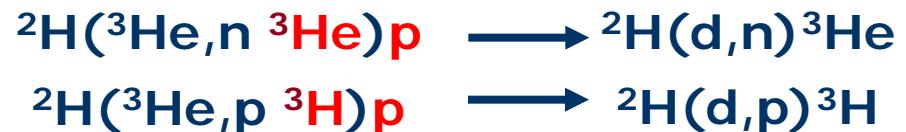


$^3\text{H}/^3\text{He}$ - p coincidences (1-2 and 1-3)

For the first time detection of
the proton spectator!

Advantages: no contribution from target break-up;
detector granularity ensured → angular resolution of the order of 0.1°;
100% detection efficiency

Not possible with neutron detectors



Data analysis follows standard procedure: here only the final steps

Extraction of the two-body cross section (1)

R-matrix by C. Angulo and P. Descouvemont (NPA 639 (1998) 733)

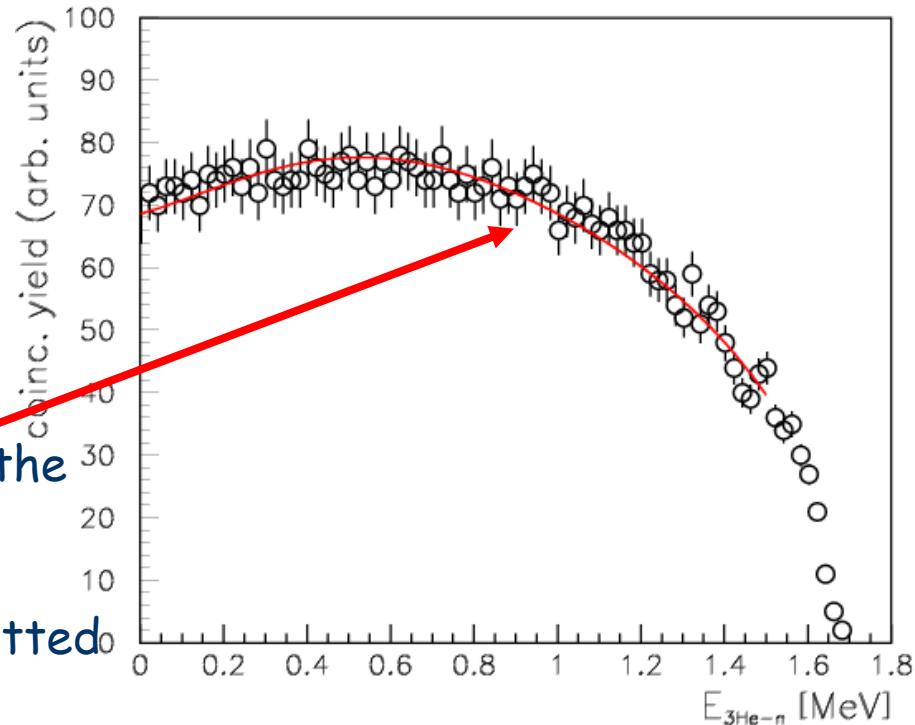
Inclusion of both $l=0$ and $l=1$ components in the cross section, whose energy dependence is very well represented by their penetrabilities

$$\frac{d\sigma}{dEd\Omega}(d + d \rightarrow C + c) = \frac{1}{E_{cm}} \sum_{l=0,1} C_l P_l^2 T_l(k_{dd}R)$$

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

Free parameters are scaling factors C_l and channel radius R : determined from the fit of the theoretical distributions to the measured coincidence yields

Two coincidence yields per channel to be fitted at the same time

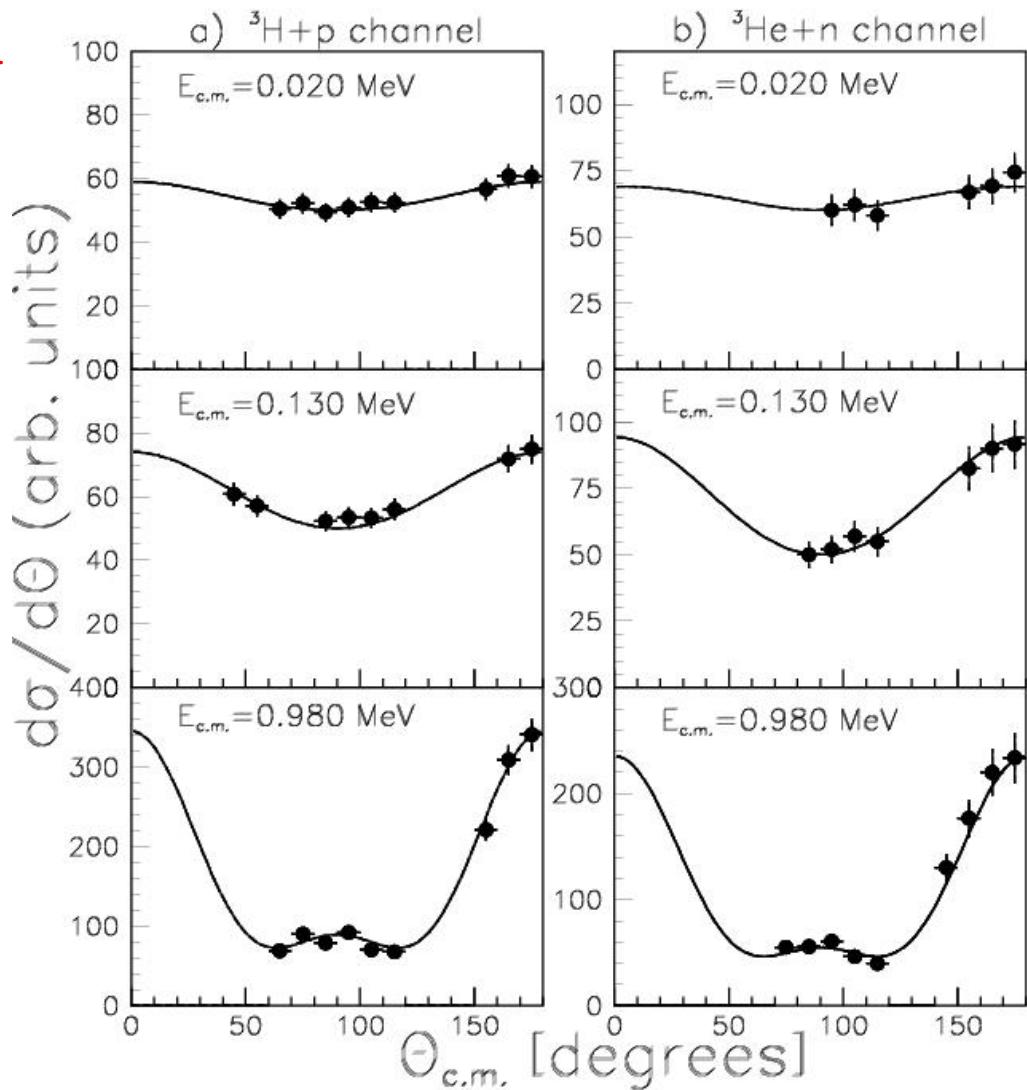


Extraction of the two-body cross section (2)

$$\frac{d\sigma}{d\theta_{c.m.}} = \frac{\text{Coinc. yield at fixed } \Delta E_{c.m.}}{KF |\phi(p_s)|^2}$$

Solid lines: fit of direct data by

A. Krauss *et al.*, Nucl. Phys. A 465, 150 (1987)
R.L. Schulte *et al.*, Nucl. Phys. A 192, 609 (1972)

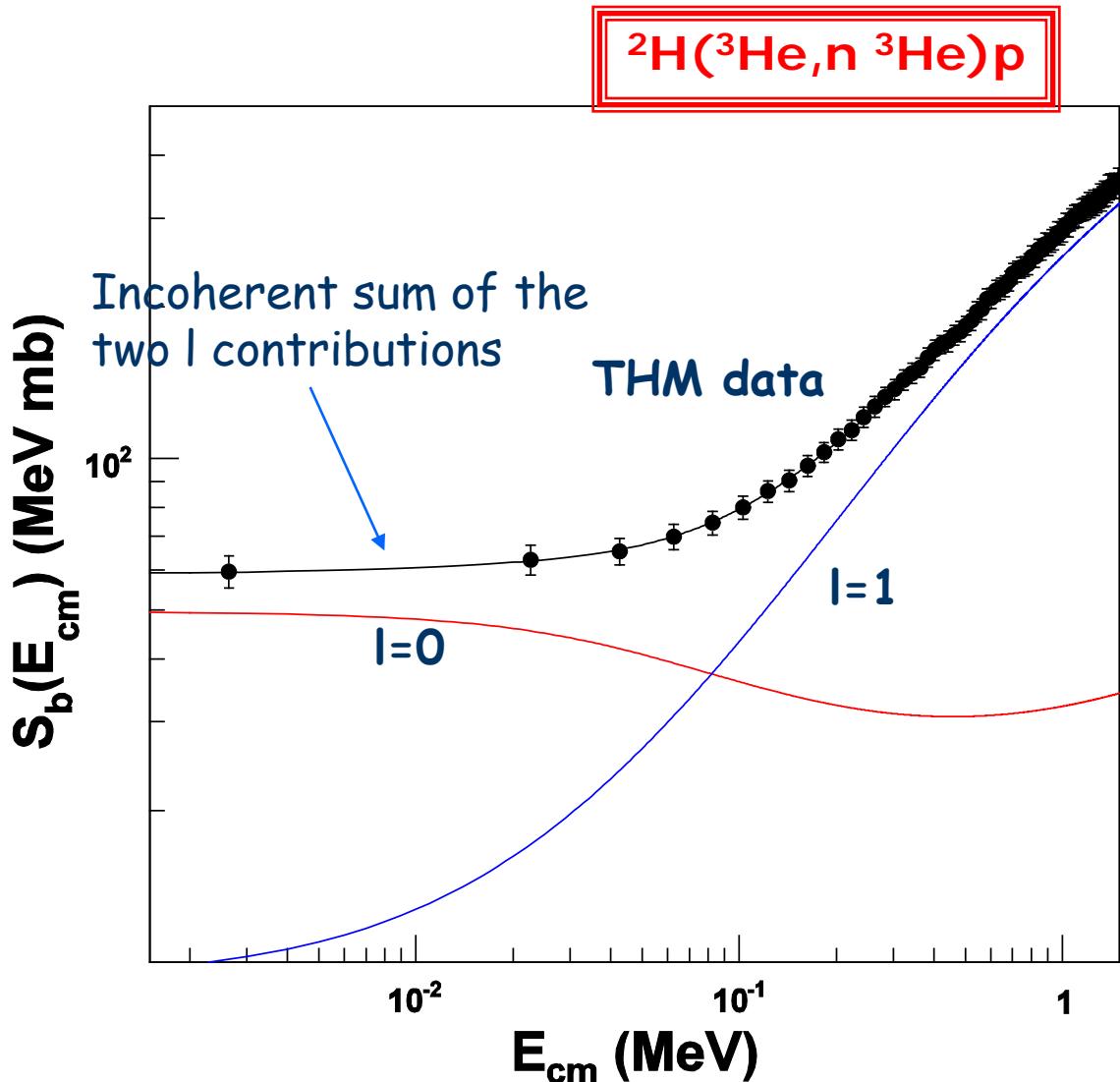


Extraction of the two-body cross section (3)

$$S(E) = \sigma(E) E e^{2\pi\eta}$$

With the deduced scaling ratio of the s and p waves, $\rightarrow S(E)$ factor after normalization to direct data

Direct data have different accuracies \rightarrow weighted normalization to available direct data from 15 keV to 1.5 MeV



Extraction of the two-body cross section (4)

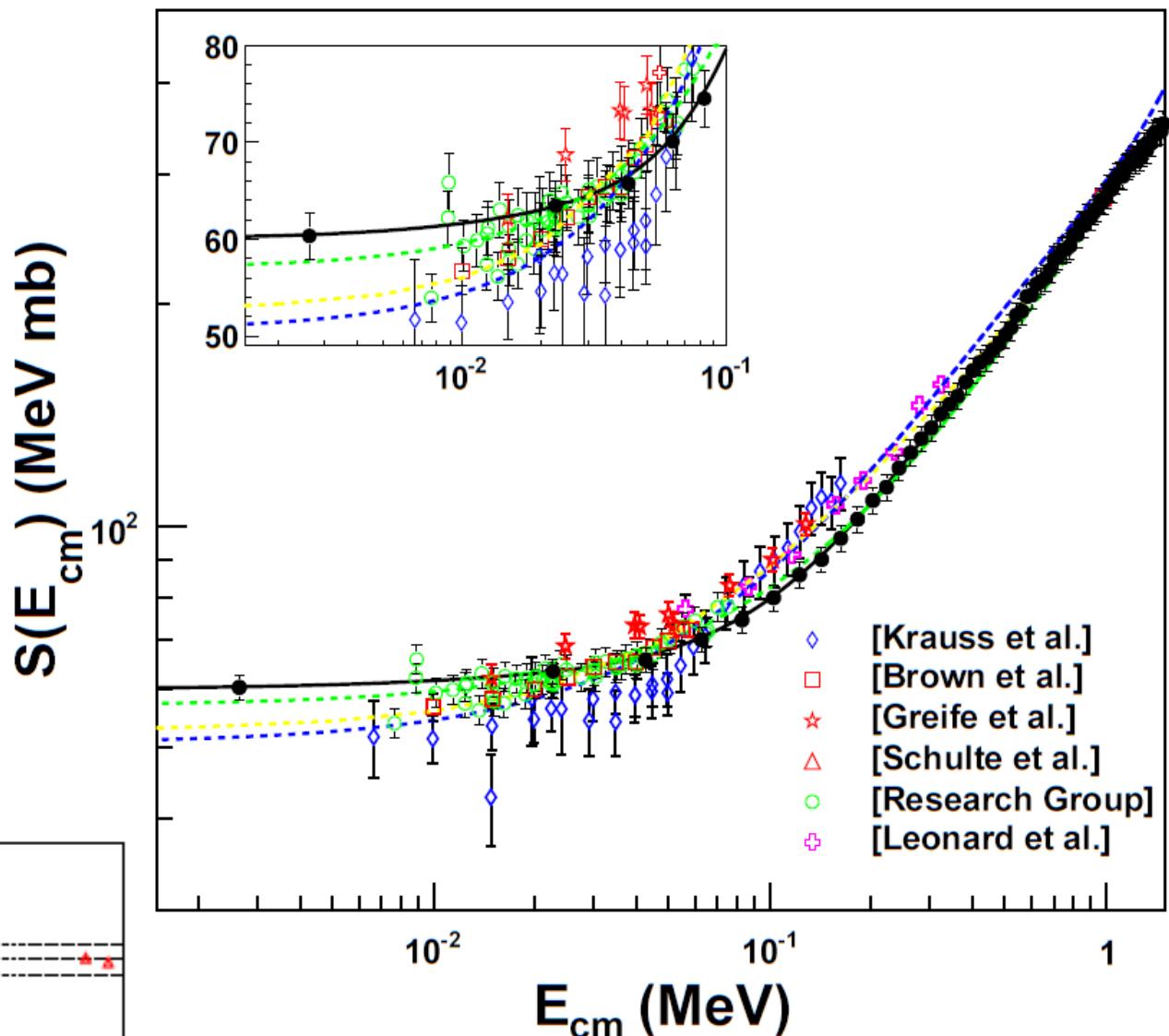
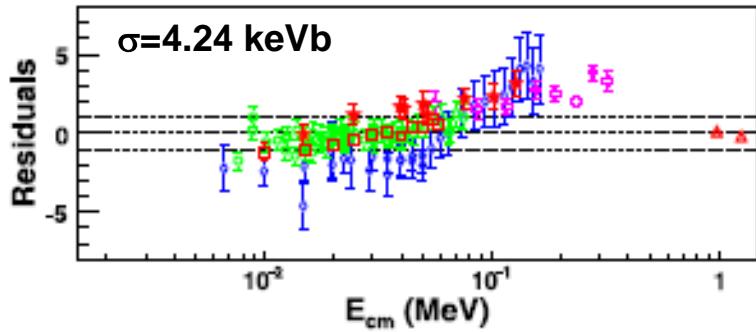
Comparison between
the incoherent sum
black line) and direct
data (colored symbols)

Yellow line: polynomial
expansion reported in the
NACRE compilation

C. Angulo et al., NPA 656, 3 (1999)

Blue line: from
R.H. Cyburt, PRD 70, 023505 (2004)

Green line: from
P. Descouvemont et al., At. Data Nucl. Data
Tables 88, 203 (2004)



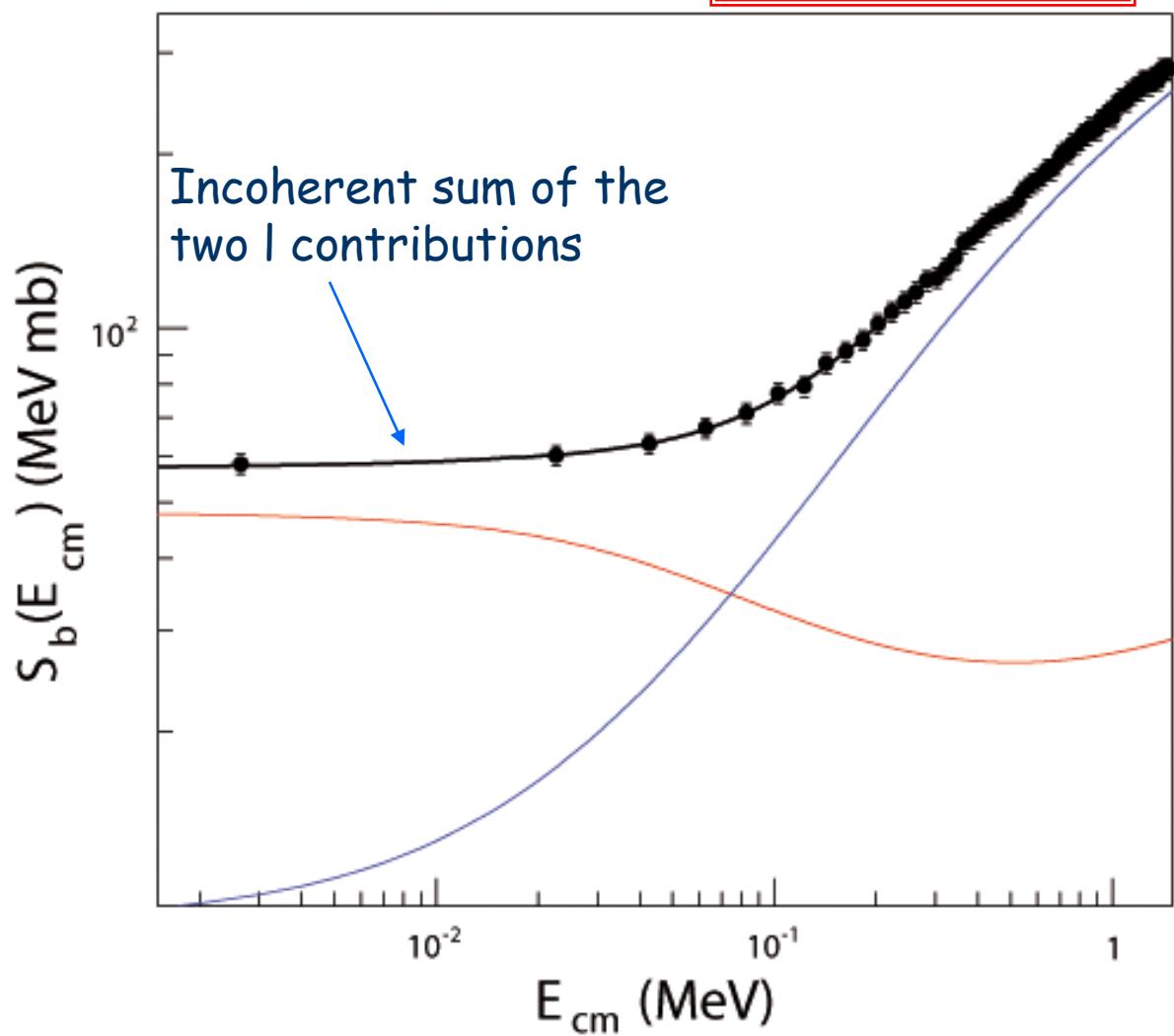
A. Tumino et al., Few Body Syst. 50 (2011) 323

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

Extraction of the two-body cross section (3)

$^2\text{H}(\text{He}^3, \text{p} \text{ } ^3\text{H})\text{p}$

$$S(E) = \sigma(E) E e^{2\pi\eta}$$



Extraction of the two-body cross section (4)

Direct data at 15 keV
normalized to the THM bare
 $S(E)$ and fitted with

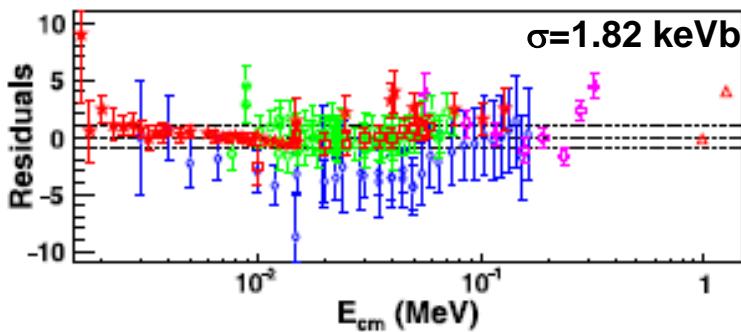
$$f_{\text{lab}}(E) = \exp(U_e/E)$$

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

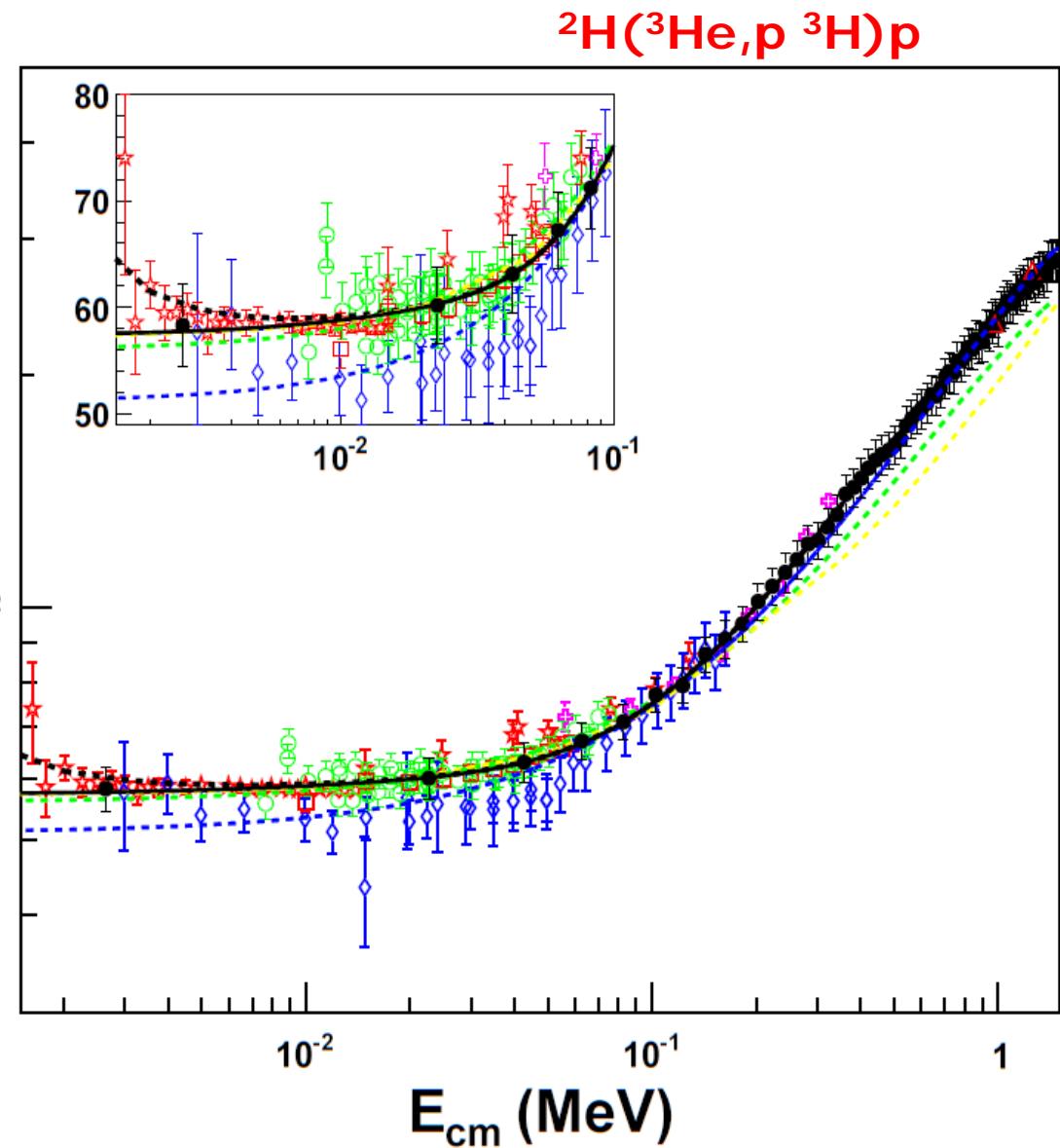
with the screening potential
 U_e as free parameter:

$$\rightarrow U_e = 13.2 \pm 1.8 \text{ eV}$$

In agreement with the
adiabatic limit



$$S_b(E_{\text{cm}}) (\text{MeV mb})$$



Some numbers

$S(0)$ for ${}^3\text{He} + \text{n}$ [keV b]	$\Delta S(0)$ [keV b]	Ref.
60.1	1.9	Present results from THM
53 keV		C. Angulo et al. (NACRE)
50.67 keV		R.H. Cyburt
57.2 keV	3.5	P. Descouvemont et al.

$S(0)$ for ${}^3\text{H} + \text{p}$ [keV b]	$\Delta S(0)$ [keV b]	Ref.
57.4	1.8	Present results from THM
56 keV		C. Angulo et al. (NACRE)
51.15 keV		R.H. Cyburt
57.1 keV	1.8	P. Descouvemont et al.

However, none of the lines provide the correct slope of the THM data throughout the investigated region, with deviations ranging from few percents to 15%-20%.

Conclusions

$^2\text{H}(^3\text{He}, n ^3\text{He})^1\text{H}$ and $2\text{H}(^3\text{He}, p ^3\text{H})^1\text{H}$: first experiments where the spectator is detected

$^3\text{He} = d \oplus p$ cluster configuration

S(E) factor extracted from 2 keV to 1.5 MeV, throughout the energy region of interest for pure and applied physics and up

Estimate of screening potential only for the $^3\text{H}+p$ channel because of the lack of direct data for the $^3\text{He}+n$ channel in the ultra-low energy region. $U_e = 13.2 \pm 1.8$ eV in agreement with the adiabatic limit

... next step: calculation of the reaction rate

and investigation of fusion dynamics in plasmas

Thank you!

The collaboration

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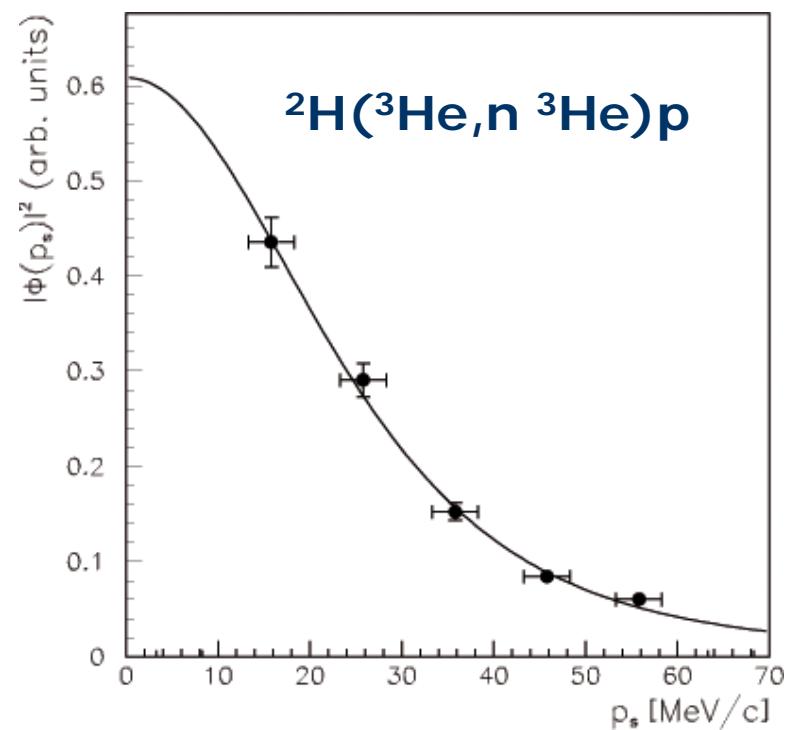
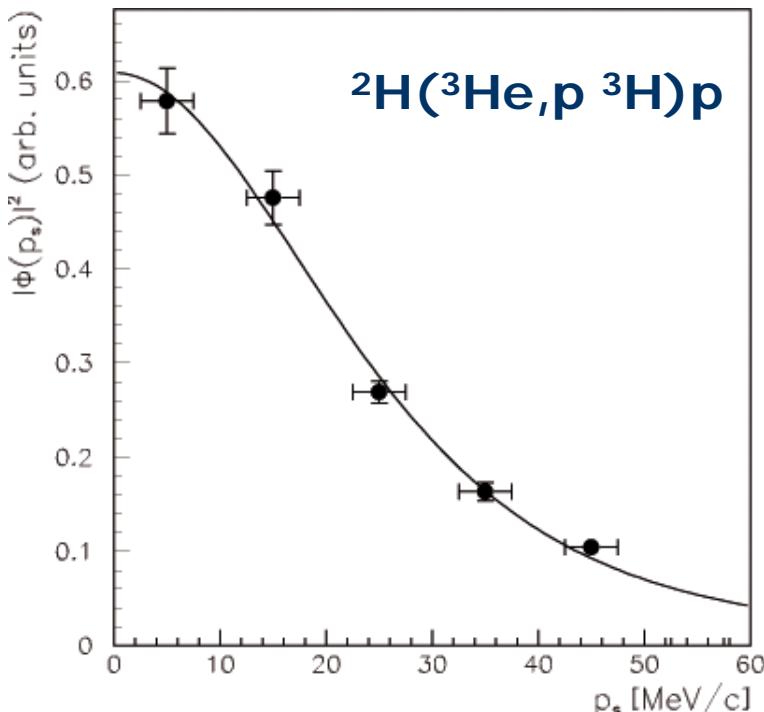
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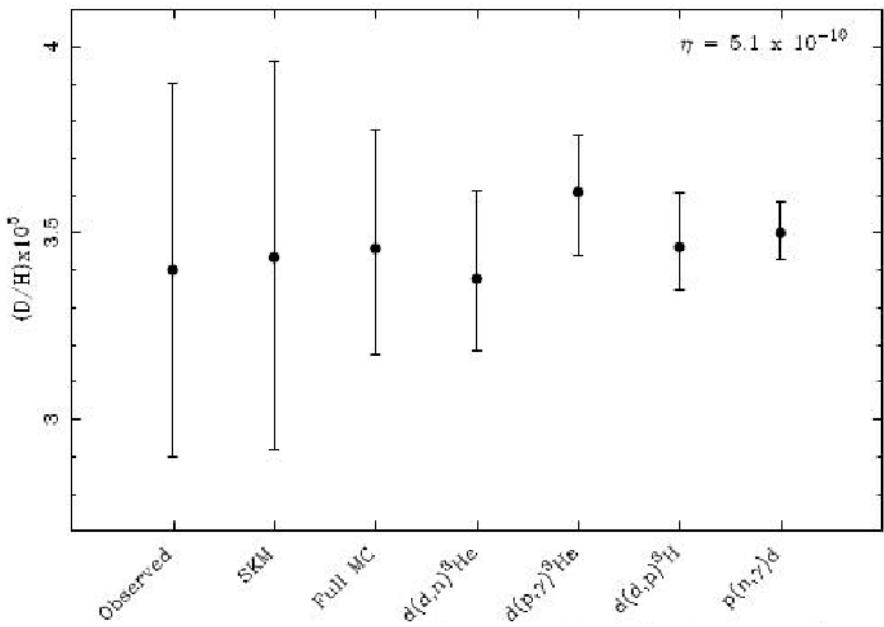
Selection of the quasi-free mechanism

Comparison between the experimental momentum distribution and the theoretical one (for ${}^3\text{He}$ given by the Eckart function) → QF mechanism

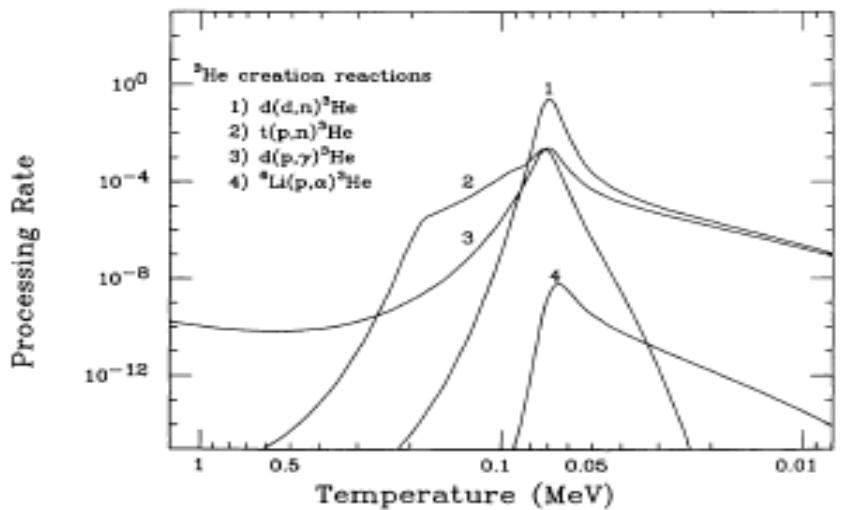
$$|\Phi(\vec{p}_s)|^2 \propto \frac{d^3\sigma}{(KF) \left(\frac{d\sigma_{dd}}{d\Omega} \right)^N}$$



Deuterium and uncertainty of η

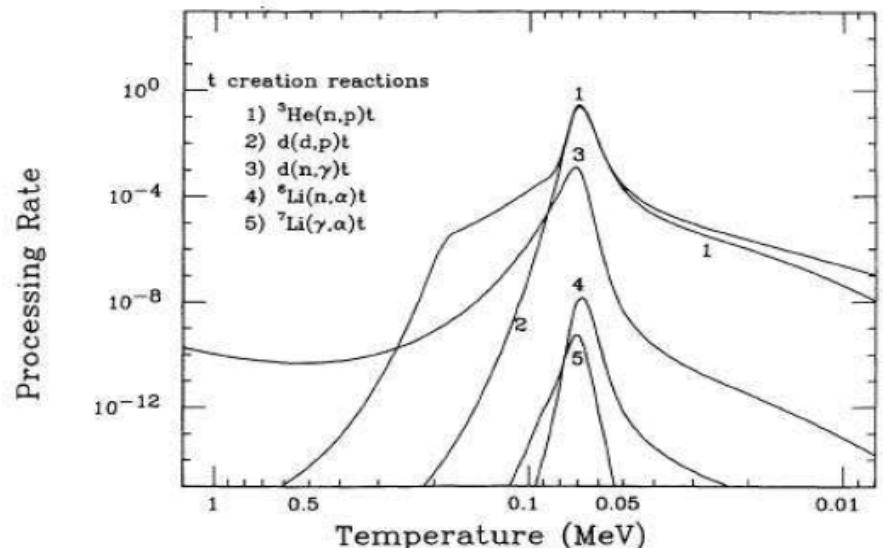


[Smith et al., 1993]



Uncertainty on η from deuterium:

50% conservative
50% cross section uncertainty of reactions involving deuterium.



Selection of the 3-body channels

