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Indirect study of the 2H(d,p)3H and 2H(d,n)3He reactions at astrophysical energies via the Trojan Horse method

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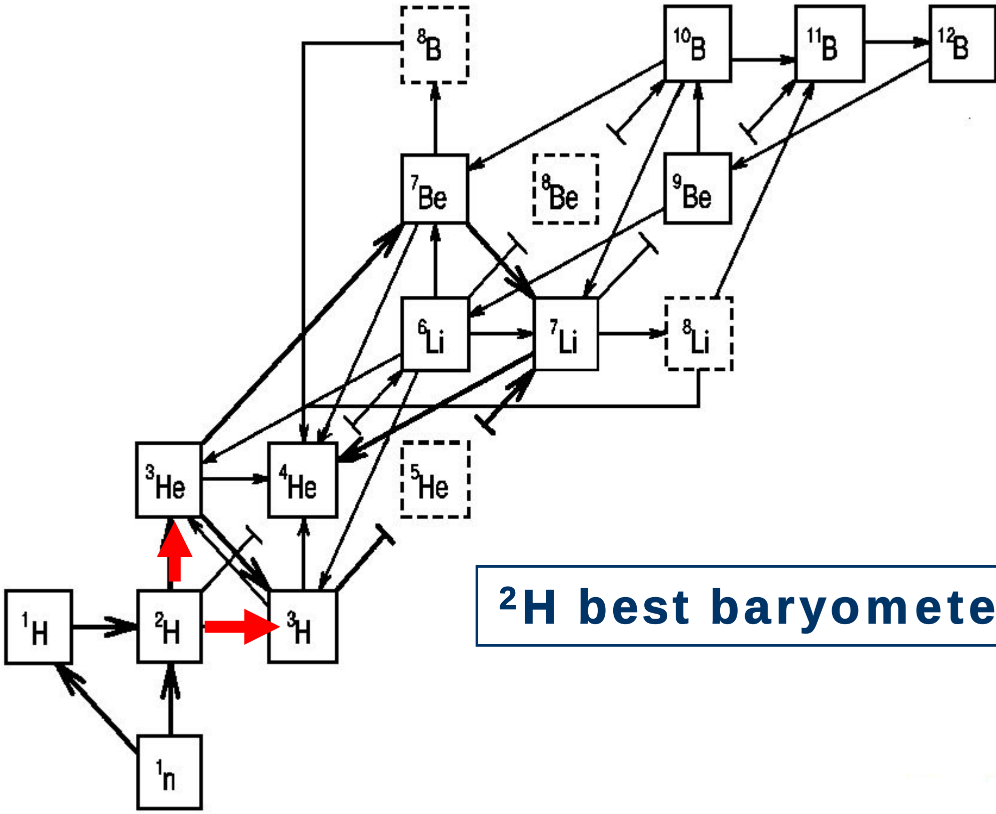
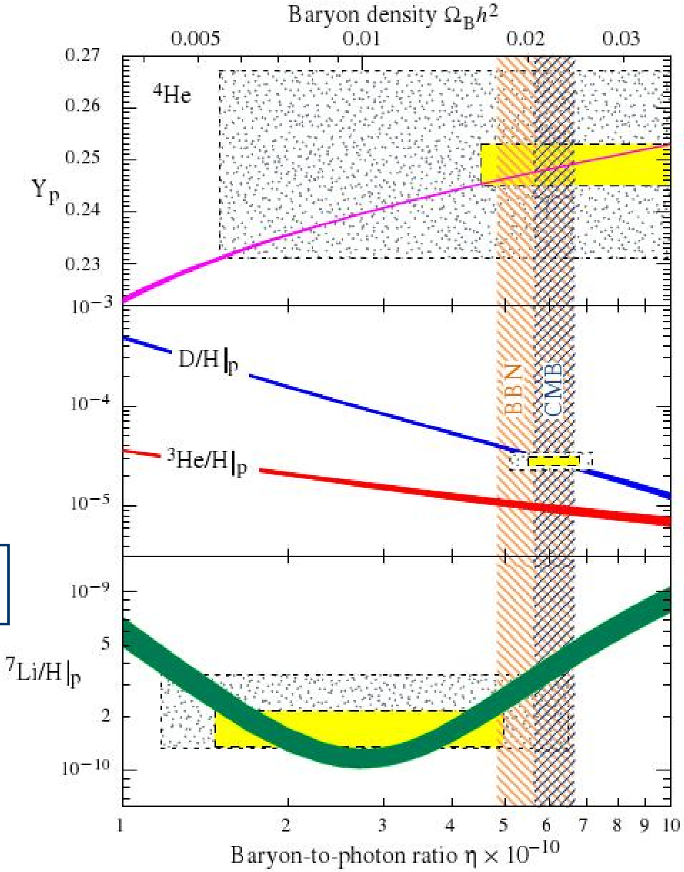
2H+2H reactions in the primordial nucleosynthesis

$T \approx 10^9 \div 10^{11}$ K – $0.1 \div 10$ MeV $t \approx 10^2 \div 10^3$ s



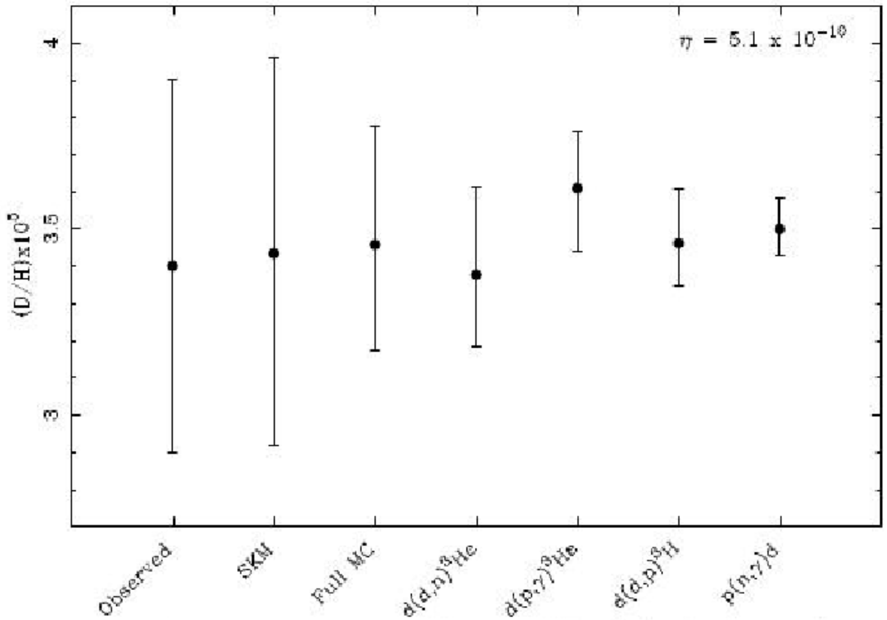
^{2}H best baryometer!!!



Range of interest: 50-350 keV

$$\eta = \frac{n_B}{n_\gamma}$$

Deuterium and uncertainty of η

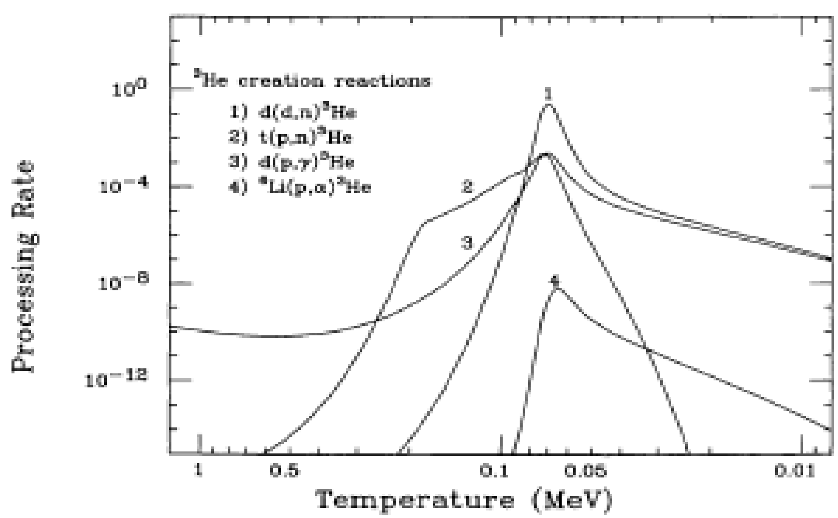


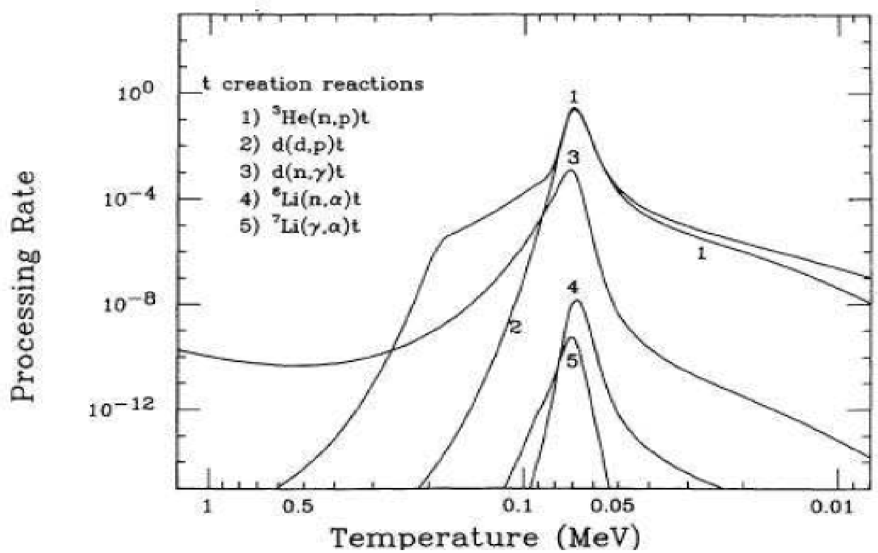
Uncertainty on η from deuterium:

50 % observative

50 % cross section uncertainty of reactions involving deuterium.

[Smith et al., 1993]





$^2H+^2H$ interaction at low energy: other contexts of interest

In the *Pre Main Sequence* phase (PMS) of the stellar evolution protostar moves in the Hayashi track to the Main Sequence, and it is all convective ($T \approx 10^6$ K - 10^{-4} MeV). The protostar burns deuterium with the reactions:

$^2H(p,\gamma)^3He$
$^2H(d,\gamma)^4He$
$^2H(d,p)^3H$
$^2H(d,n)^3He$
$^2H(^3He,p)^4He$
$^2H(^3He,\gamma)^5Li$
$^2H(^4He,\gamma)^6Li$

Range of interest : 0-10 keV

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

Range of interest : 0-30 keV

Total range of interest : 0-350 keV

Status of art of the 2H+2H reactions

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

Open problems:

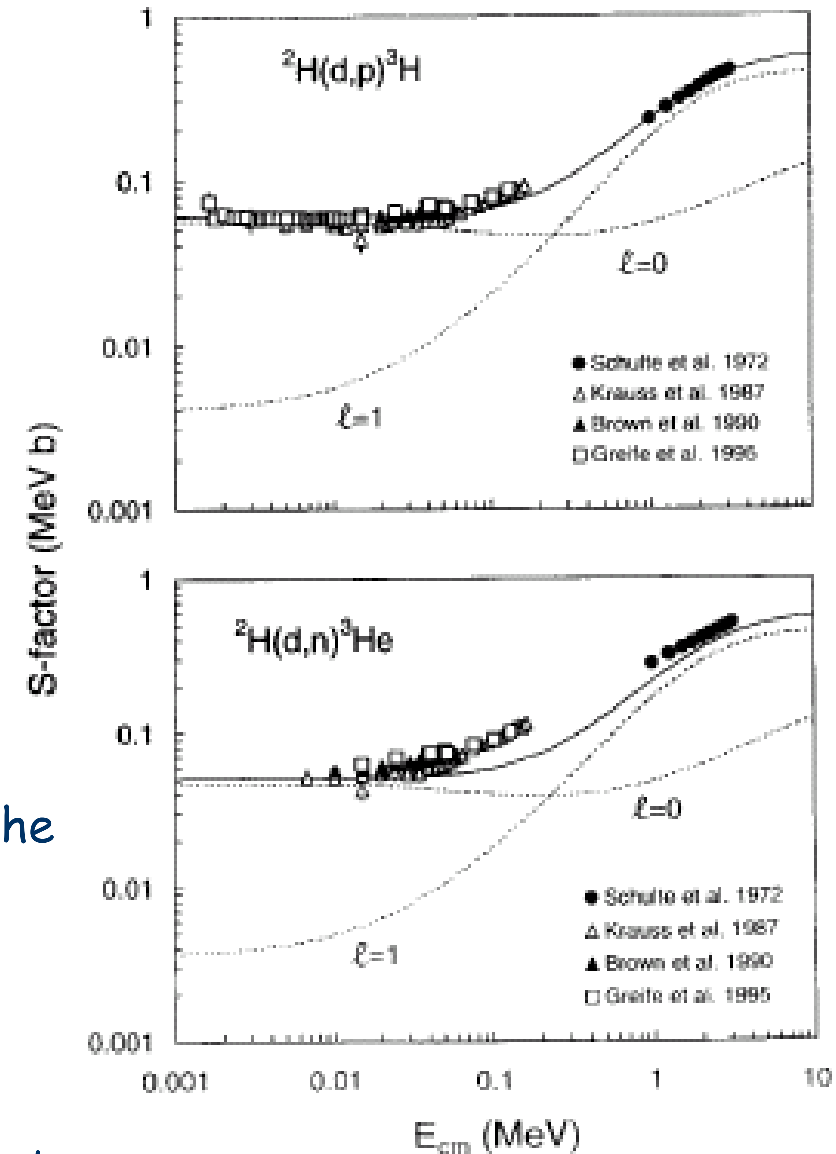
Missing data in the higher energy relevant BBN region: E_{cm} = 50 – 350 keV

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

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

With l=0 → $J^\pi = 0^+$ and 2^+ ,,
With l=1 → $J^\pi = 0^-$, 1^- and 2^-

…however…in this case R-matrix fit dominated by the penetrability factors T_0 and T_1



Trojan Horse Method

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

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

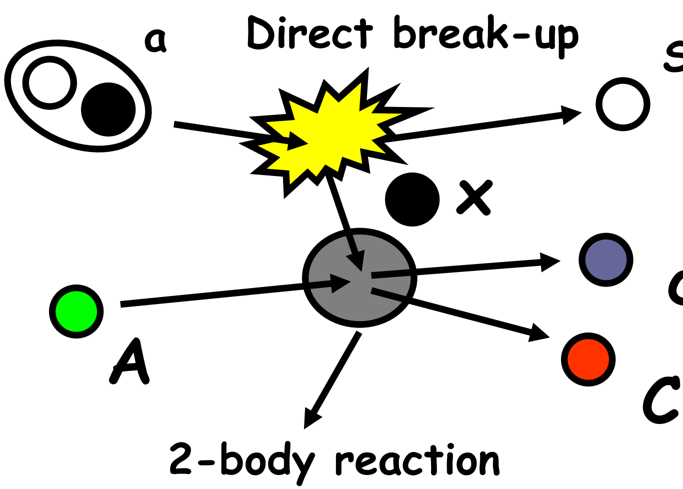
a: x $\oplus$ s clusters

Quasi-free mechanism

- ✓ only x - A interaction
- ✓ s = spectator (p_s~0)

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

NO electron screening



C. Spitaleri et al, PRC 60 (1999) 055802
A. Tumino et al., PRL 98 (2007) 252502
M. La Cognata et al., PRL 101 (2008) 152501

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

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

THM experiment

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

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

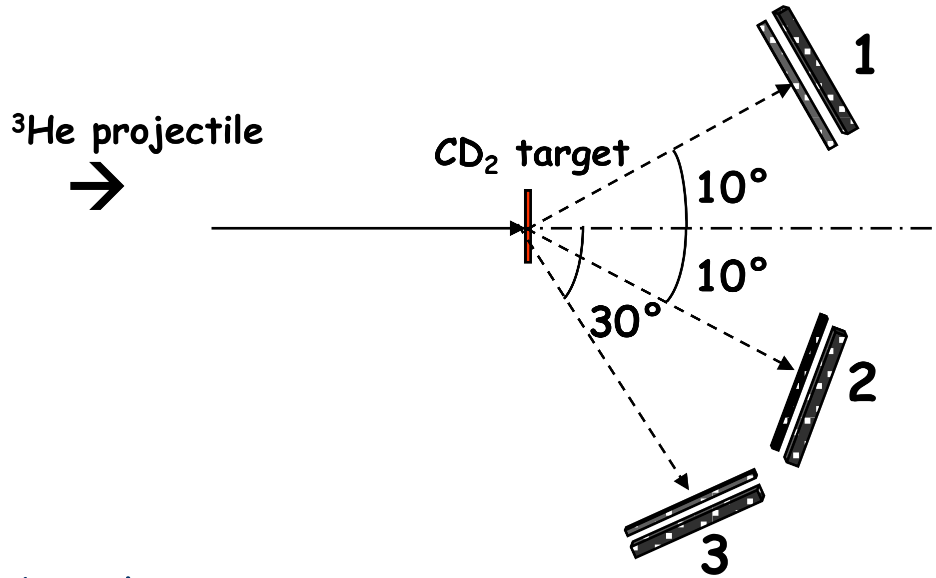
Aims:

* 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}H/^{3}He – p concidences (1-2 and 1-3)

For the first time detection of the proton spectator!

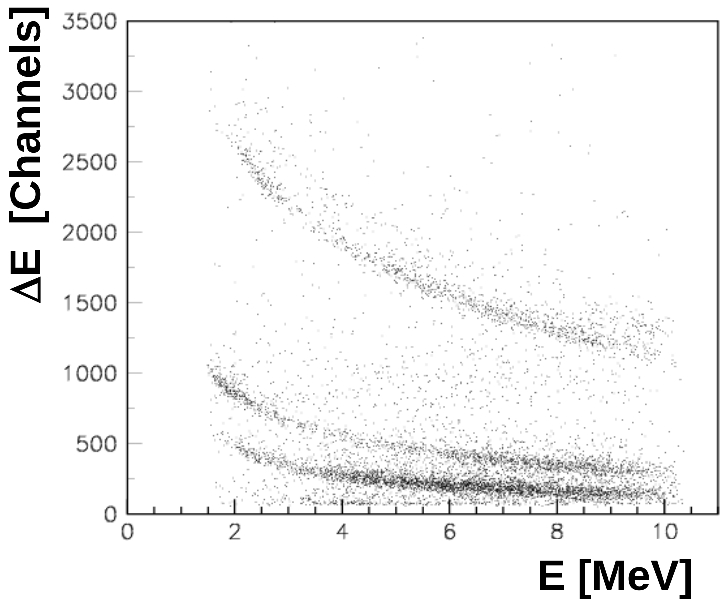
Advantages: no contribution from target break-up;
dector granularity ensured → angular resolution of the order of 0.1°;
100% detection efficiency

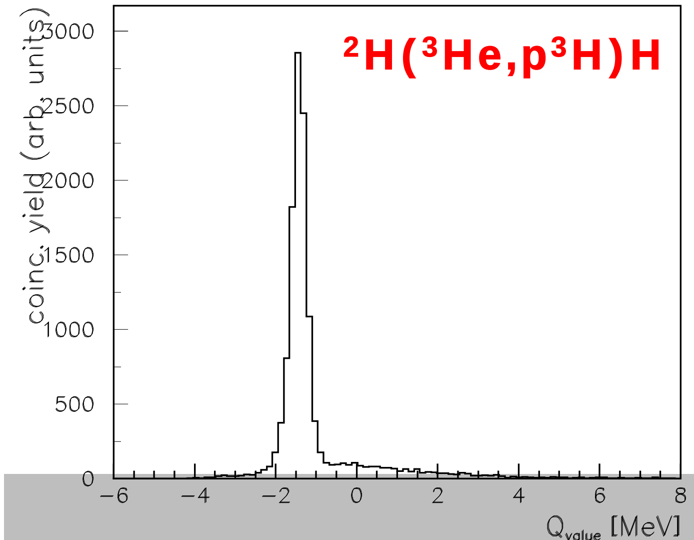
Not possible with neutron detectors

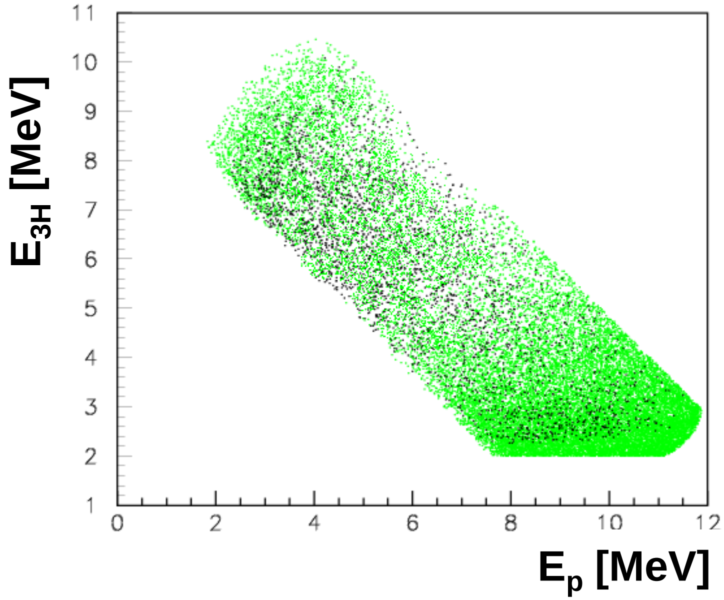
^{2}H(^{3}He,n ^{3}He)p ⟶ ^{2}H(d,n)^{3}He

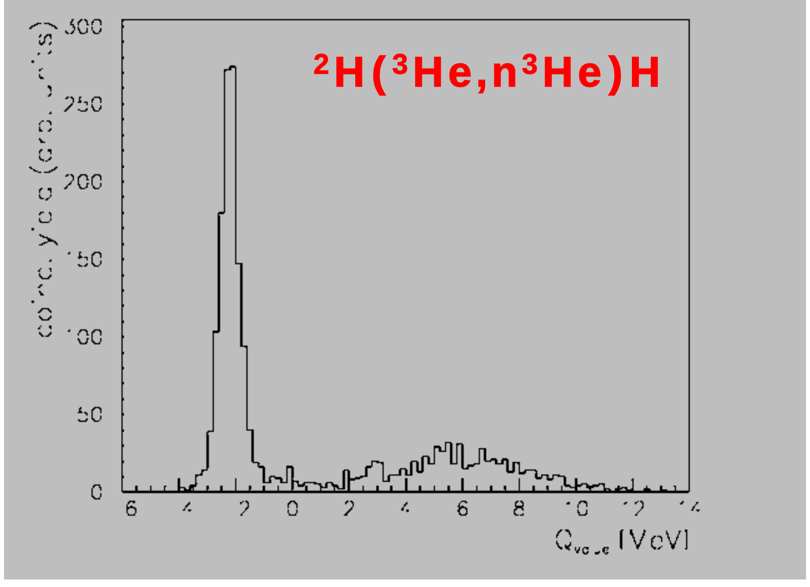
^{2}H(^{3}He,p ^{3}H)p ⟶ ^{2}H(d,p)^{3}H

Selection of the 3-body channels





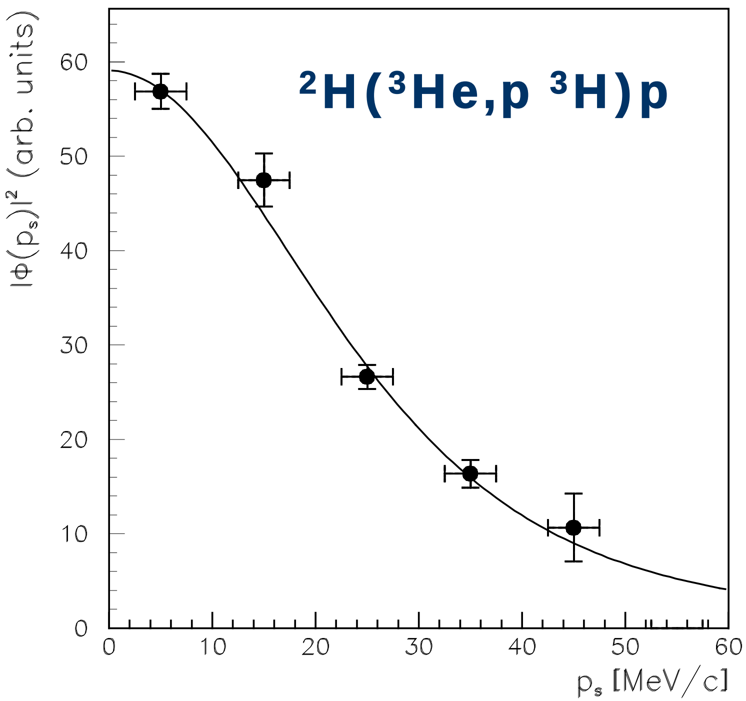


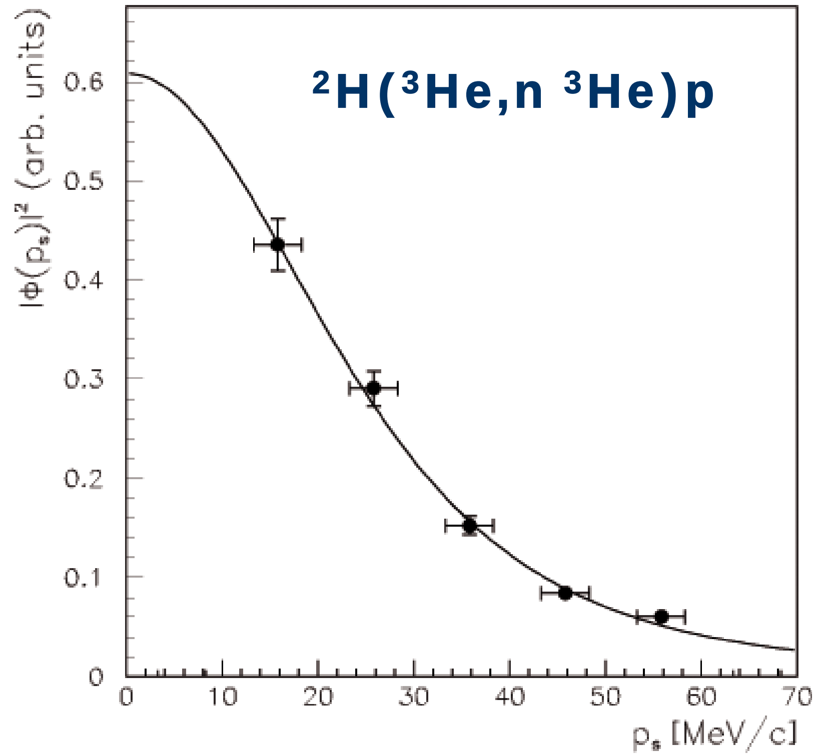


Selection of the quasi-free mechanism

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

$$|\Phi(\overrightarrow{p_s})|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_t d\Omega_p dE_p}}{(KF)\left(\dfrac{d\sigma_{dd}}{d\Omega}\right)^N}$$





Extraction of the two-body cross section (1)

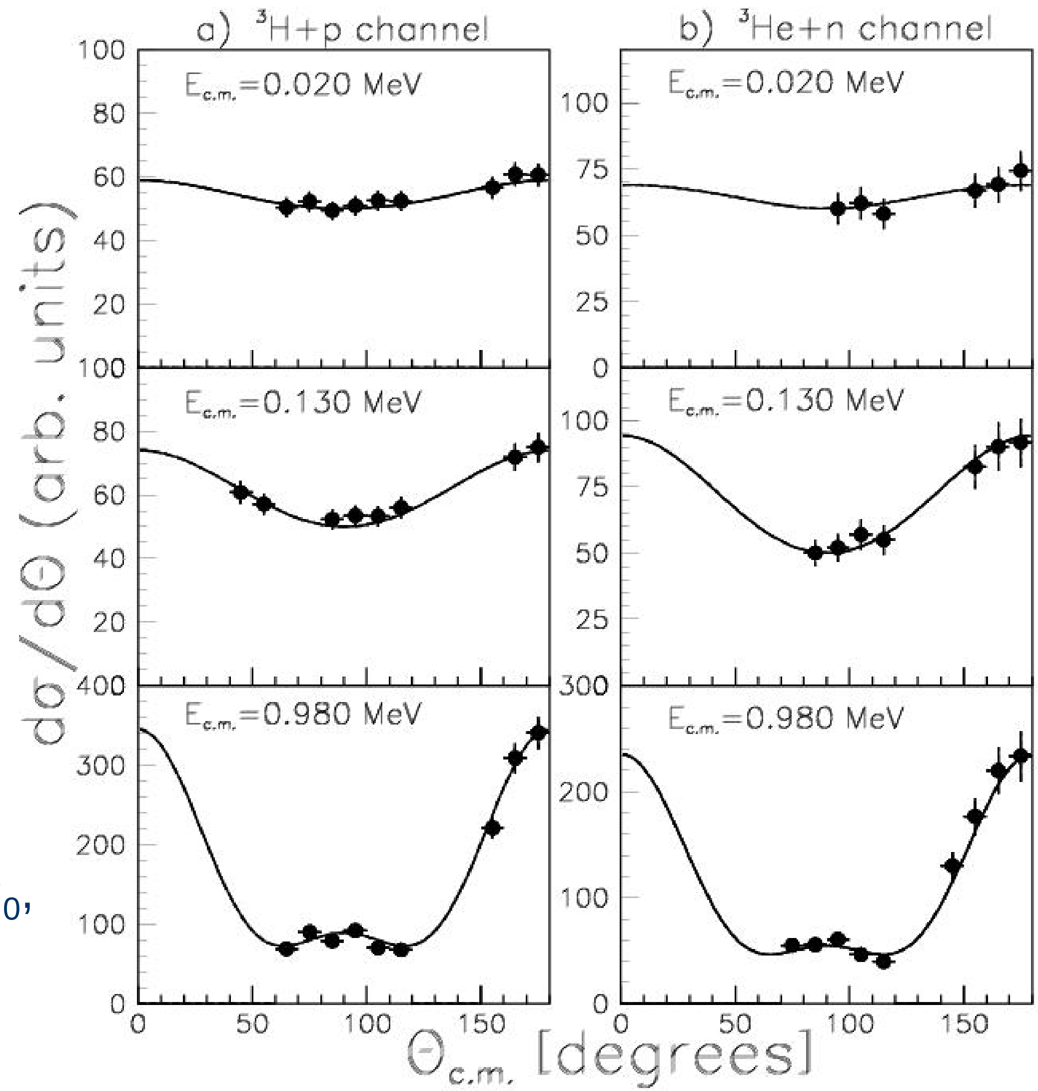
Monte Carlo simulation of the three-body cross section under the assumptions:

- PWIA approach

- Quasi-free contribution is the only reaction mechanism

- a p_s window of 40 MeV/c is considered

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



Solid lines: linear combinations of P_0, P_2 and P_4 from

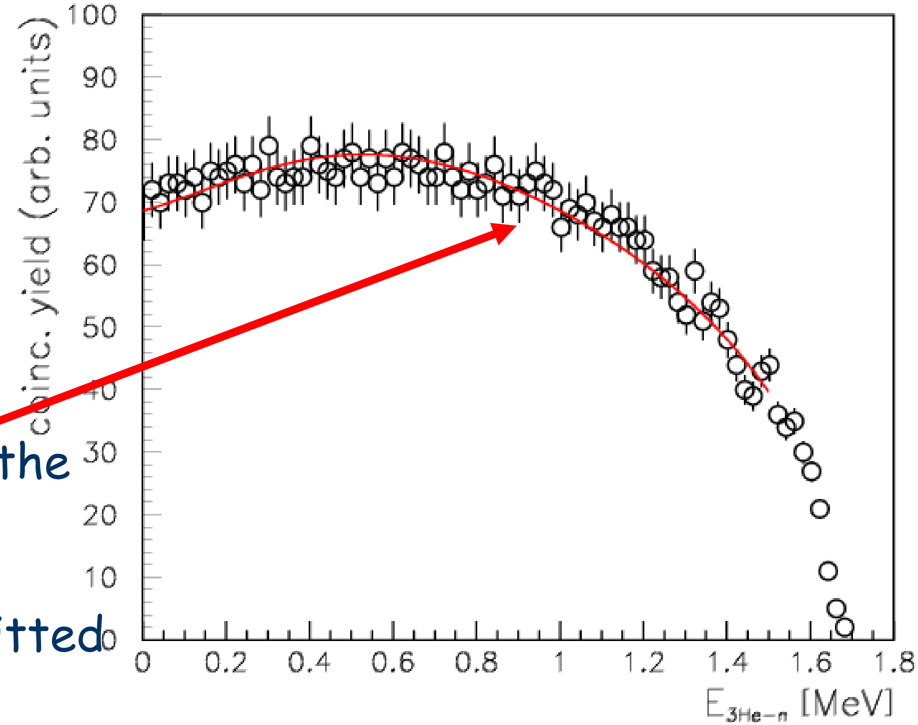
A. Krauss *et al.*, Nucl. Phys. A465, 150 (1987)
R.L. Schulte *et al.*, Nucl. Phys. A192, 609 (1972)

Extraction of the two-body cross section (2)

We learn from the R-matrix parameterization by P. Descouvemont et al., that the energy dependence of the s- and p-wave contributions is very well represented by their penetrabilities

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

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



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

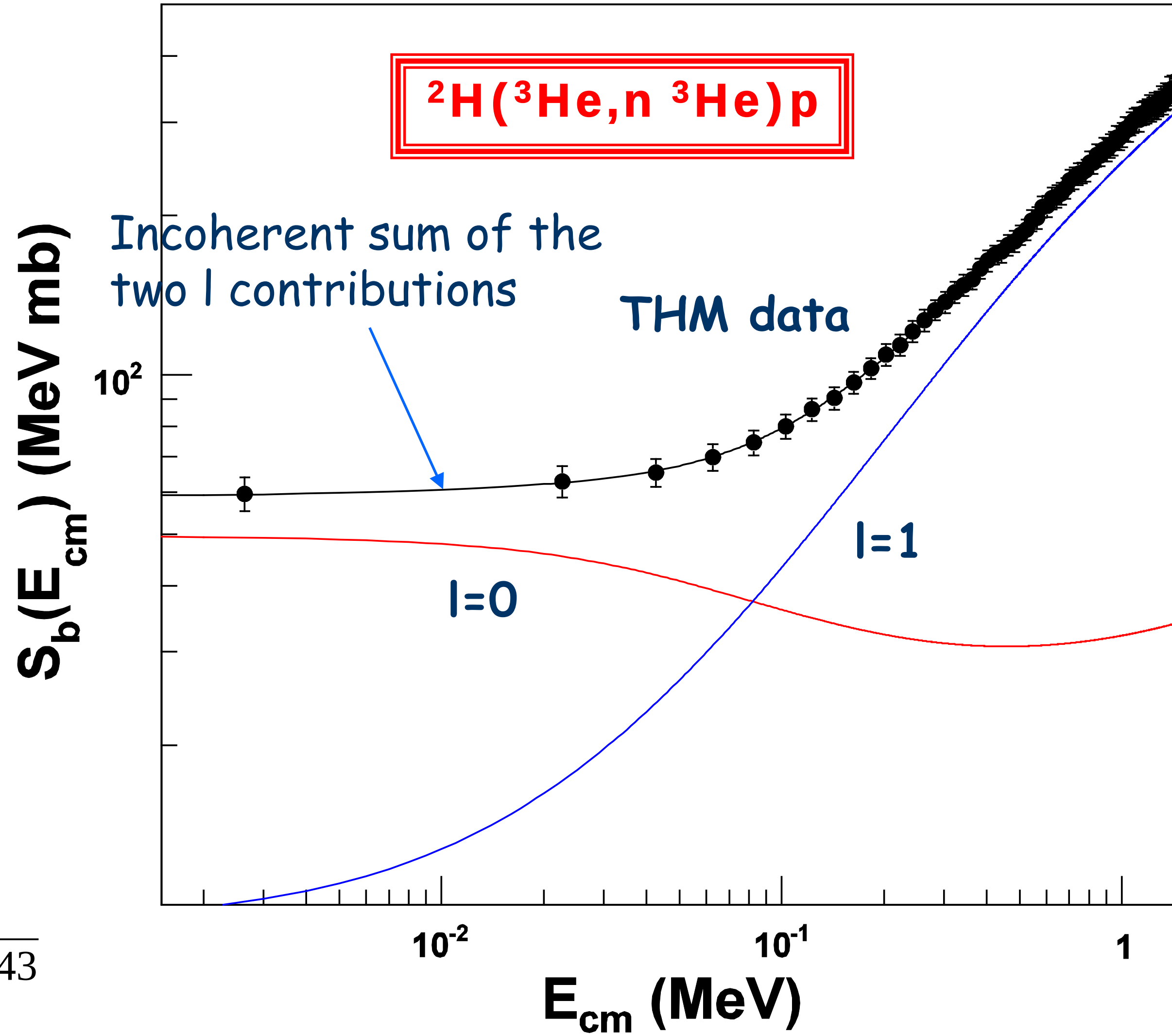
Two coincidence yields per channel to be fitted at the same time

Extraction of the two-body cross section (3)

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

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

Normalization involves 43 TH point → statistical error (about 4%) reduced by $\sqrt{43}$



normalization error of about 1%

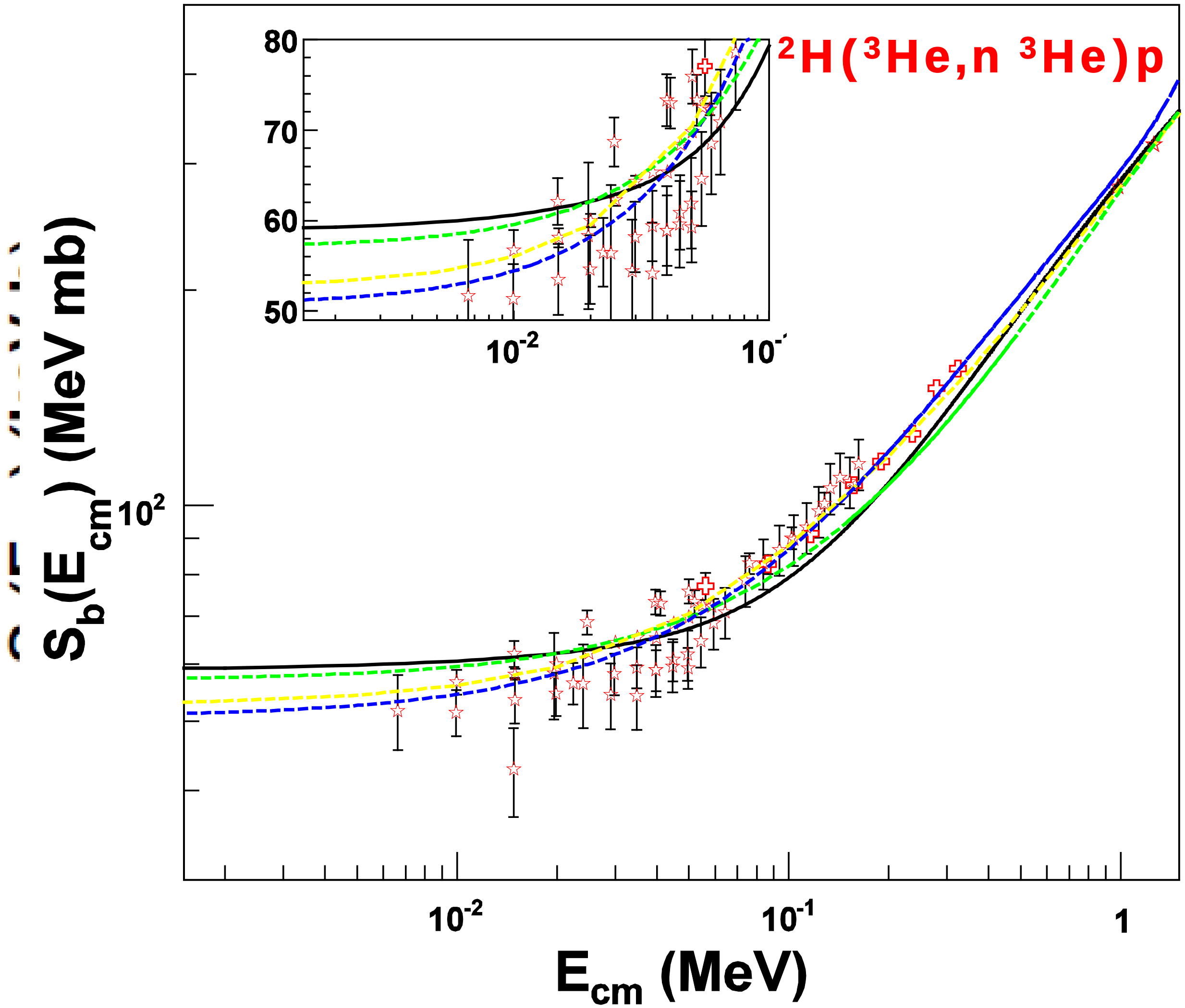
Extraction of the two-body cross section (4)

Comparison between the incoherent sum black line) and direct data (red points)

Yellow line: polynomial expansion reported in the NACRE compilation

Blue line: calculation from the Cyburt compilation

Green line: calculation by P. Descouvemnont et al.



[7] A. Krauss et al., Nucl. Phys. **A465**, 150 (1987)
[8] R.E. Brown and N. Jarmie, Phys. Rev. **C41**, 1391 (1990)
[9] U. Greife et al., Z. Phys. **A351**, 107 (1995)
[10] The First Research Group, The First Research Division, Chin. J. Nucl. Phys. 9 (6) 723 (1985)
[11] R.L. Schulte et al., Nucl. Phys. **A192**, 609 (1972)
[13] D.S. Leonard et al., Phys. Rev. C **73**, 045801 (2006)

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)

Some numbers

S(0) values from THM and from compilations:

S(0) [keV b]	ΔS(0) [keV b]	Ref.
59.1	0.6	Present results from THM
56 keV		C. Angulo et al. NPA656 (1999) 3
50.67 keV		R.H. Cyburt, PRD70 (2004) 023505
52.4 keV	3.5	P. Descouvemont et al. Data Nucl. Data Tables 88 (2004) 203

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%-17%.

No screening potential estimate was possible due to the lack of direct data points in the ultra-low energy region

This will be possible for the ^{3}H+p channel

Conclusions

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

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 will be possible only for the $^{3}H+p$ channel because of the lack of direct data for the $^{3}He+n$ channel in the ultra-low energy region

… next step: calculation of the reaction rate

and investigation of fusion dynamics in plasmas

Thank you!

The collaboration

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