The Electron Screening Effect
in Nuclear Astrophysics

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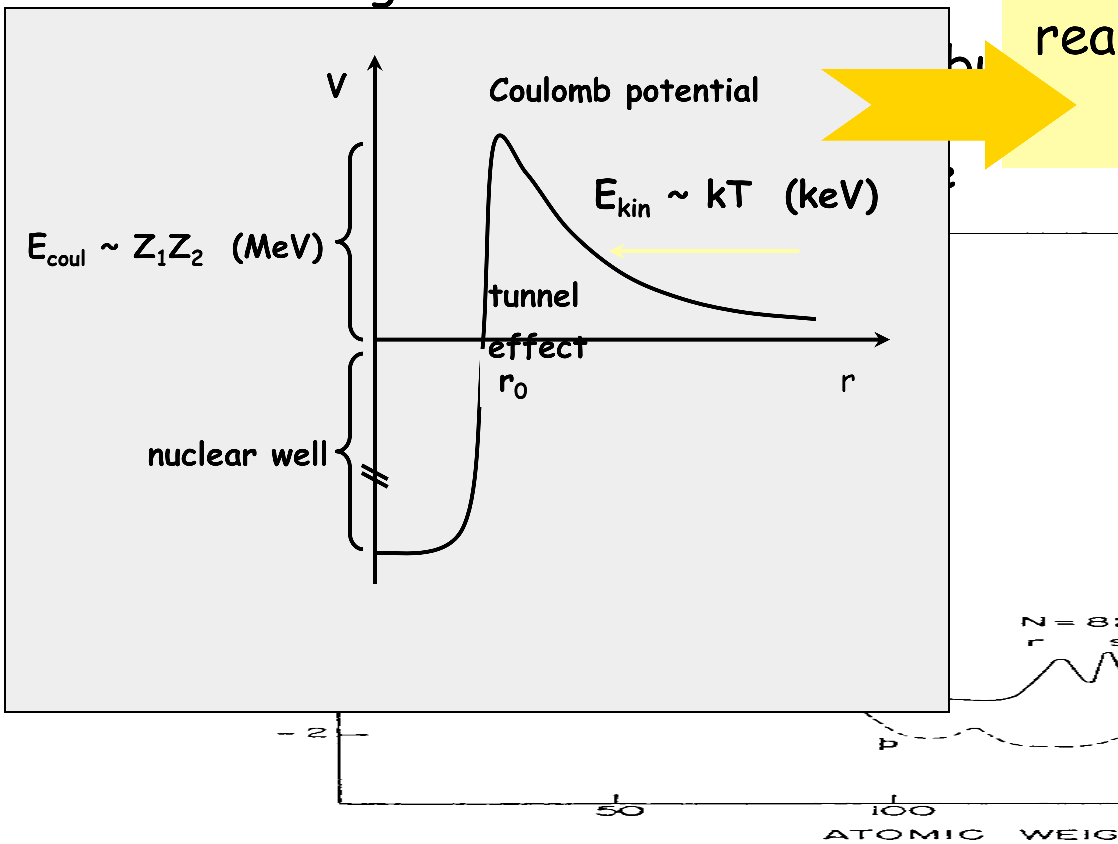
As we have seen in previous talks there are Several open issues which need a strong contribution from experimental nuclear astrophysics

- **Understand energy production in stars**
- **BBN**
- **Nucleosynthesis**
- **Explosive phenomena**

The main problem in the charged particle cross section measurements at astrophysical energies is the presence of the Coulomb barrier between the interacting nuclei



reactions occur through

<u>TUNNEL EFFECT</u>

tunneling probability

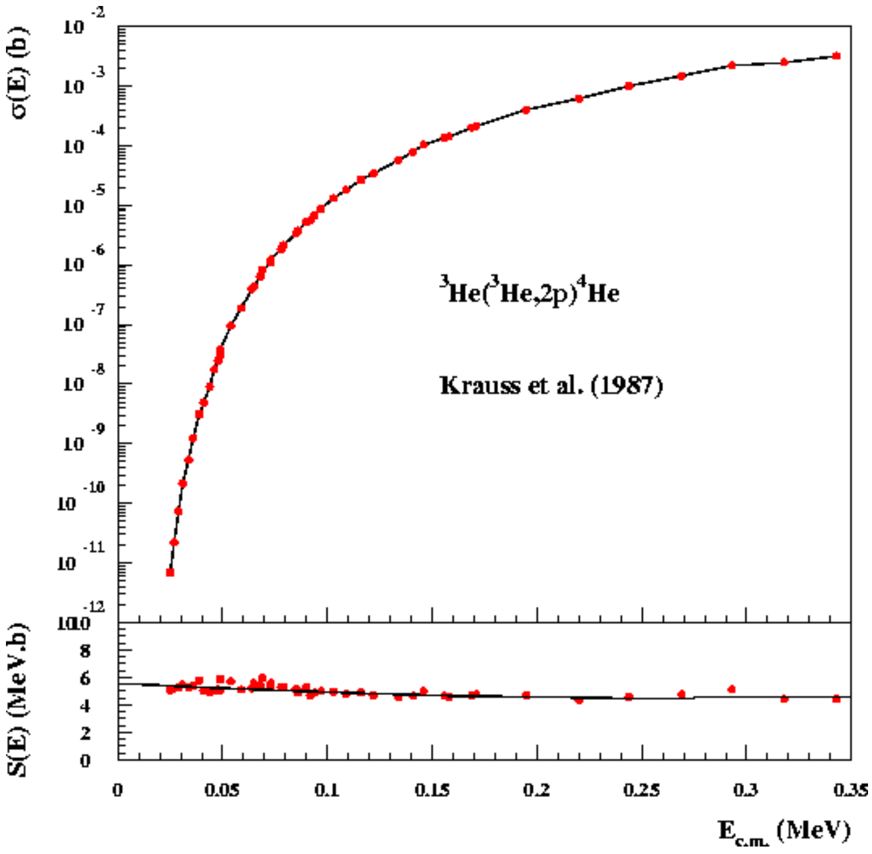
$$P \propto \exp(-2\pi\eta)$$

$2\pi\eta$ = GAMOW factor

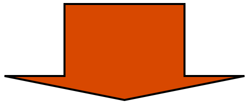
in numerical units:

$$2\pi\eta = 31.29\, Z_1Z_2(\mu/E)^{\frac{1}{2}}$$

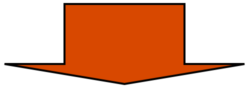
μ in amu and E_{cm} in keV



@ Gamow energies



σ in the range nano-picobarn



in general, their direct evaluation is

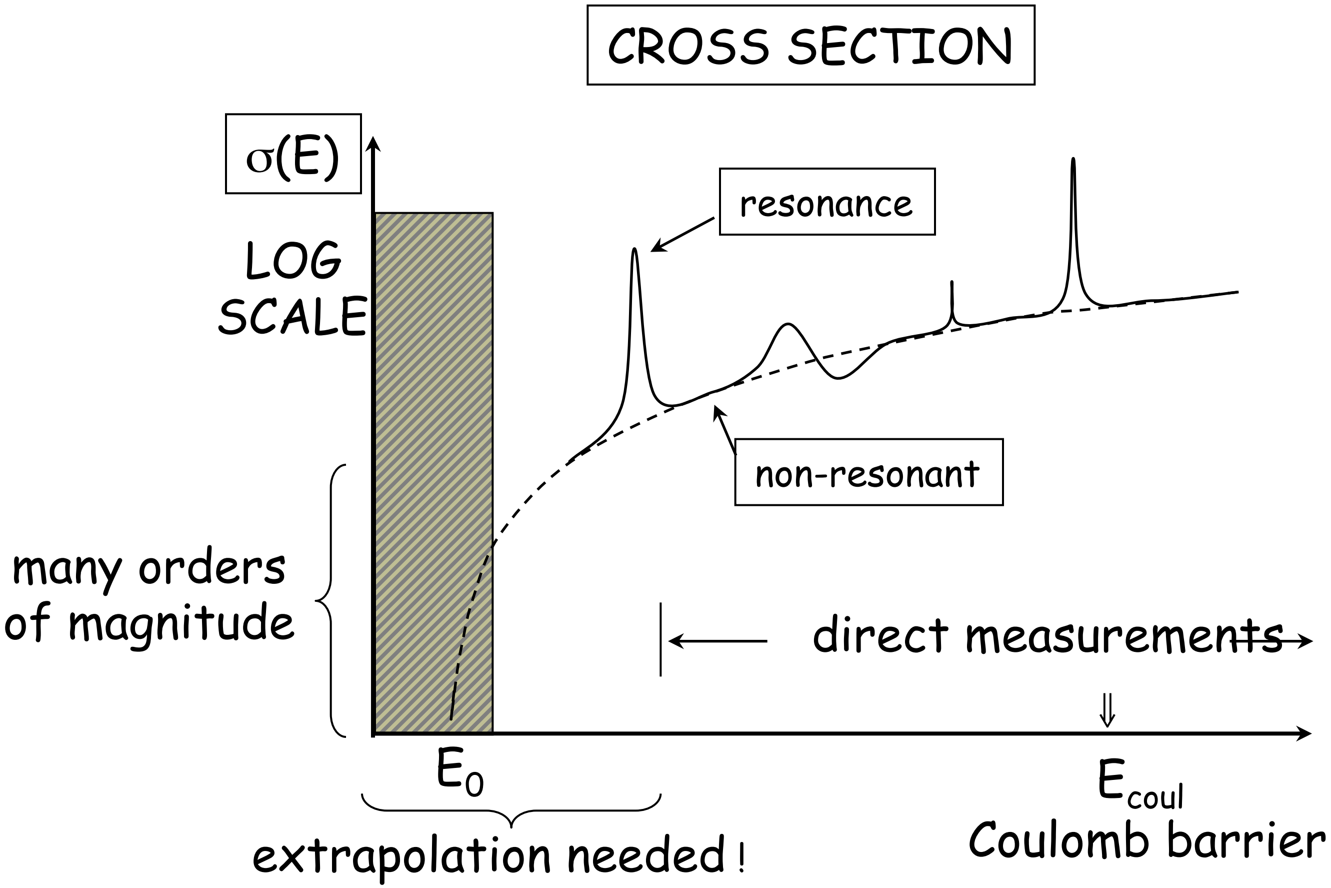
-severely hindered

-and in some cases even beyond present technical possibilities.

Possible solutions: underground measurements, extrapolations

Experimental procedure

Bare Nucleus Astrophysical S(E)-factor is introduced.
energies (Gamow energies) could be estimated by extrapolating measurements performed at higher energies



The DANGER OF EXTRAPOLATION ...

large uncertainties in the extrapolation!

Necessary is Maximize the signal-to-noise ratio

SOLUTIONS

- IMPROVEMENTS TO INCREASE NUMBER OF DETECTED PARTICLES

4π detectors

New accelerator at high beam intensity

- IMPROVEMENTS TO REDUCE THE BACKGROUND

Use of laboratory with natural shield - (underground physics)

Use of magnetic apparatus (Recoil Mass Separator)

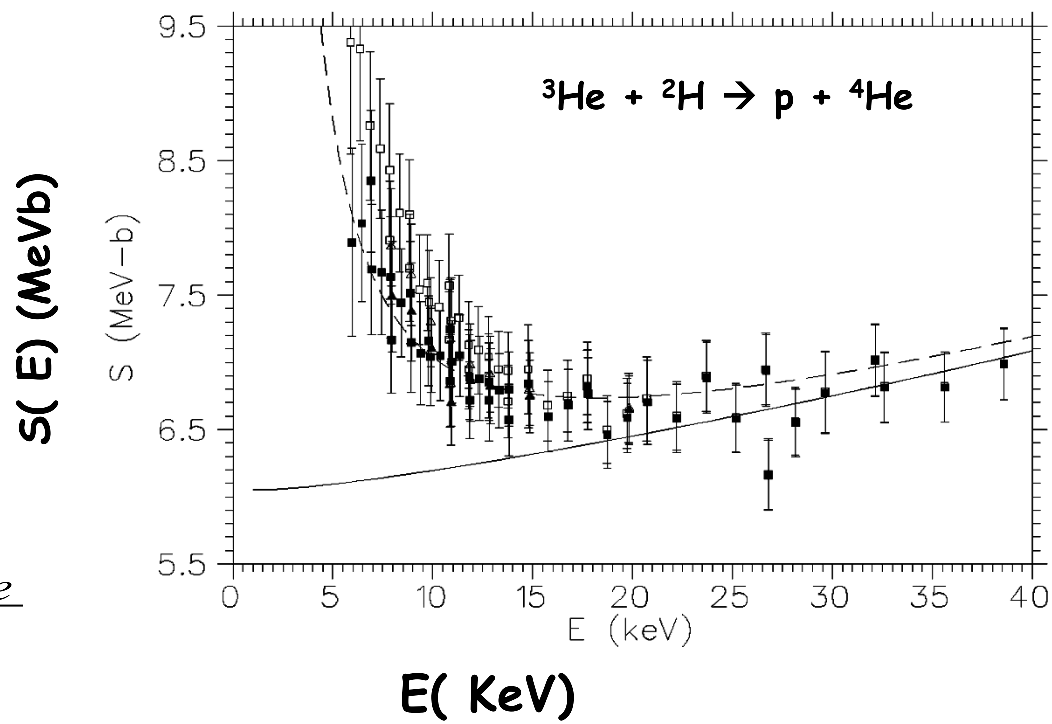
However

The electron screening effect must be taken into account

(Assenbaum,Langanke,Rolfs: Z.Phys.327(1987)461)

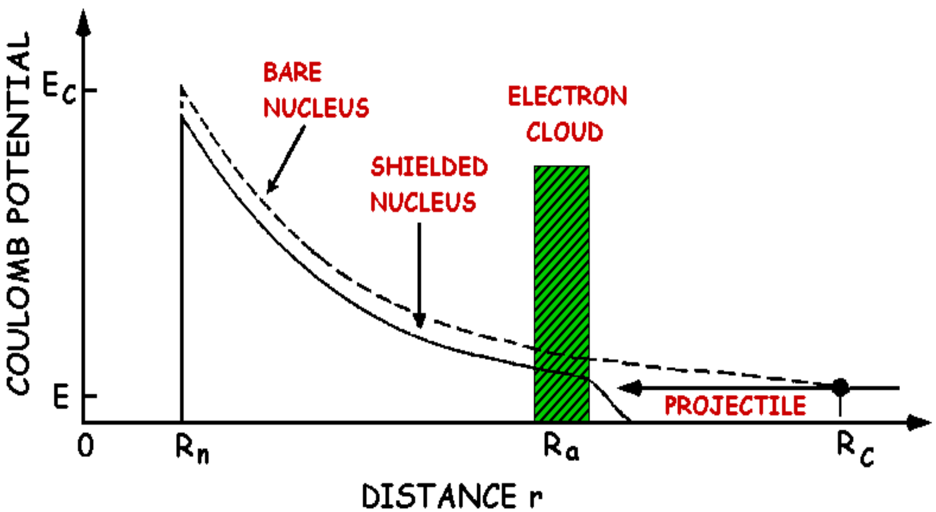
In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{lab}(E)$ –factor in the astrophysical $S_b(E)$-factor has been found

$$S_{Sh} \propto S_b \cdot e^{\frac{\pi\eta U_e}{E}}$$



Electron Screening

At astrophysical energies the presence of electron clouds must be taken into account in laboratory experiments.



The atomic electron cloud surrounding the nucleus acts as a screening potential U_e

- Phenomenological approach

(Assenbaum H.J. et al.: 1987, Z. Phys., A327, 461)

$$U_e = \frac{Z_1 Z_2 e^2}{R_a} \qquad R_a \approx \frac{R_B}{Z_1}$$

R_B: raggio di Bohr

- Adiabatic approximation

Adiabatic approximation (low velocity case)

If $v_p << v_B = Z\alpha c$ (low velocity case) the electrons continuously rearrange their orbits while projectile and target approach each other, i.e. the electron wave function re-adjust itself continously

Bracci et al. (1990)

at any time it is an eigenfunction of the two-center Hamiltonian.

$^3He(d,p)^4He$	119 eV
$^7Li(p,a)^4He$	186 eV
$^6Li(d,a)^4He$	186 eV

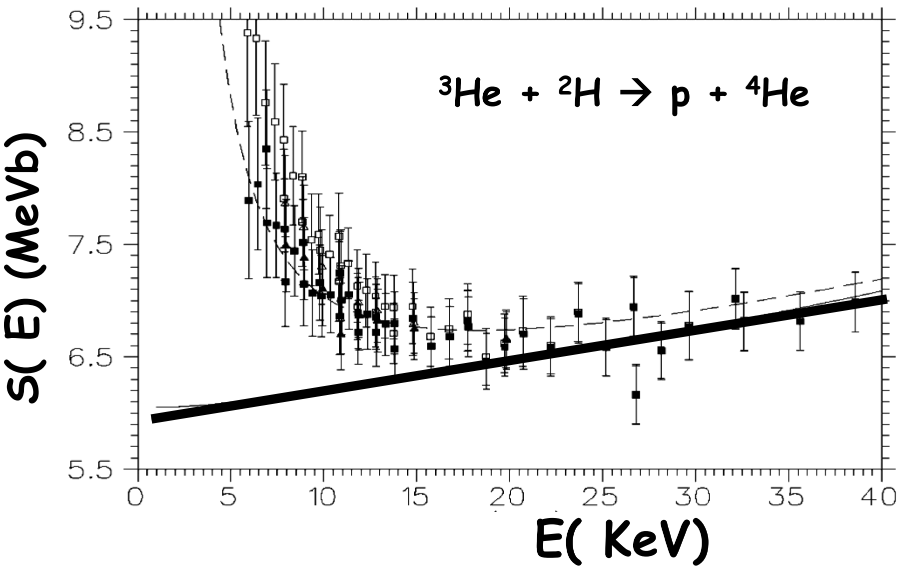
In this approximation the electron screening potential is

$$U_{ad} = E^{(1)} + E^{(2)} - E^{©}$$

with E(i) electronic binding energy of the i-th atom and E© the electronic binding energy of the compound nucleus

Electron screening in the laboratory

Direct Measurements



An experimental measurement of U_e allows:

- a determination of S_b (applications)
- to study electron screening in laboratory conditions and then in stellar plasma

Stellar Screening ≠ Laboratory Screening

Experimental Data (Shielded)

Extrapolation of S_b (Bare) Autofitting procedure

Correction for stellar screening (Debye-Hückel theory)

Systematic discrepancy

$$(U_e)_{exp} \gg (U_e)_{ad}$$

Values of U_e were estimated for several reactions by means of comparison between direct data with extrapolations

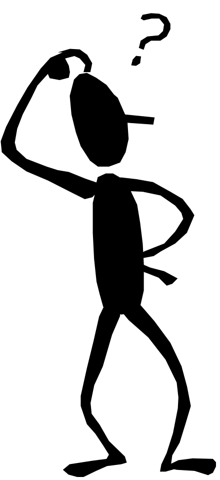
U_e (ad)	U_e $^6Li(d,\alpha)^4He$	U_e $^7Li(p,\alpha)^4He$	U_e $^6Li(p,\alpha)^3He$
186 eV	330 ± 120 eV	300 ± 160 eV	440 ± 80 eV

(Engstler S. et al.: 1992, Z. Phys., A342, 471)
(Prati P. et al.: 1994, Z. Phys., A350, 171)
(Zahnow D. et al.: 1997, Z. Phys., A359, 211)

Works made in a long campaign by Rolfs' group

Possible explanations:

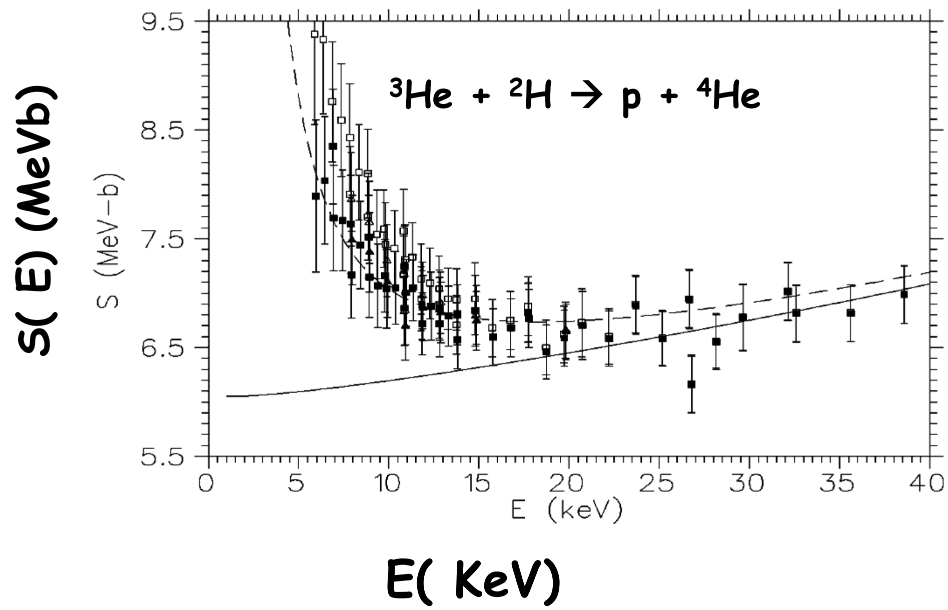
- lack of knowledge for energy loss at E<100 keV;
- extrapolation of $S_b(E)$ at astrophysical energies;
- theoretical models of electron screening (atomic physics)



IN SUMMARY…

To avoid extrapolations, experimental techniques were improved;

(R.Bonetti et al: Phys. Rev. Lett.82,(1999),5205)



After improving measurements (at very low energies), electron screening effects were discovered;

To extract from direct (shielded) measurements the bare astrophysical $S_b(E)$ -factor, extrapolation were performed at higher energy

Can a metallic environment simulate stellar plasma?

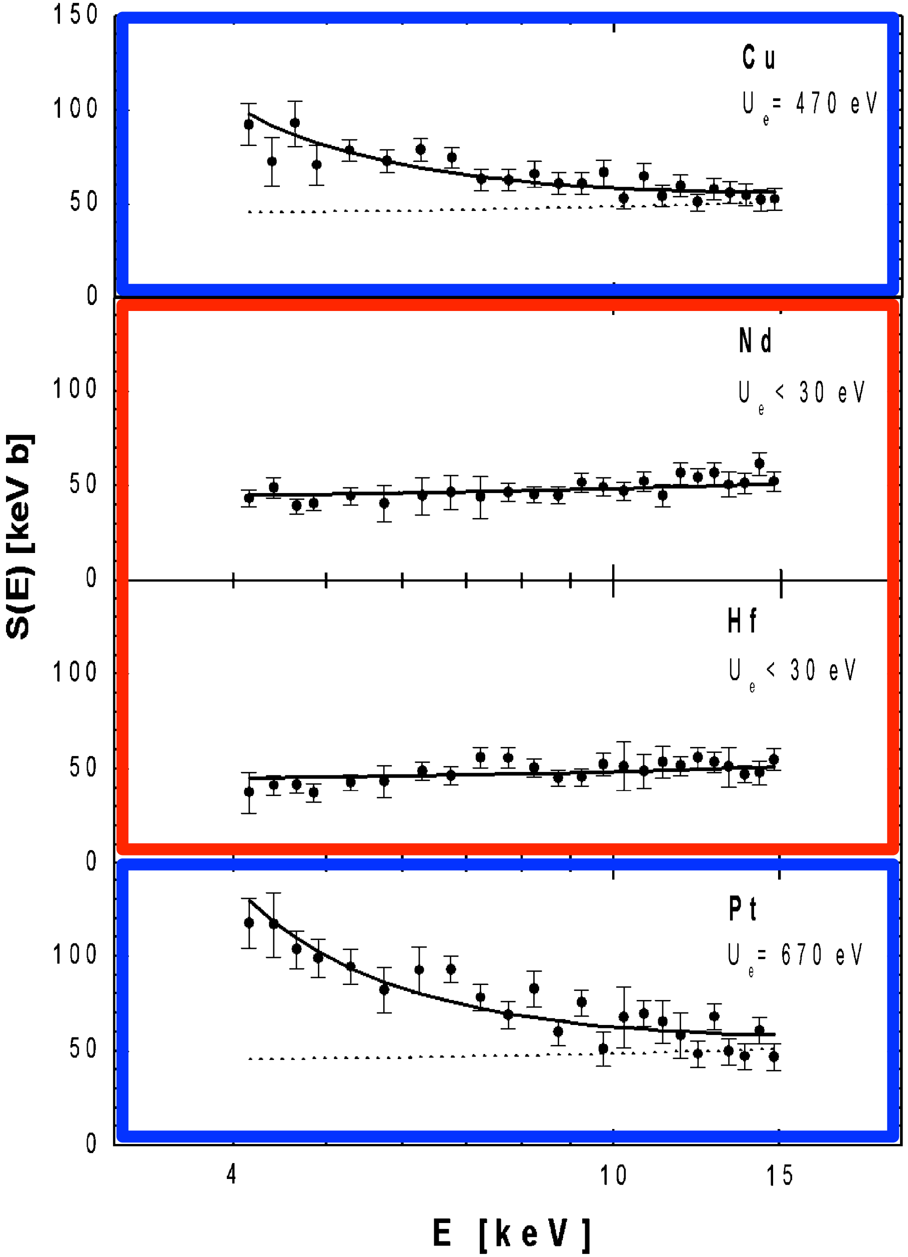
Czerski K. et al.: Europhys. Lett. 54 (2001) 449

Study of electron screening for D(d,p)t in deuterated targets (Ti,Al,Zr)
"the plasma of the poor"

U_e (D-metal) ~ 10-30 times than in U_e (D-gas)

Systematic study (58 samples) of Ue in D(d,p)t in deuterated metals

- Electron screening potential was measured for d(d,p)t reaction with deuterons implanted in metals
- Large values (Ue>> adiabatic approx.) were measured
- Several years of work of Claus' group in Bochum (with Catanese contaminants), Berlin, Japan and other places



A more enhanced screening effect is seen in metals (blue) (U_{ad}=30 eV)

Raiola et al. EPJ A,2002 & 2004

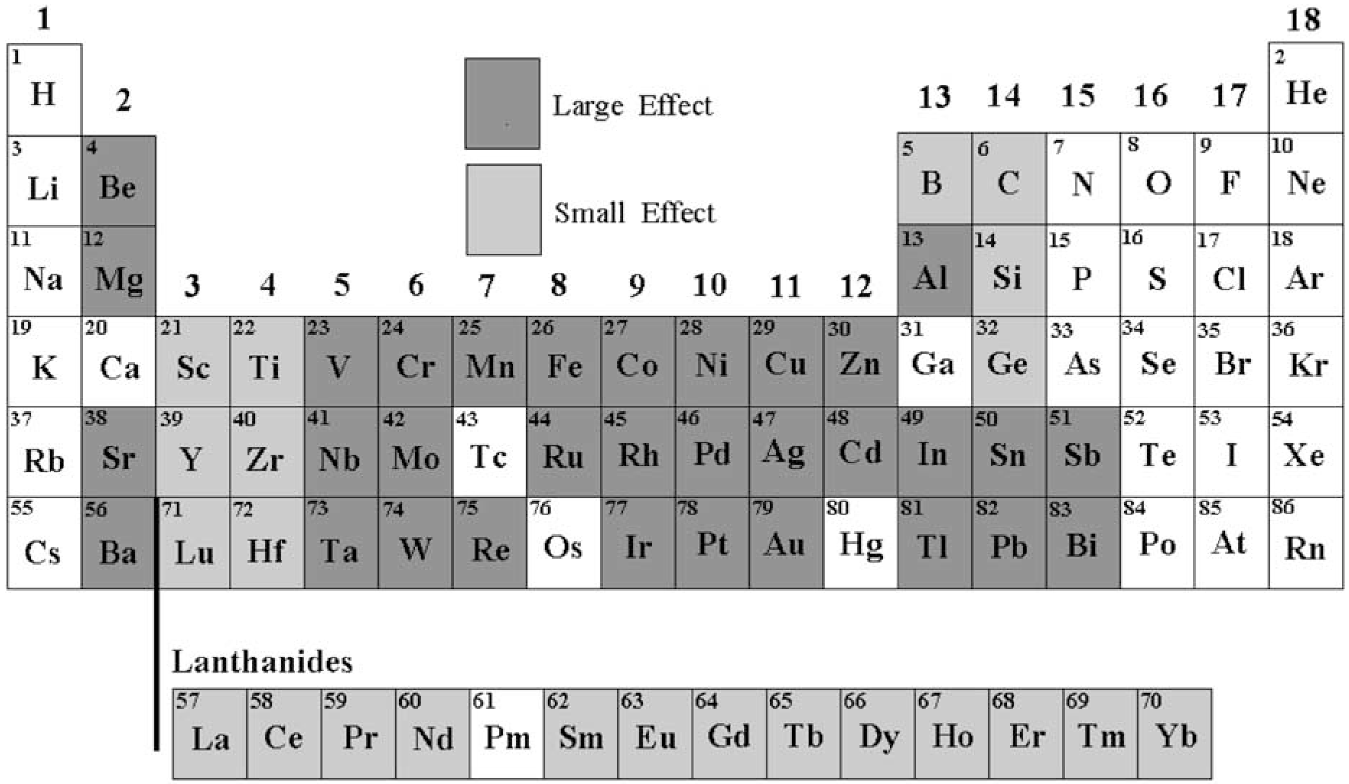


Fig. 2. Periodic table showing the studied elements, where those with low U_e values ($U_e < 100$ eV, small effect) are lightly shadowed and those with high U_e values ($U_e \geqslant 100$ eV, large effect) are heavily shadowed.

Idea: quasi-free electrons in a metal could simulate free electrons in stellar plasma (classical picture).

$$R_{Debye} = \left(\frac{\varepsilon_0 kT}{n\rho_a e^2} \right)^{1/2}$$

$$U_e = \frac{Z_1 Z_2 e^2}{R_{Debye}}$$

$$U_e \propto T^{-1/2}$$

Example:

$T = 293\ K$

$n = 1$

$\rho_a = 6 * 10^{22}\ cm^{-3}$

$U_e = 300\ eV$

Electron screening in stars is rather different than in lab … and to assume stellar plasma behaves like "poor plasma" in metals is just a hipothesis

Up to now: Correction of the reaction rate for stellar screening (Debye-Hückel theory)

$$U_e = \frac{Z_1 Z_2 e^2}{R_{Debye}} \qquad f_{star} \propto \langle \sigma v \rangle \, e^{\frac{\pi \eta U_e}{E}}$$

i.e. it is assumed a correction to the bare nucleus reaction rate which depends on stellar plasma conditions

Independent measurements of bare nucleus S(E) factor and electron screening potential U_e are needed !!!

NEW METHODS ARE NECESSARY

-to measure cross sections at never reached energies

-to retrieve information on electron screening effect when ultra-low energy measurements are available.

INDIRECT METHODS ARE NEEDED

Main Indirect Metods

a) - Coulomb dissociation

to study radiative capture reactions

b) - Asymptotic Normalization Coefficients (Anc) …to extract direct capture cross sections using peripheral

transfer reactions

c) – Beta Delay decays studies and other methods

d) - The Trojan Horse Method (THM)

to extract charged particle reaction cross sections using

the quasi-free mechanism…

Trojan Horse Method (outlook)

Main application:

Charged particle bare nucleus cross section measurements at astrophysical energies

Basic idea:

It is possible to extract astrophysically the relevant two-body cross section σ

$$B + x \rightarrow C + D$$

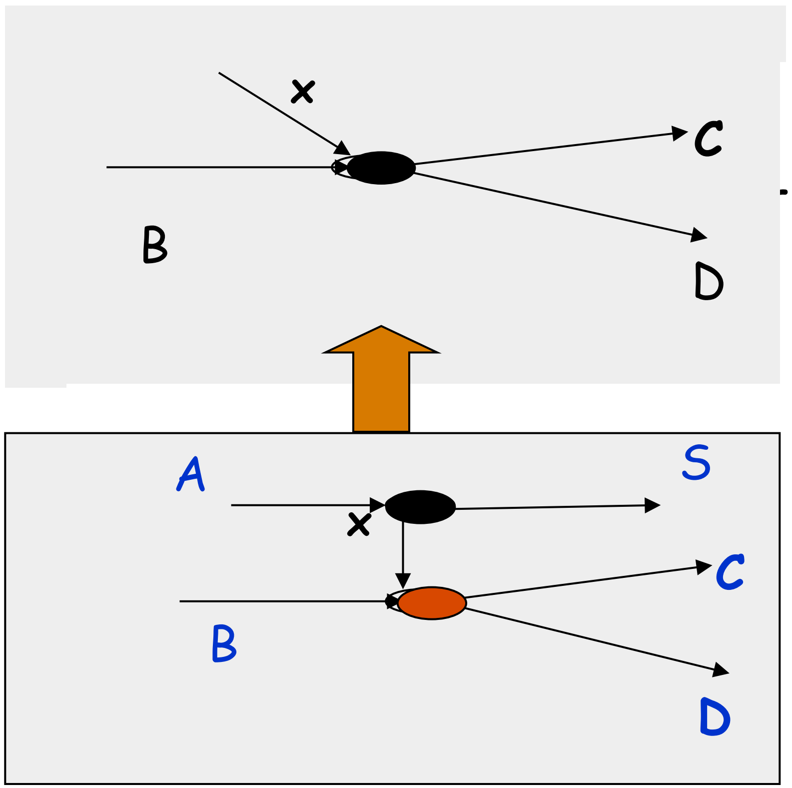
from quasi- free contribution of an appropriate three-body reaction

$$A + B \rightarrow C + D + S$$

SEE SILVIO'S LECTURE

Trojan Horse Method (outlook)

Quasi-Free mechanism



Basic idea:

It is possible to extract astrophysically the relevant two-body cross section σ

B + x → C + D

from quasi- free contribution of an appropriate three-body reaction

-The A nucleus present a strong cluster structure: A = x ⊕ S clusters

-The x cluster (participant) interacts with the nucleus B

B + x → C + D

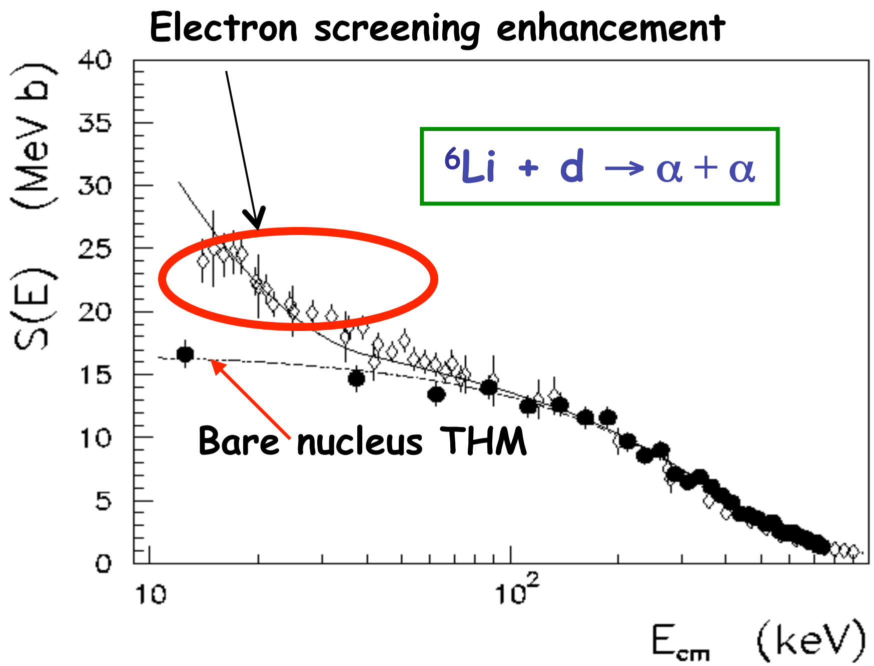
-The S cluster acts as a spectator

(it doesn' t take part to the reaction)

A + B → C + D + S

SEE SILVIO'S LECTURE

Results for Lithium I



U_e=340±50 eV

U_{ad}=186 eV

S_0=16.9 MeV b

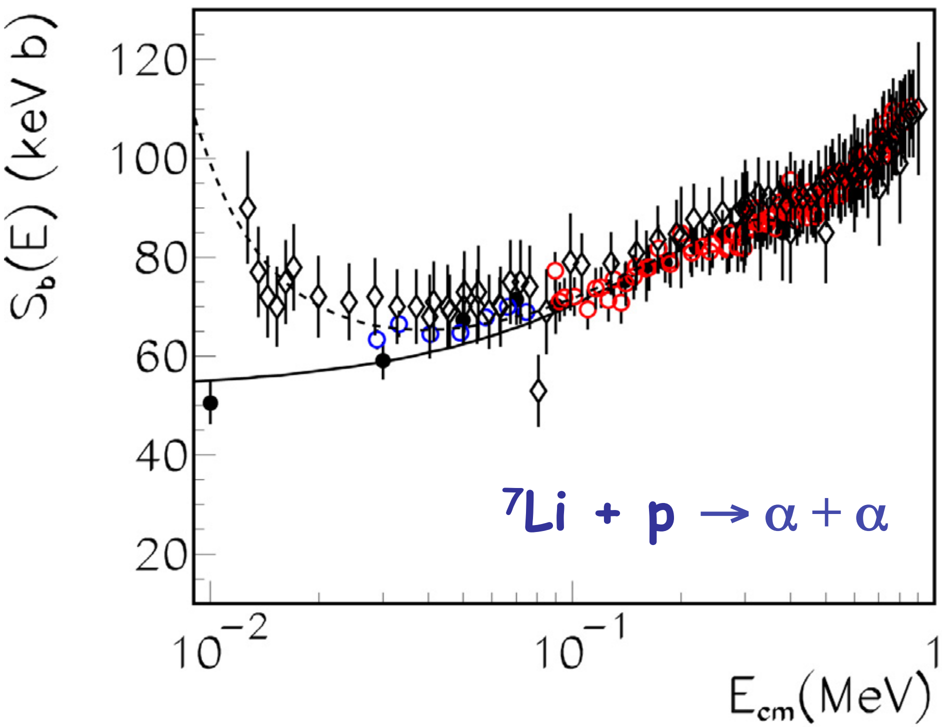
◊ Engstler S. et al.: 1992, Z. Phys., A342, 471

• C. Spitaleri et al.: 2001, Phys. Rev. C. 63, 055801

S. Cherubini et al.: 1996 Ap. J., 457, 855

- No screening effect at E<100 keV for indirect data;
- Direct and indirect methods are complementary;
- Independent determination of $S_b(E)$ and U_e;
- Previous extrapolations of S_b are confirmed.

Results for Lithium II (see talk Lamia)



U_e=425 ±60 eV

U_{ad}=186 eV

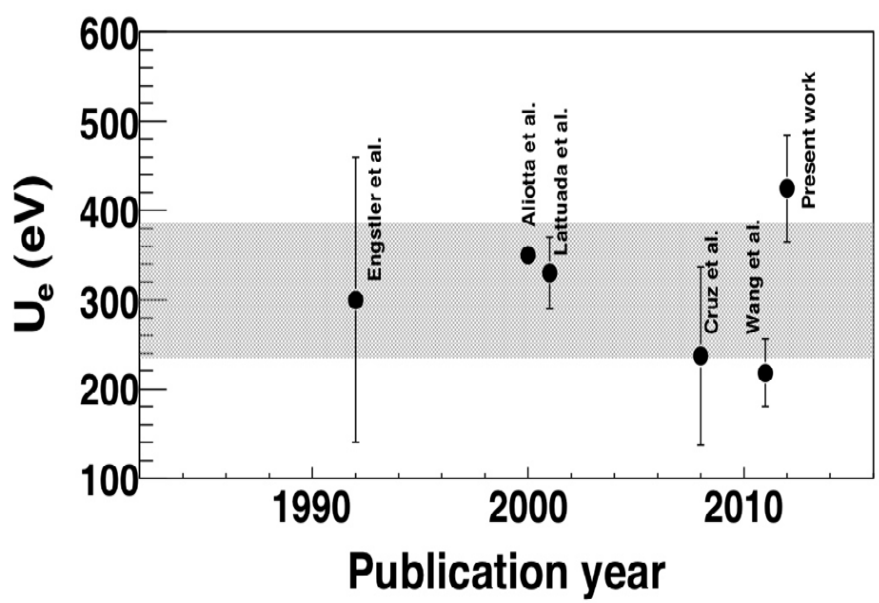
S_0=53 ± 5 keV b

◊ Engstler S. et al.: 1992, Z. Phys., A342, 471

- **Lamia L. et al.: 2012, Astr. & Astroph. 158**

Pizzone R.G. et al.: 2003, A.& A.. 9, 435

- Previous extrapolations of $S_b(E)$ are confirmed;
- Independent measurement of U_e.



RESULTS FOR LITHIUM III

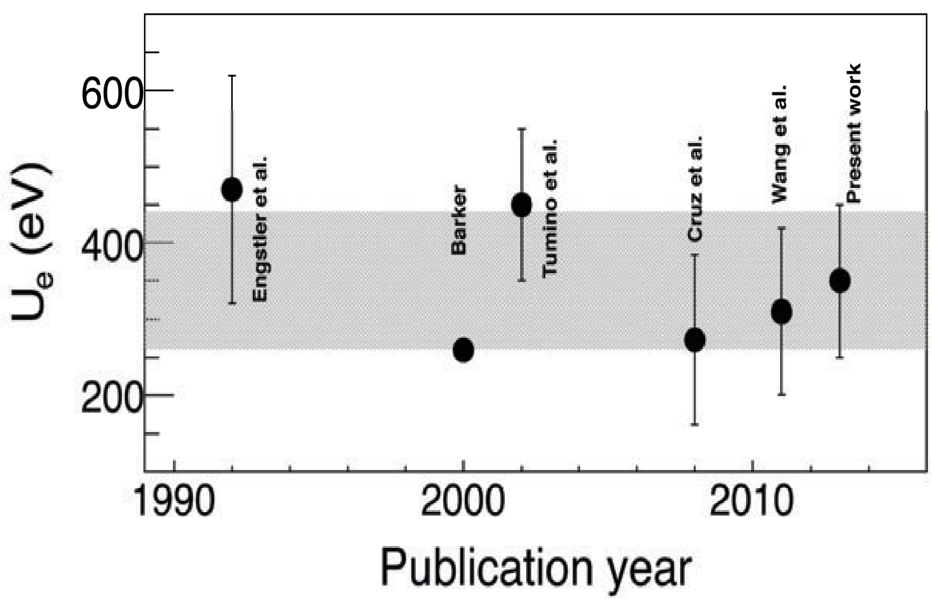
(see Talk Lamia)

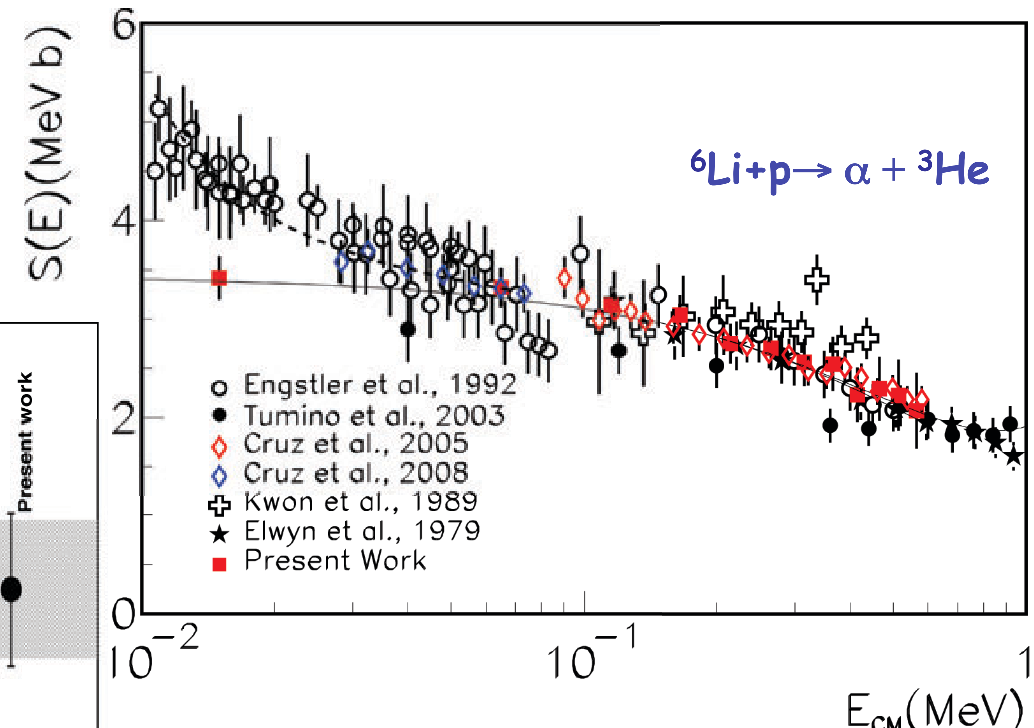
U_e=355 ±100 eV

U_{ad}=186 eV

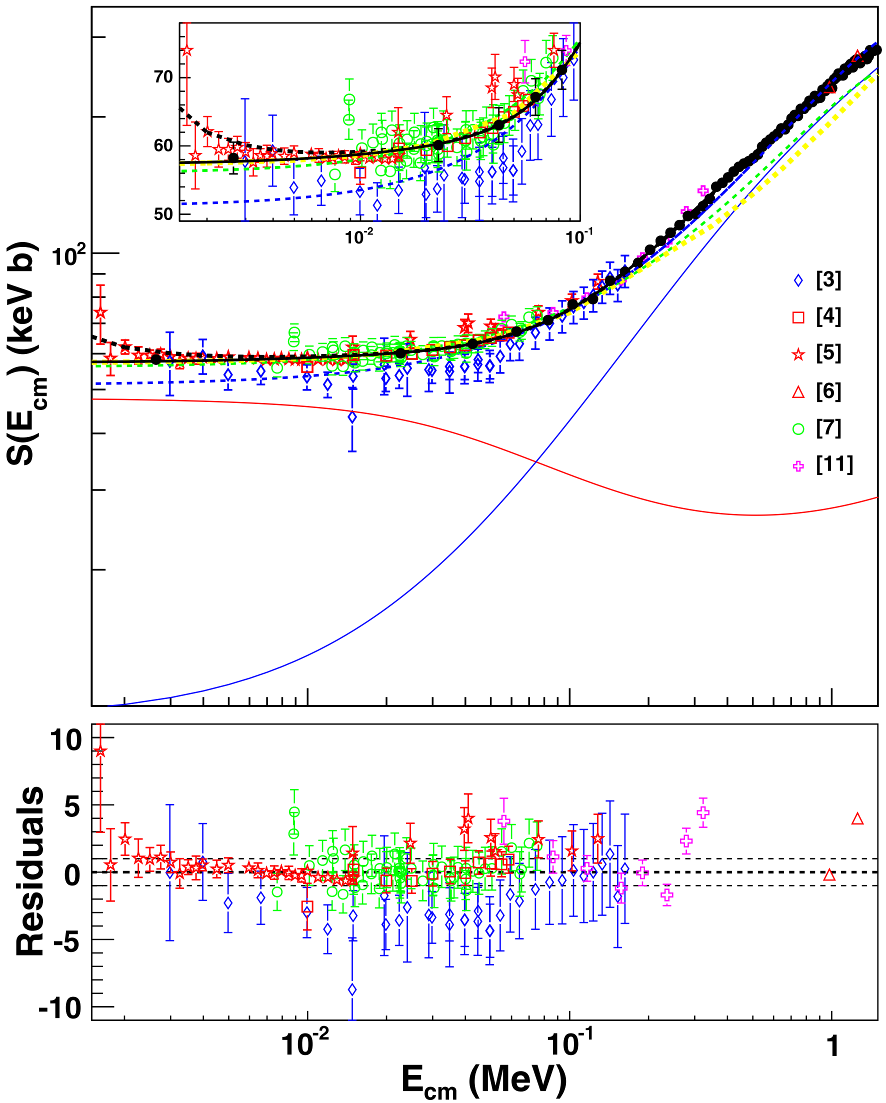
S_0=3.44 ± 0,35 MeV b

L. Lamia et al., in press on APJ **(2013)**
R.G. Pizzone et al A.& A. 2005, 5754





Results for d(d,p)t



U_e= 13,2±2 eV

U_{ad}=14 eV

S_0=57.4 ± 1,8 keV b

Only case in agreement with adiabatic limit, investigation still going on.

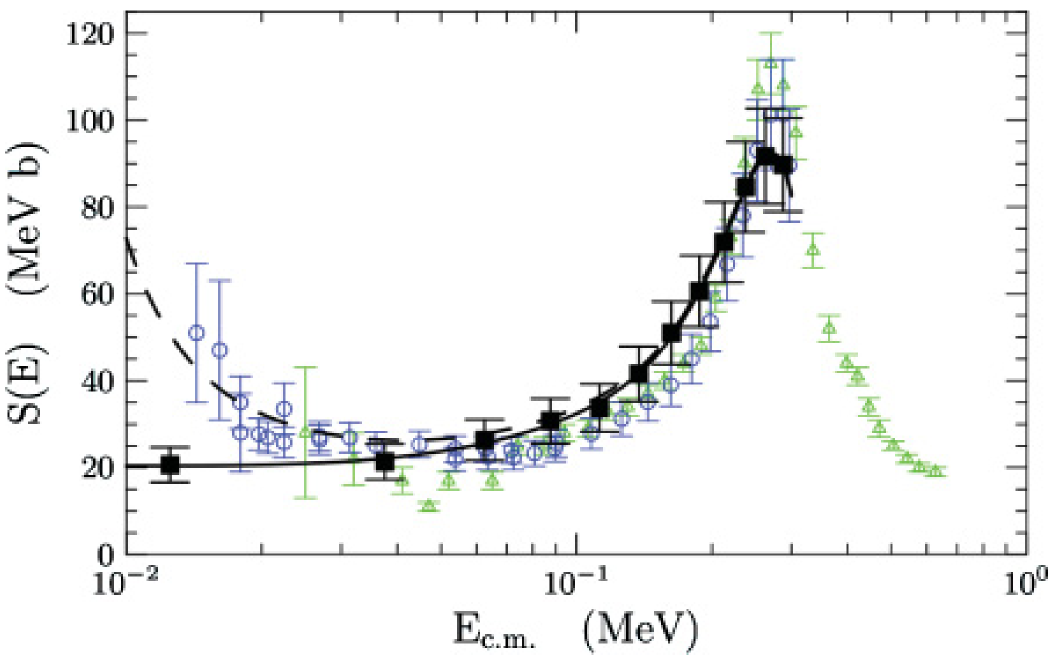
A. Tumino et al. Phys. Lett. B 700 (2011)

RESULTS FOR $^{9}Be(p,\alpha)^{6}Li$

U_e=676 ±86 eV

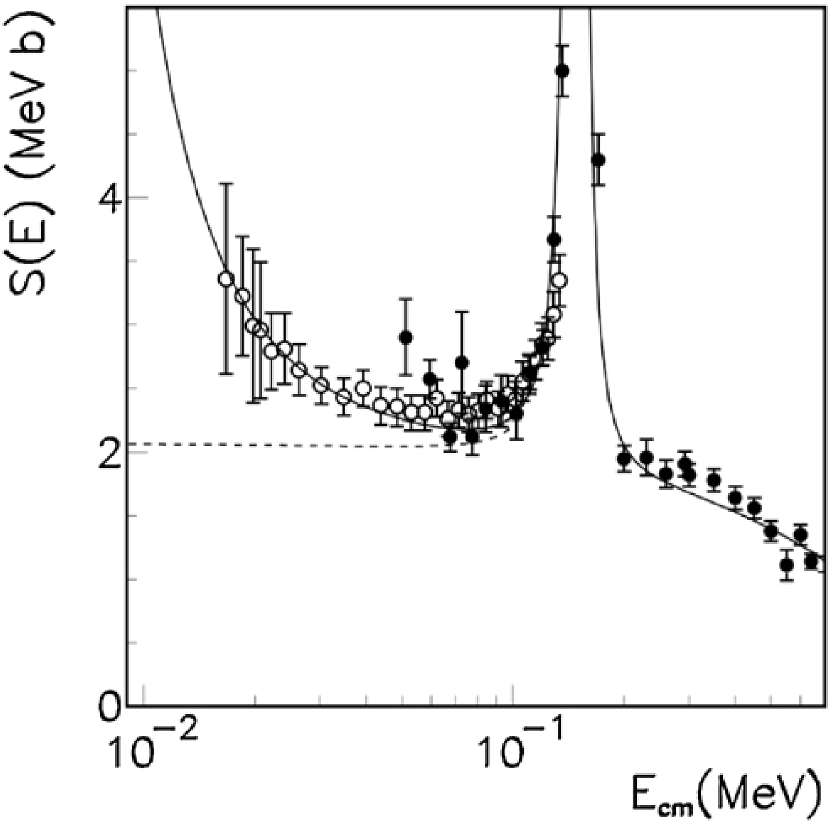
U_{ad}=240 eV

S_0=21 ± 0,8 MeV b



Q. Wen et al., PHYS. REV. C **78**, 035805 (2008)

Results for $^{11}B + p$



$U_e = 472 \pm 160$ eV

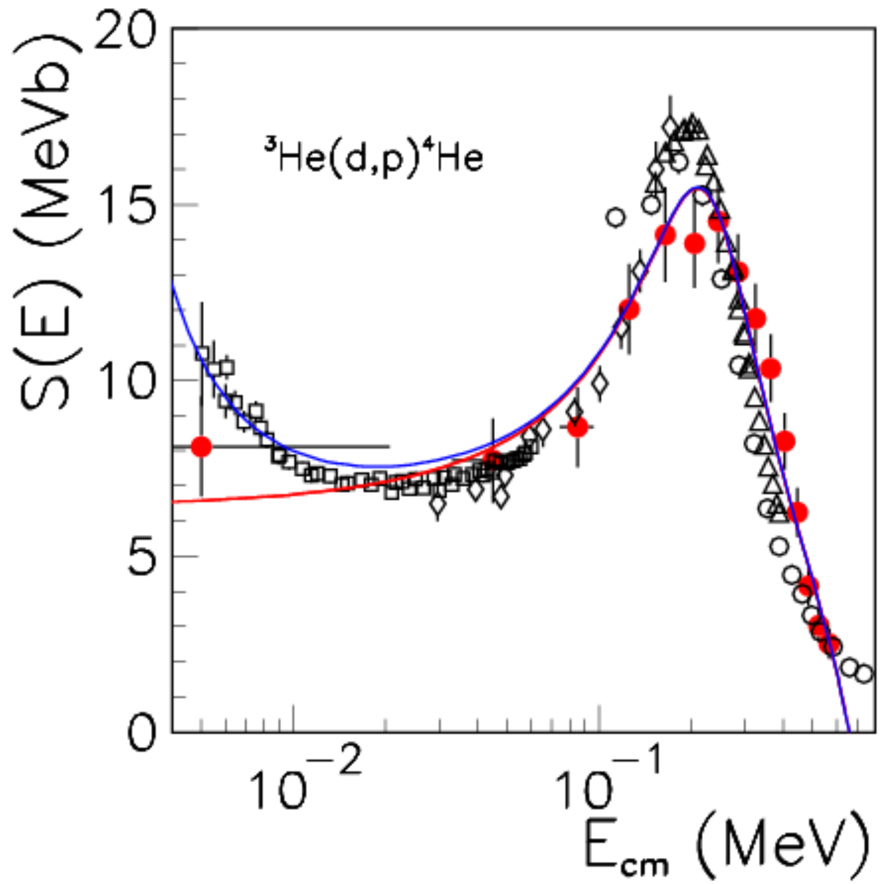
$U_{ad} = 340$ eV

$S_0 = 2{,}07 \pm 0{,}41$ MeV b

L. Lamia et al. J. Phys. G 39 (2012) 015106

▪ For the $^3He(d,p)^4He$ case (La Cognata et al. 2005):

U_e (theo)	U_e(THM) ^{3}He+d	U_e (Dir) ^{3}He+d
115 eV	155 ± 15 eV	175 ± 30 eV



The reaction $^3He(d,p)^4He$ is important for primordial nucleosynthesis as well as stellar one.

- **Summary for reactions on the examined isotopes:**

Previous extrapolations for bare nucleus S(E)-factor as well as the electron screening potential are confirmed (statistical error only)

Systematic Discrepancy with adiabatic limit as in direct data

Isotopic effect confirmed

Still very active field of research

New possibility: plasma physics, lasers applications …

The best is yet to come!!

References

- Assembaum et al., Z. Phys. A, 327, 461-468
- C. Bertulani's Lecture
- F. Strieder et al., Naturwissenschaften, 88, 2001
- R.G. Pizzone et al. , Nucl. Phys. A, 834, 673c
- C. Spitaleri et al., Nucl. Phys. A, 719, 99c 2003
- S. Cherubini's Lecture
- Raiola F. et al., Eur. Phys. J. A, 27, 79

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