Few-body reactions investigated via the Trojan Horse Method

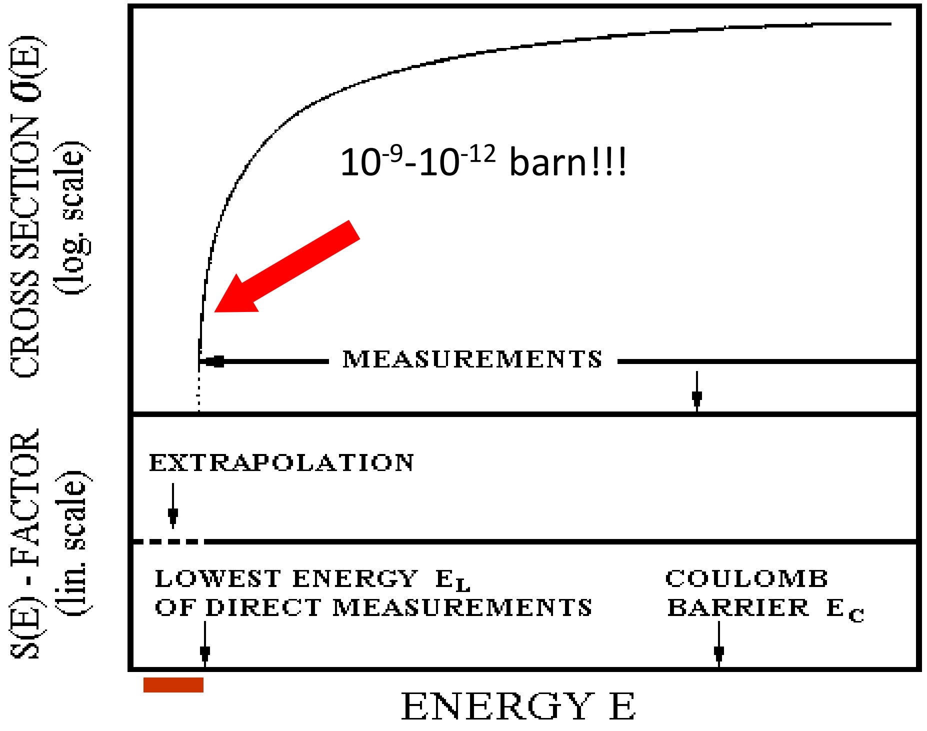
Roberta Spartà
Catania - Italy

Outline

- The need of indirect methods and THM basics
- p-p scattering and suppression of the Coulomb barrier
- d-d reactions and the polar invariance test (clusters)
- News on THM

Nuclear astrophysics: troubles for measurements @ low energies

The main problem at astrophysical energies is the presence of the Coulomb barrier between the interacting nuclei

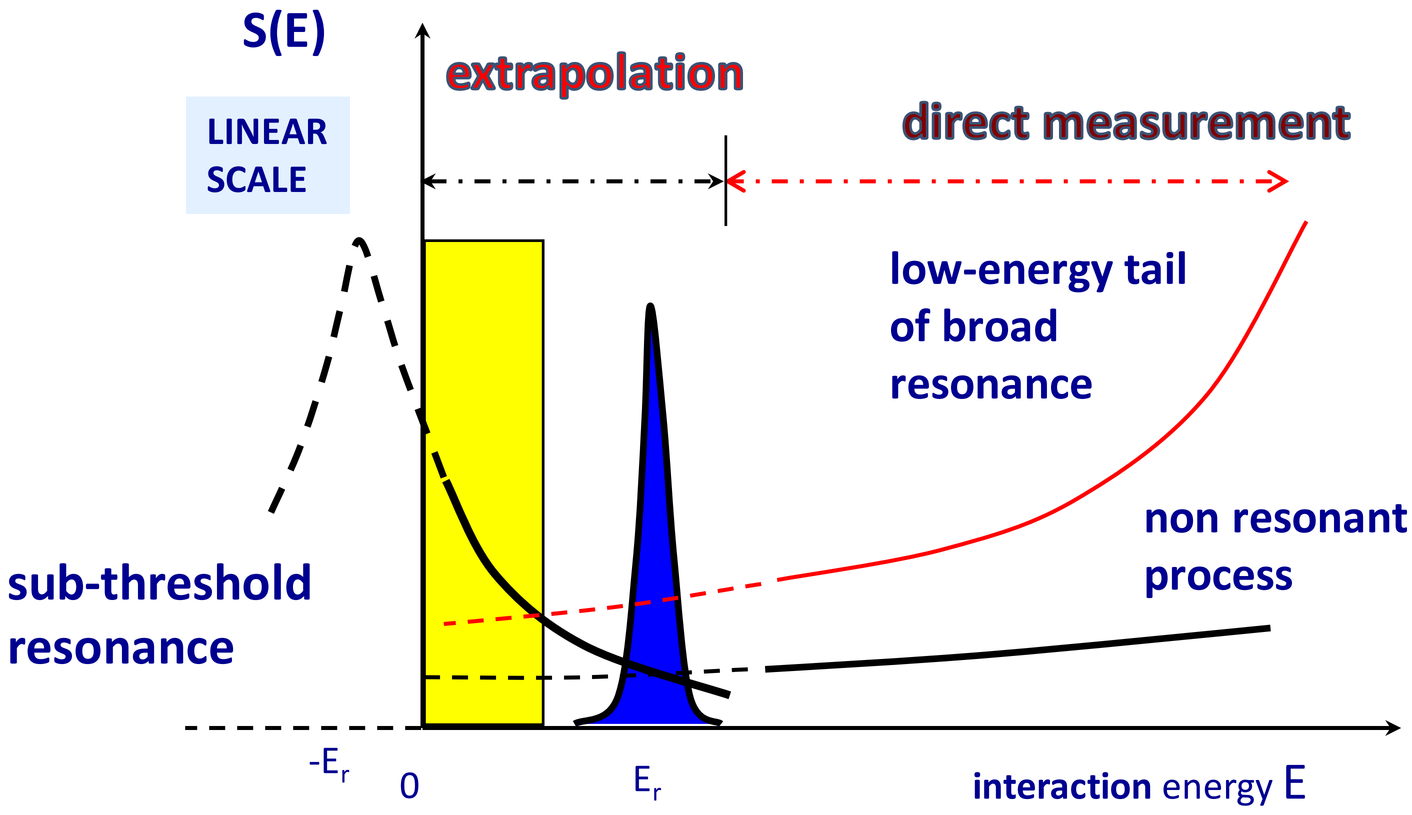


Nuclear astrophysics: troubles for measurements @ low energies

Solutions:

DANGEROUS! large uncertainties

1) Extrapolation



Nuclear astrophysics: troubles for measurements @ low energies

Solutions:

1) Extrapolation

2) Direct measure with high S/N

IMPROVEMENTS TO REDUCE THE BACKGROUND

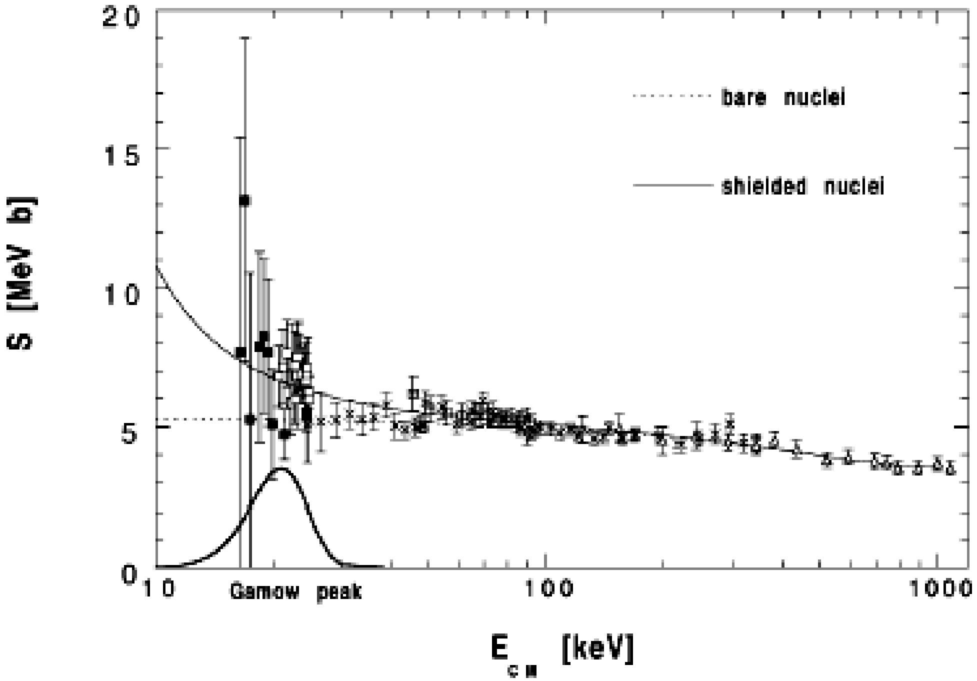
> Laboratory with natural shield (underground physics)

IMPROVEMENTS TO INCREASE THE NUMBER OF DETECTED PARTICLES

> 4π detectors

> New accelerators with high intensity beam

$^3He(^3He,2p)^4He$



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

At lowest energy: σ ~ 20 fb → 1 event/month

Nuclear astrophysics: troubles for measurements @ low energies

Solutions:

1) Extrapolation

2) Direct measure with high S/N

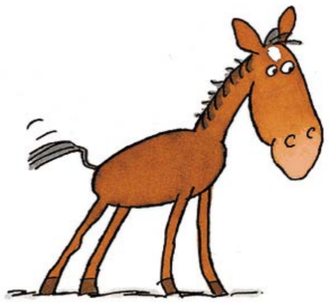
3) Indirect methods (…THM)

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.

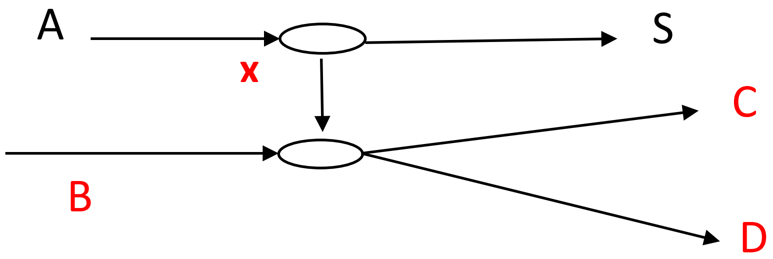


INDIRECT METHODS ARE NEEDED

Complementary to direct measurements

THM: how can we overcome the Coulomb barrier?

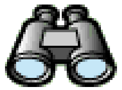
Main idea: to get the 2-body reaction cross section
selecting the quasi-free mechanism from the one of a properly chosen 3-body reaction



A+B→C+D+S
The 3-body reaction
you perform in the lab

x+B→C+D
The binary
reaction you're
interested in

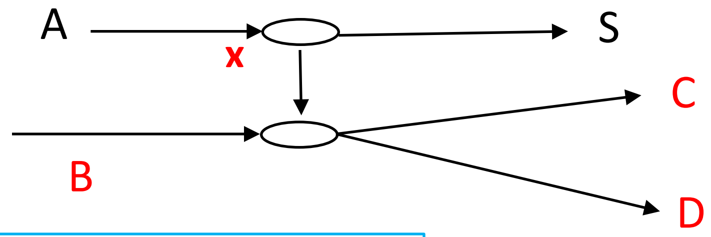
A is the Trojan Horse nucleus

x+S 

THM: how can we overcome the Coulomb barrier?

The incoming energy E_A of the incident particle is greater than the Coulomb barrier energy $(E_{AB})_{Coul.\ Bar.}$

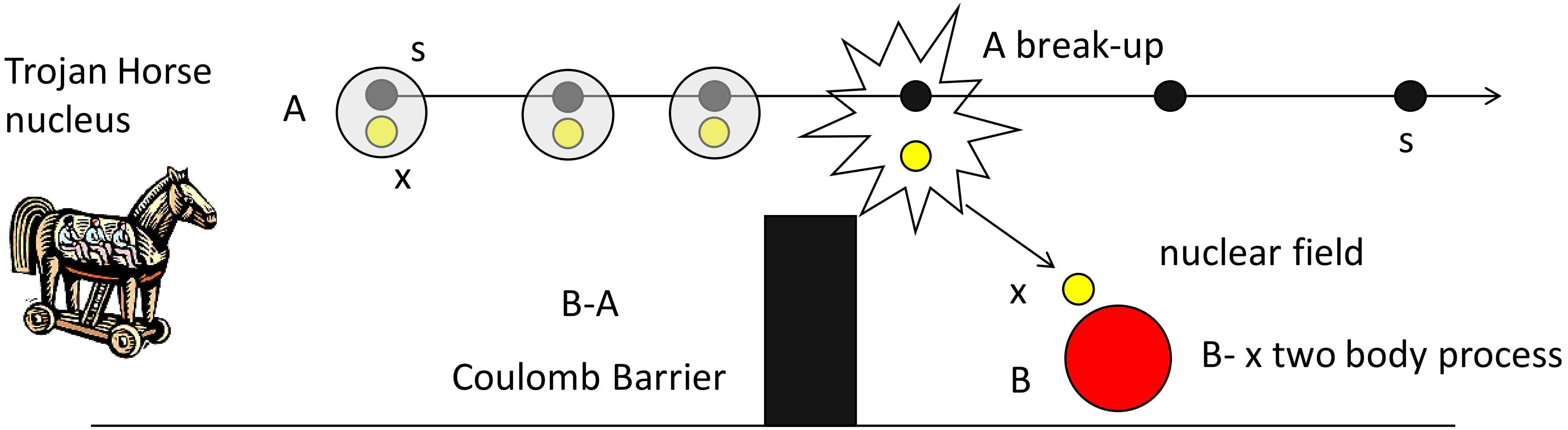
$$E_A > (E_{AB})_{Coulomb\ Barrier}$$



The nucleus A is brought into nuclear field of nucleus B and the cluster x induces the reaction

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

Coulomb effects and electron screening are negligible



Nuclear “city walls”

THM: how can we overcome the Coulomb barrier?

At which energy the 2-body reaction takes place?

(interested to very low energies for astrophysical interest)

$$E_{qf} = E_{Bx} - B_{x\text{-}S} = E_{cD} - Q_{2b}$$

Where

E_{Bx} is the beam energy in the center of mass of the two body reaction

$B_{x\text{-}S}$ binding energy of the two clusters inside the Trojan Horse plays a key role in compensating for the beam energy

THM: how can we overcome the Coulomb barrier?

At which energy the 2-body reaction takes place?

(interested to very low energies for astrophysical interest)

$$E_{qf} = E_{Bx} - B_{x\text{-}S} = E_{cD} - Q_{2b}$$

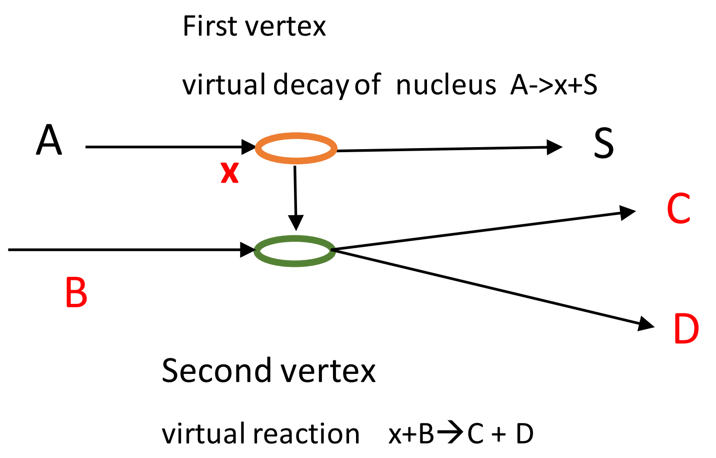
Where

E_{Bx} is the beam energy in the center of mass of the two body reaction

$B_{x\text{-}S}$ binding energy of the two clusters inside the Trojan Horse plays a key role in compensating for the beam energy

(under proper kinematical conditions)

THM: how can we overcome the Coulomb barrier?



We use IA to describe the QF mechanism: the spectator in the exit channel keeps the same momentum inside the TH nucleus.

In PWIA the cross section of the 3-body reaction can be factorized in two terms corresponding to the two vertices

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_D} \propto KF |F(q)_{xS}|^2 \left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\to C+D}$$

kinematical factor

$|F(q_{xS})|^2$ describes the intercluster (x-S) momentum distribution

(ds/dΩ) two-body cross section of the virtual reaction x + B→ C + D

THM: how can we overcome the Coulomb barrier?

$$\left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\rightarrow C+D} \propto \frac{\dfrac{d^3\sigma}{dE_C d\Omega_C d\Omega_D}}{KF\,|F(q)_{xS}|^2}$$

Measured
and **well above the Coulomb barrier**

Calculated

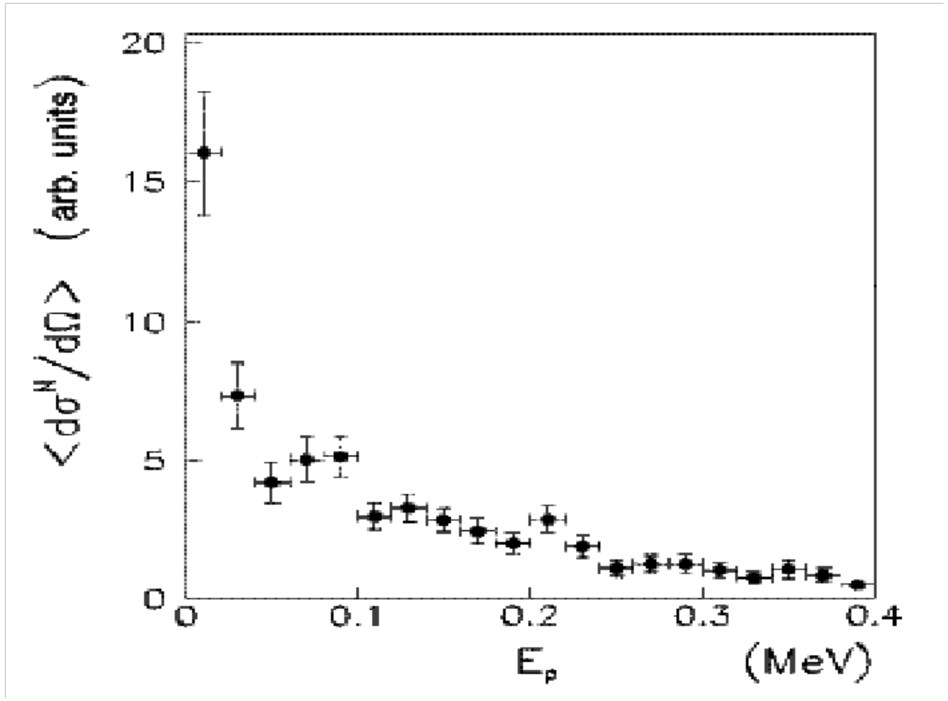
Measured

Coulomb effects and electron screening are negligible

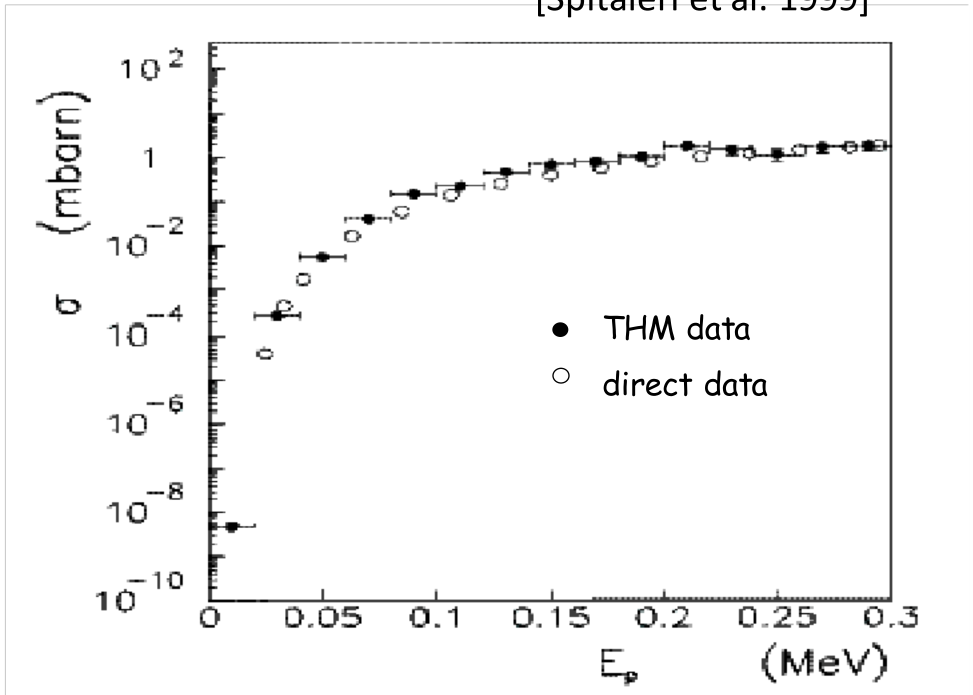
$E_{qf} \sim 0$

THM: how can we overcome the Coulomb barrier?

$^{7}Li + p \rightarrow \alpha + \alpha$



[Spitaleri et al. 1999]



$$\left[\frac{d\sigma}{d\Omega}\right]^{TH}_{x+B\rightarrow C+D} * P_l \propto \left[\frac{d\sigma}{d\Omega}\right]^{OES}_{x+B\rightarrow C+D}$$

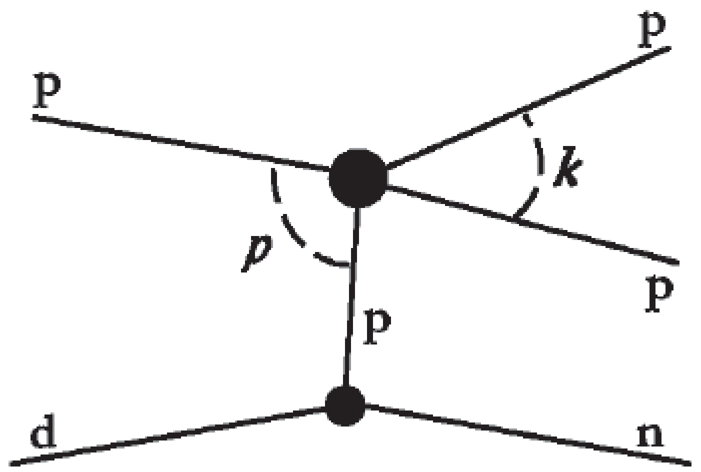
The p-p scattering

Perfect to test the Coulomb barrier effects suppression in THM

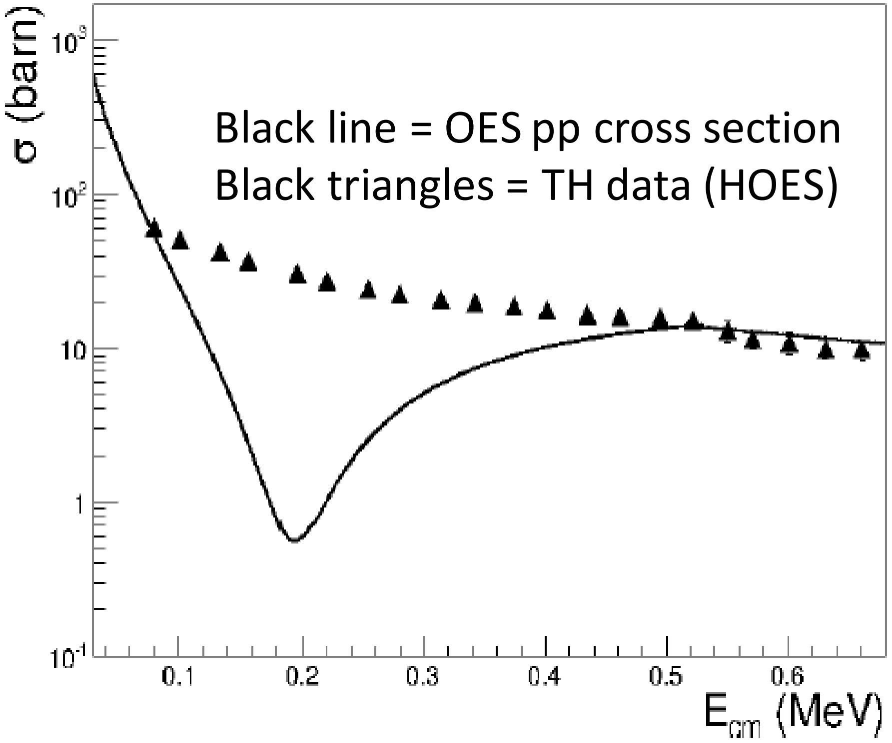
Mott scattering + interference (Coulomb + Nuclear)

HOES case (THM): no interference

[Tumino et al. 2007 (PRL)]



The p-p scattering

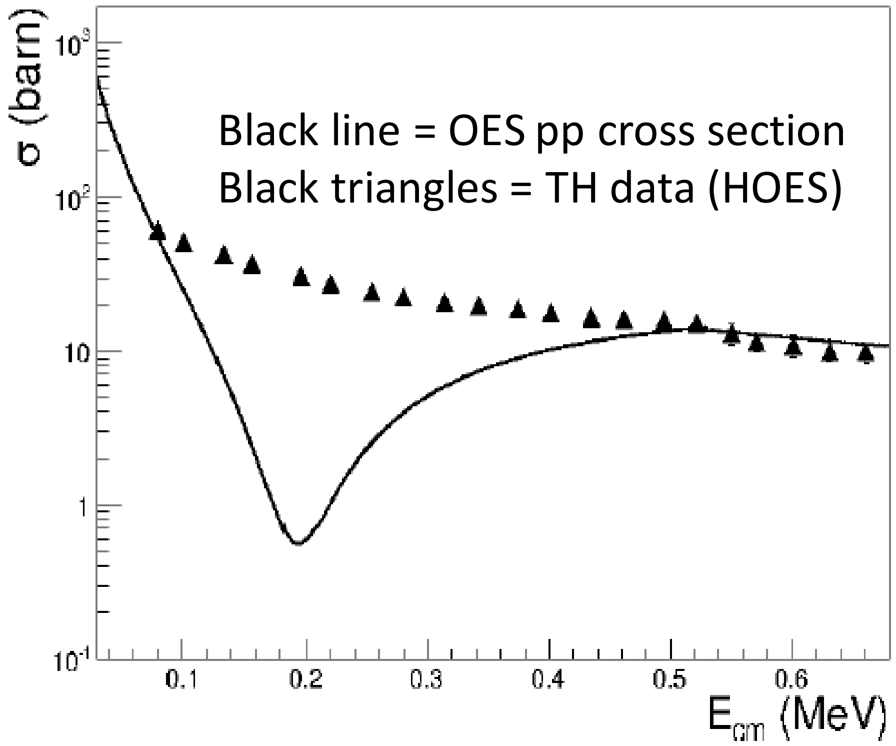


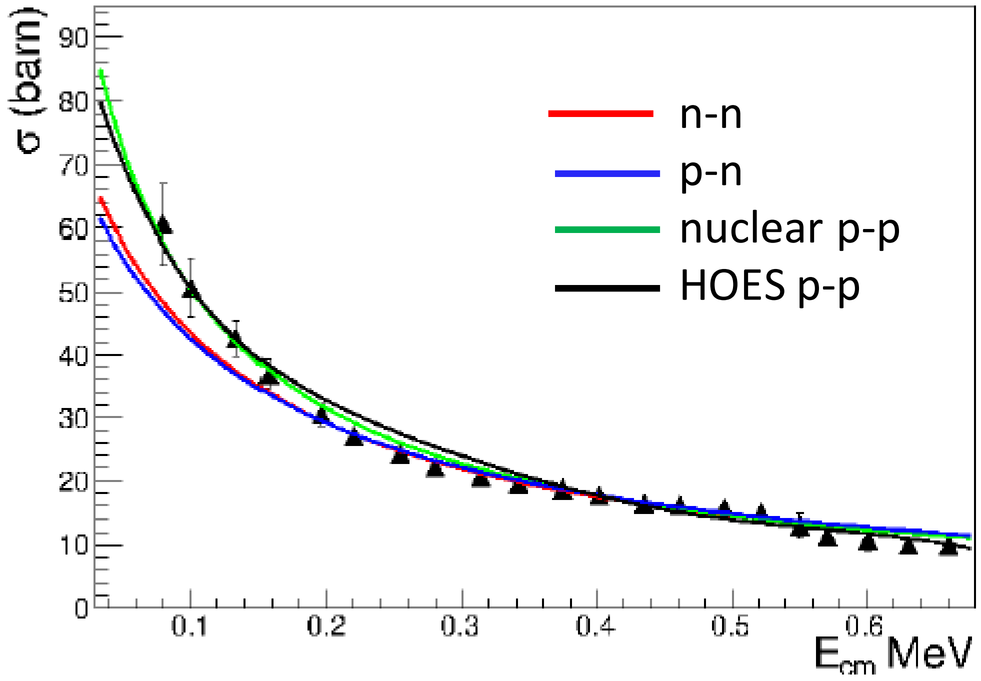
[Tumino et al. 2007 (PRL)]
[Tumino et al. 2008 (PRC)]

No Coulomb-nuclear interference deep experimentally observed

The p-p scattering

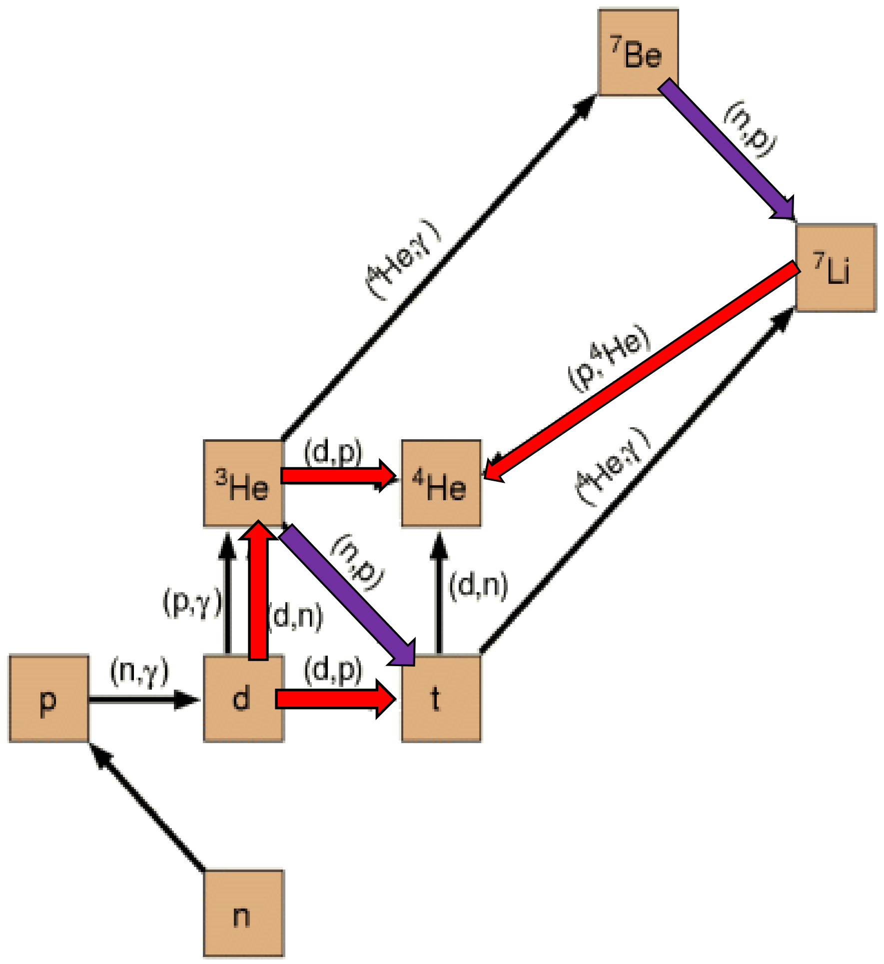
[Tumino et al. 2007 (PRL)]
[Tumino et al. 2008 (PRC)]





No Coulomb-nuclear interference deep experimentally observed

Many astrophysical scenarios explored…i.e. the BBN



- d(d,p)t

[Rinollo et al. 2005 (NPA)] [Tumino et al. 2014 (ApJ)]

- d(d,n)^{3}He

[Tumino et al. 2014 (ApJ)]

- ^{3}He(d,p)^{4}He

[La Cognata et al. 2005 (PRC)]

- ^{7}Li(p,a)^{4}He

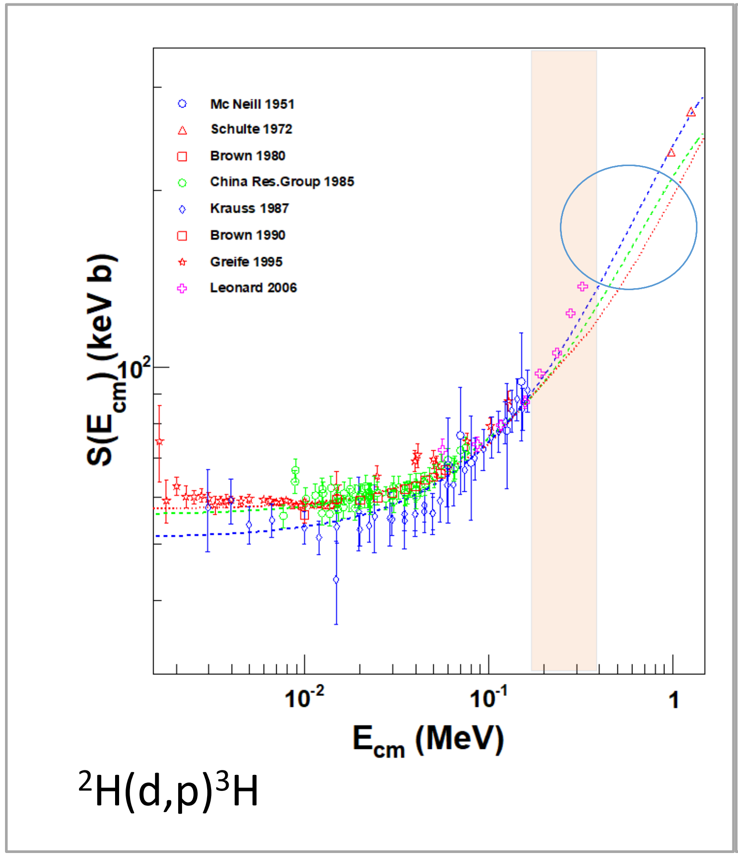
[Lattuada et al. 2001 (ApJ)] [Lamia et al. 2012 (A&A)]

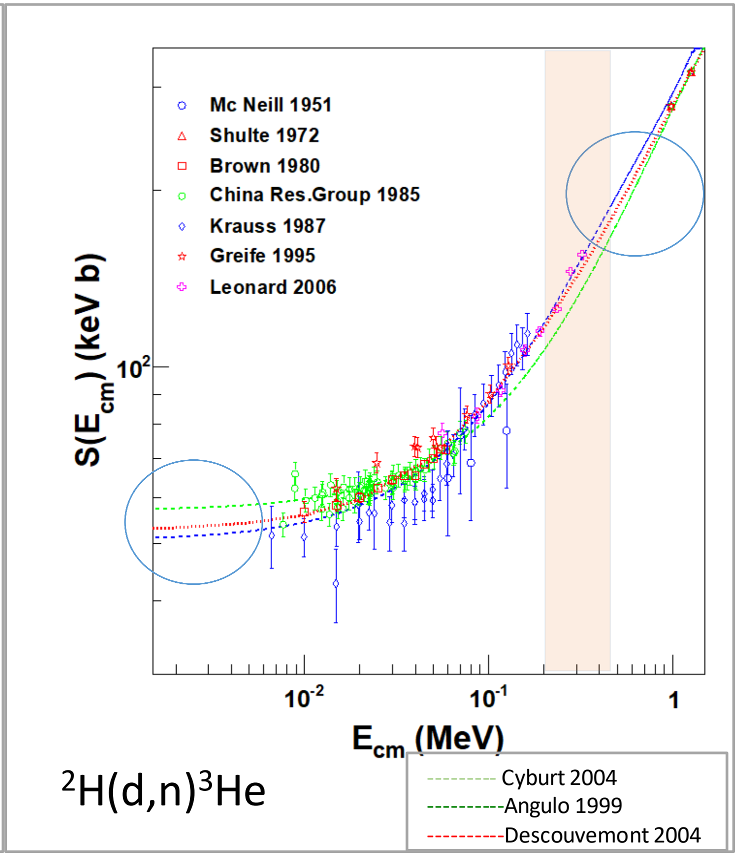
And using RIBs

- ^{7}Be(n,p)^{7}Li (in progress)
- ^{7}Be(n,α)^{4}He (in progress)

& just done: ^{3}He(n,p)t

The d-d reactions





Astrophysical motivation

The aim is the study of $^{2}H(d,p)^{3}H$ and $^{2}H(d,n)^{3}He$ (sensitivity!)
@energies relevant for the BBN scenario
(50-350 keV) → 0-1 MeV
BUT the Coulomb barrier is around 200-400 keV

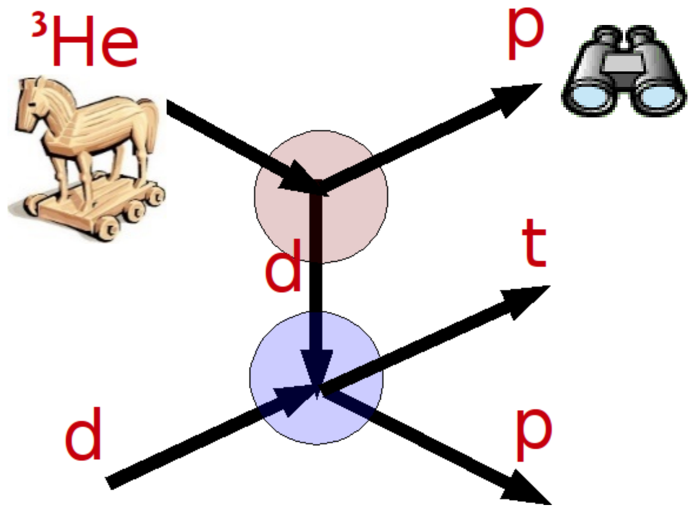
Thus we need:

- Bare nucleus cross section
- Errors reduction

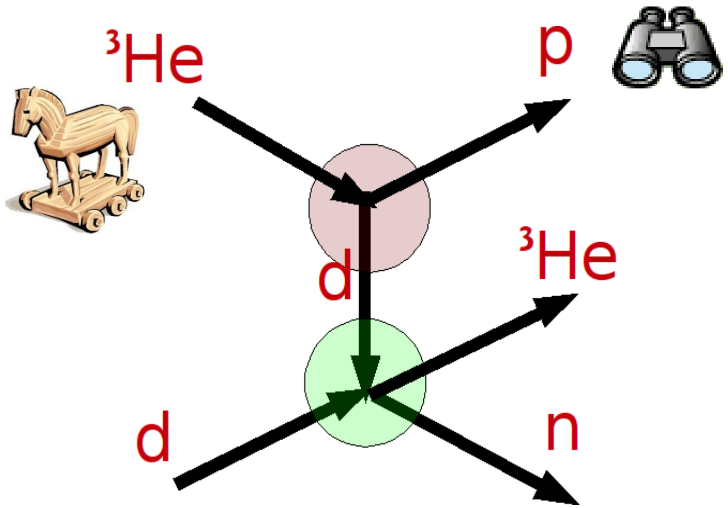
The d-d reactions

$^{2}H(^{3}He,n^{3}He)H \rightarrow ^{2}H(d,n)^{3}He$

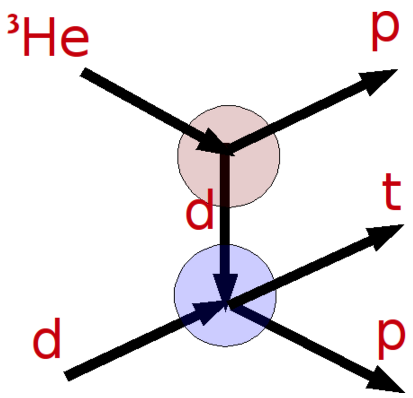
$^{2}H(^{3}He,pt)H \rightarrow ^{2}H(d,p)^{3}H$



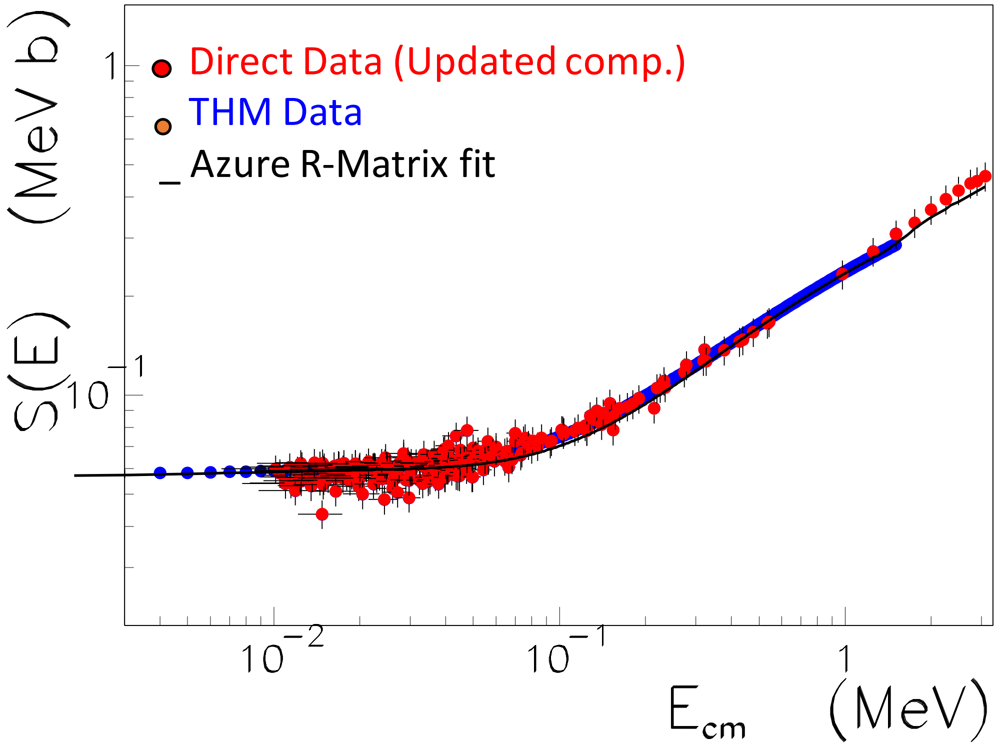
$^{3}He=d+p$



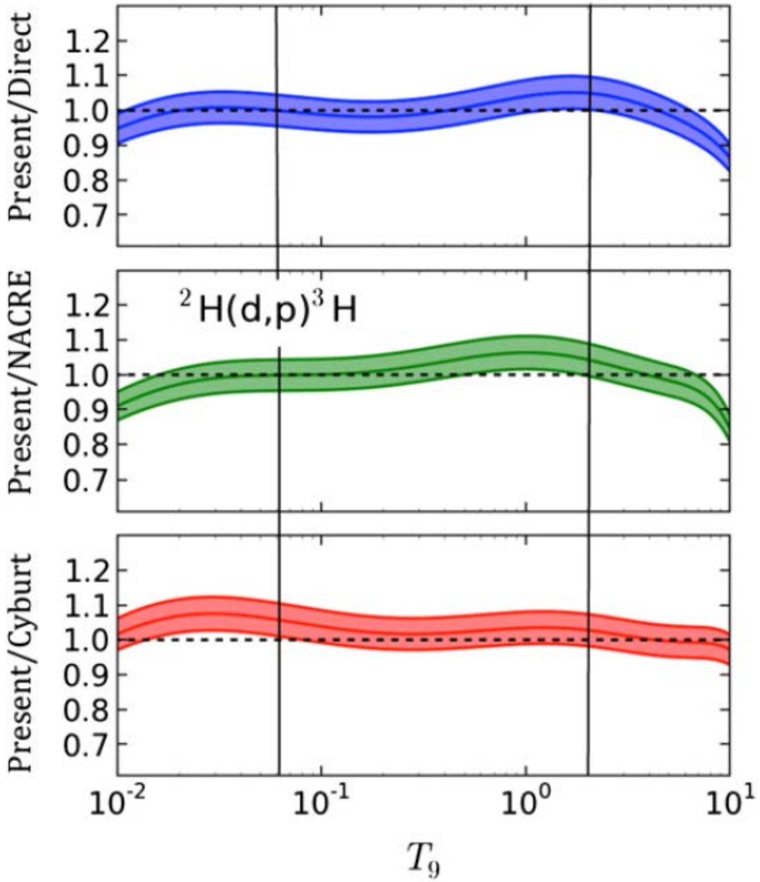
The d-d reactions



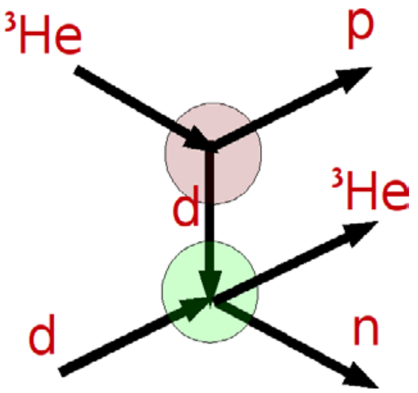
d(d,p)^{3}H



[Tumino et al. 2014 (ApJ)]
[Pizzone et al. 2014 (ApJ)]

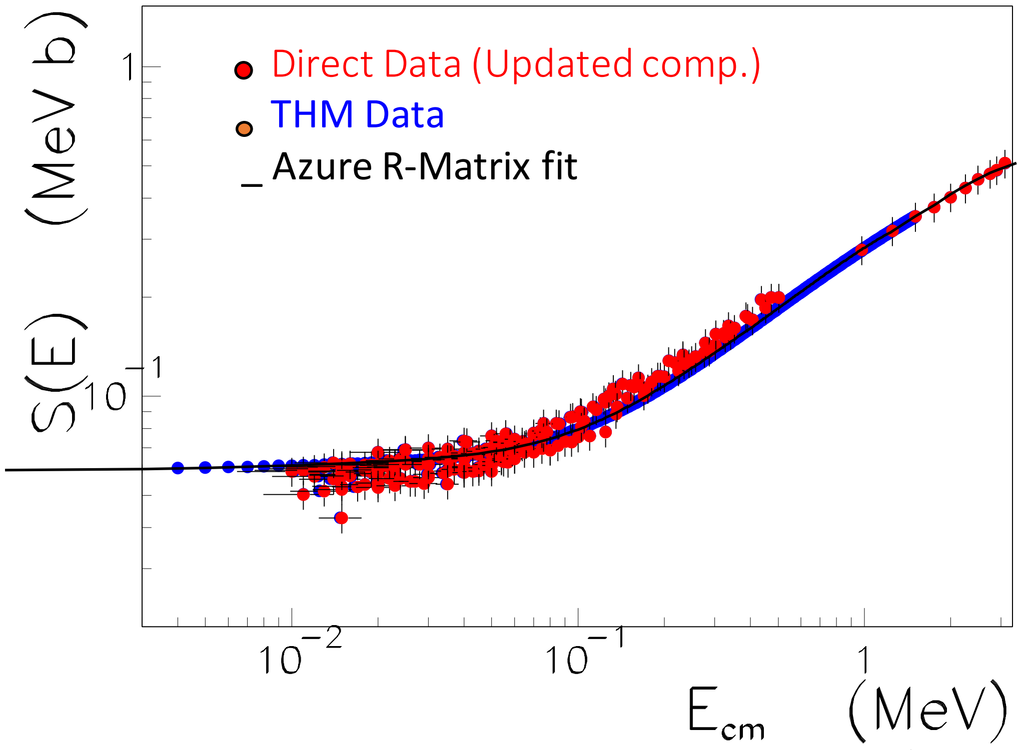


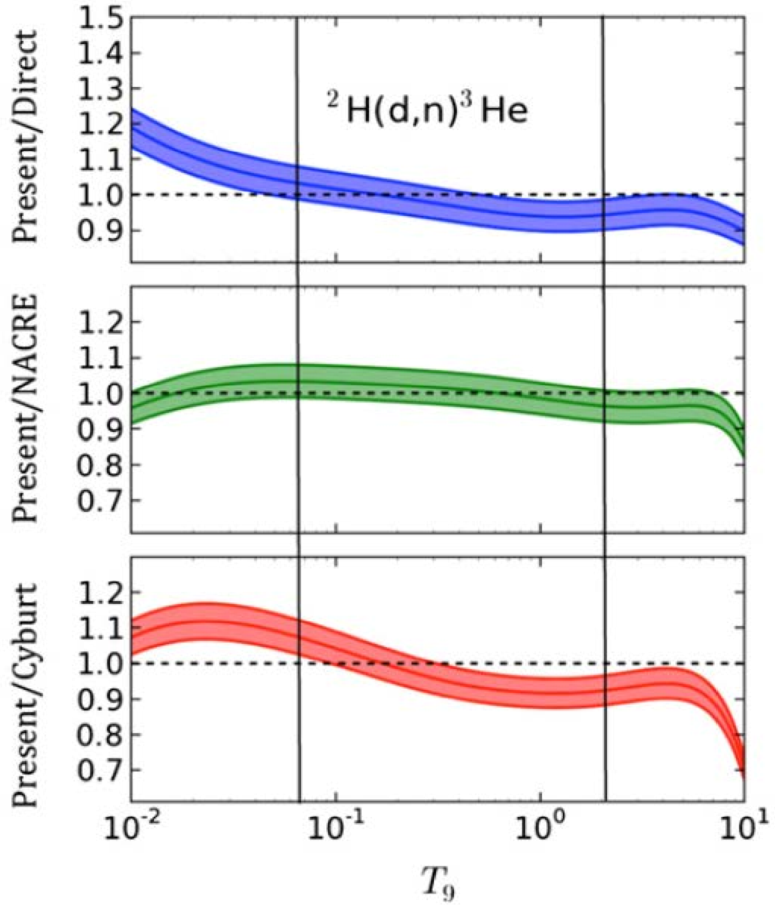
The d-d reactions



[Tumino et al. 2014 (ApJ)]
[Pizzone et al. 2014 (ApJ)]

d(d,n)^{3}He





Yields	Direct	$^2H(d,p)^3H$	$d(d,n)^3He$	$^3He(d,p)\alpha$	$^7Li(p,\alpha)^4He$	All	Observed
Y_p	0.2486	$0.2485^{+0.001}_{-0.001}$	$0.2485^{+0.000}_{-0.000}$	$0.2486^{+0.000}_{-0.000}$	$0.2486^{+0.000}_{-0.000}$	$0.2485^{+0.001}_{-0.002}$	$0.256 \pm 0.006^{(a)}$
D/H	2.645	$2.621^{+0.079}_{-0.046}$	$2.718^{+0.077}_{-0.036}$	$2.645^{+0.002}_{-0.007}$	$2.645^{+0.000}_{-0.000}$	$2.692^{+0.177}_{-0.070}$	$2.82 \pm 0.26^{(b)}$
$^3He/H$	9.748	$9.778^{+0.216}_{-0.076}$	$9.722^{+0.052}_{-0.092}$	$9.599^{+0.050}_{-0.003}$	$9.748^{+0.000}_{-0.000}$	$9.441^{+0.511}_{-0.466}$	$\geqslant 11. \pm 2.^{(c)}$
$^7Li/H$	4.460	$4.460^{+0.001}_{-0.001}$	$4.470^{+0.010}_{-0.006}$	$4.441^{+0.190}_{-0.088}$	$4.701^{+0.119}_{-0.082}$	$4.683^{+0.335}_{-0.292}$	$1.58 \pm 0.31^{(d)}$

TH rates in BBN123 code (C.A. Bertulani)

[Pizzone et al. 2014 (ApJ)]

THM@BBN: *our bare nucleus measurements confirm the Standard BBN model, including the CLiP.*
Thus, variations up to 30% in the rates do not affect what expected by observations, at least considering these 4 reactions!

Polar invariance

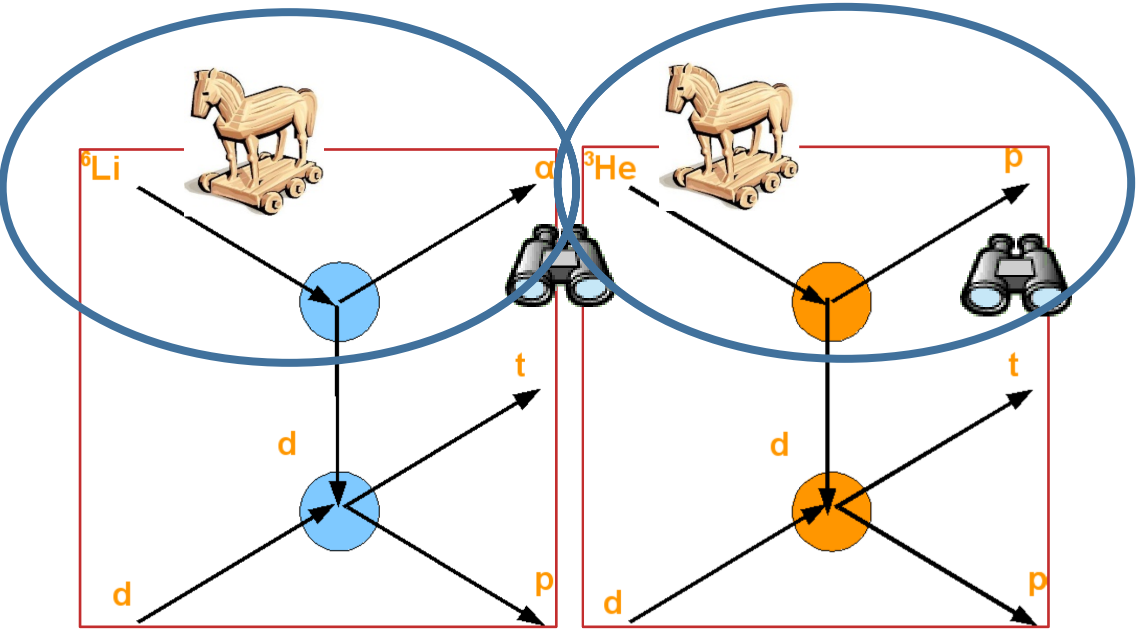
is the result indipendent on the choice of the TH nucleus?

- Possibility of description of the nucleus as 2 *clusters*, one inducing the 2body reaction
- Absence or separability *off line* in the data of events coming from sequential mechanism

Polar invariance

is the result indipendent on the choice of the TH nucleus?

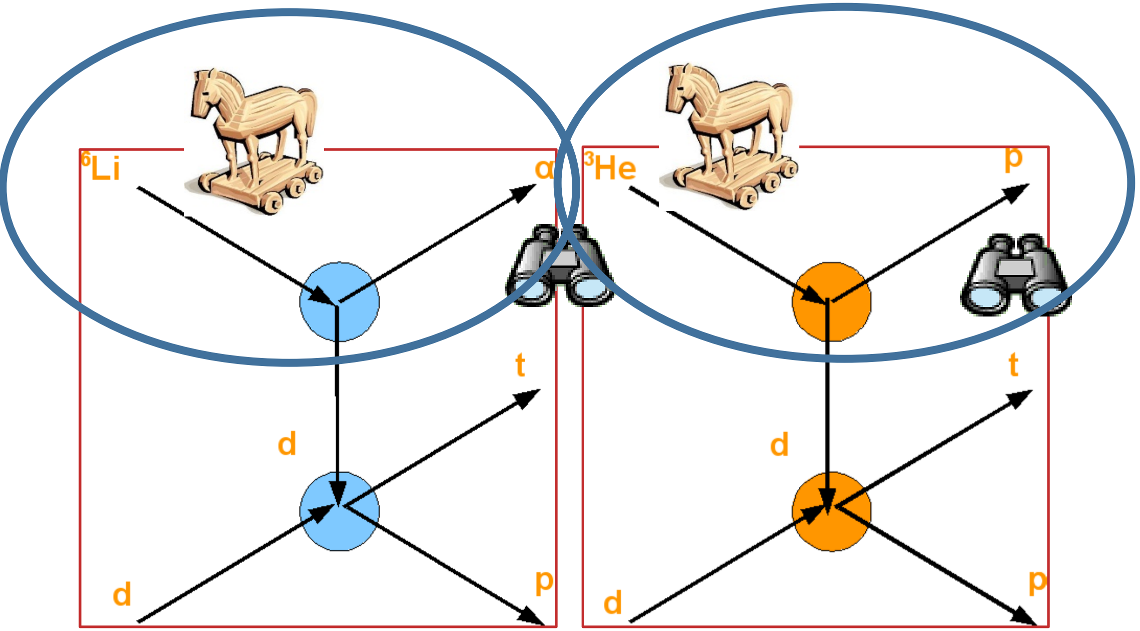
- Possibility of description of the nucleus as 2 *clusters*, one inducing the 2body reaction
- Absence or separability *off line* in the data of events coming from sequential mechanism



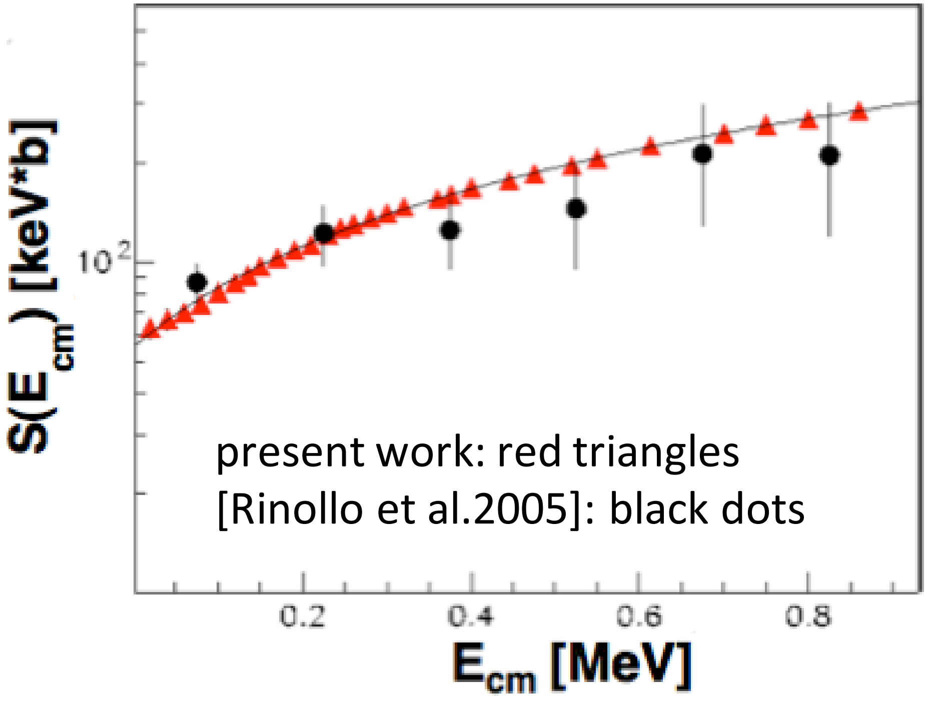
Polar invariance

is the result indipendent on the choice of the TH nucleus?

- Possibility of description of the nucleus as 2 *clusters*, one inducing the 2body reaction
- Absence or separability *off line* in the data of events coming from sequential mechanism



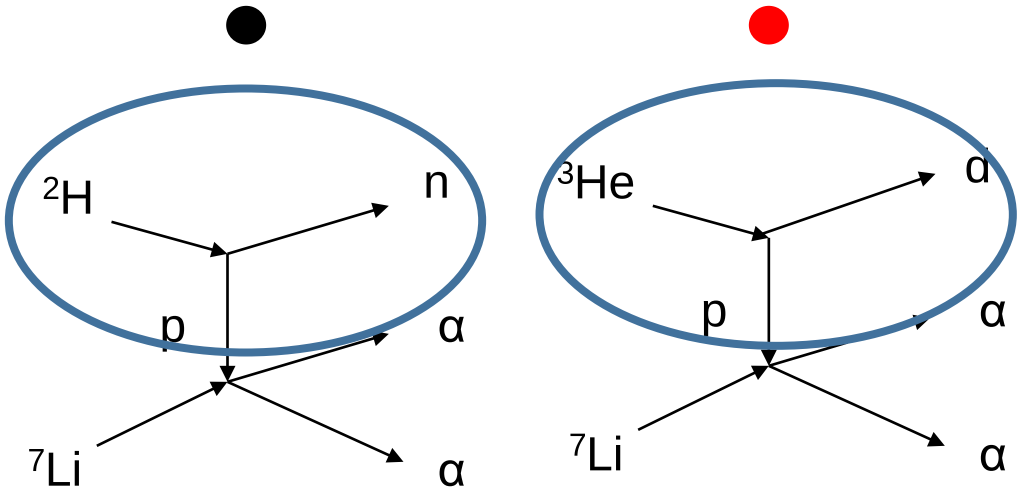
[Pizzone et al. 2013]

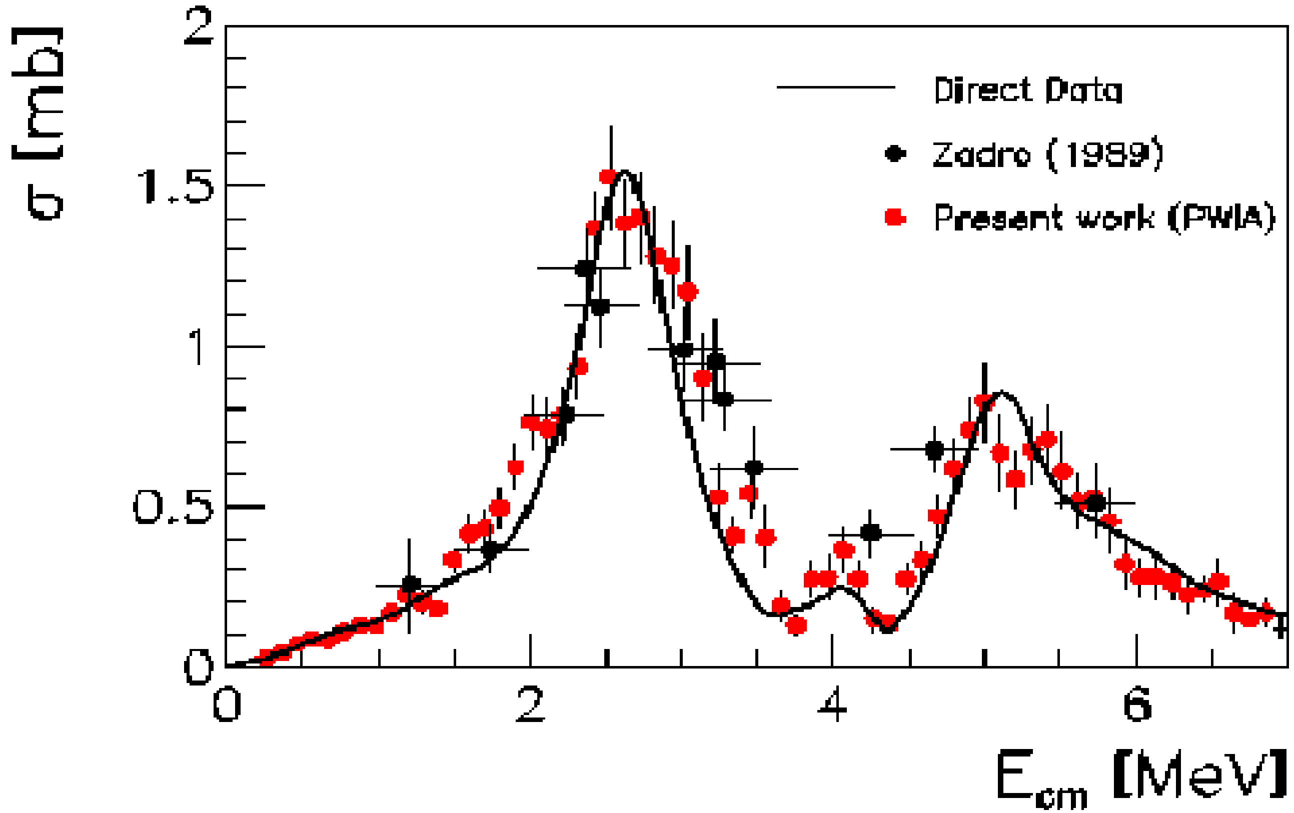


Polar invariance

This resembles previous results obtained for $^7Li(p,\alpha)\alpha$ [Pizzone et al. 2011]

….



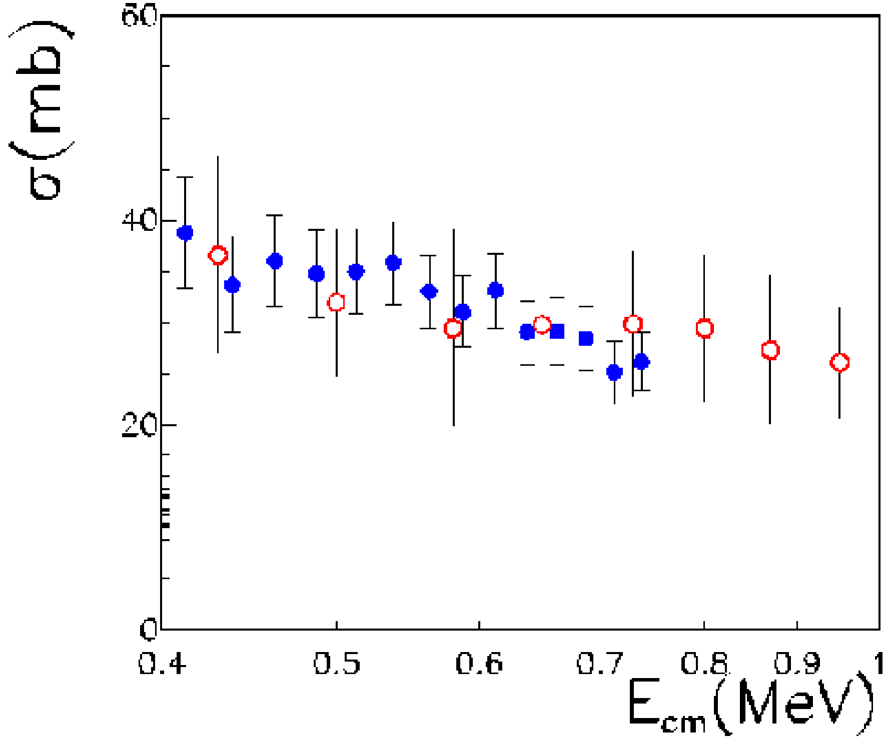


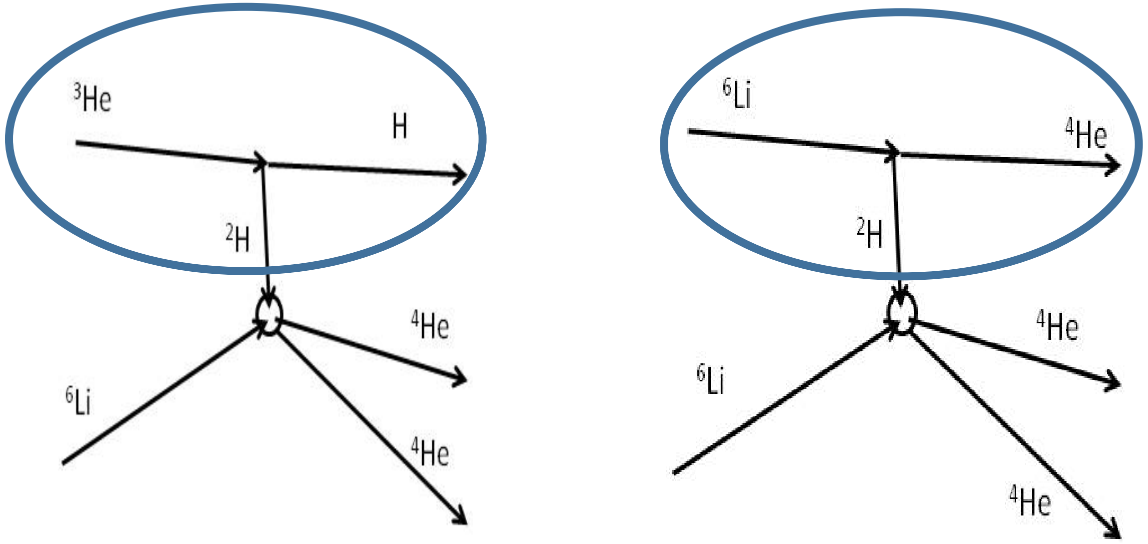
Polar invariance

… and $^{6}Li(d,a)^{4}He$ result

This reaction has been studied at astrophysical energies after ^{6}Li quasi-free break-up

[Spitaleri et al. 2001]





Within experimental errors good agreement

Conclusions

TH is based on *TH-nucleus* = 2 clusters

Is a power tool for nuclear astrophysics based on few-body systems

Recent extensions – research lines

- THM extension to n-induced reactions allow us to overcome centrifugal barrier effects
  1. Suppressed levels in direct measurements
  2. Possibility to measure angular distribution and nuclear properties
  3. Modified R-matrix approach to obtain strenght for each level

- Deuteron as virtual neutron source allow us to overcome difficulties related to neutron beam production
  1. Low cost research!
  2. Simple experimental set-up
  3. One beam energy for wide E_{cm} range

- Exotic beams applications

The AsFiN Group

@Catania C. Spitaleri, A. Bonasera, S. Cherubini, G. D'Agata, A. Di Pietro, P. Figuera, G.L. Guardo, M. Gulino, I. Indelicato, M. La Cognata, D. Lattuada, M. Lattuada, L. Lamia, G.G. Rapisarda, S. Romano, M.L. Sergi, R. Spartà, A. Tumino

@*Perugia* M. Busso, S. Palmerini, M.C. Nucci

@Napoli M. La Commara

@Padova M. Mazzocco

Collaborations

- C.N.S. Riken, Wako, Japan: S. Kubono, H. Yamaguchi, S. Hayakawa
- Riken, Wako, Japan: T. Motobayashi
- CIAE, Beijing, China: S. Zhou, C. Li, Q. Wen
- Nuclear Physics Institute, ASCR, Rez, Czech Rep.: V. Kroha, V. Burjan, J. Mrazek, I. Sivacek
- Texas A&M Commerce USA: C. Bertulani
- Nipne IFIN Bucharest: L. Trache
- ELI-NP Bucharest: C. Matei, D. Balabanski
- Atomki, Debrecen, Hungary: G. Kiss
- CSNSM, Orsay, France : A. Coc , F. Hammache, N. De Sereville
- Florida State University USA: I. Wiedenhofer
- Notre Dame University USA: M. Wiescher
- University of Catalunya: J. Jose
- Rudjer Boskovic Institute Zagreb Croatia: N. Soic, M. Milin
- University of Pisa: S. Degl'Innoccenti, P. Prada Moroni

Thanks for your attention