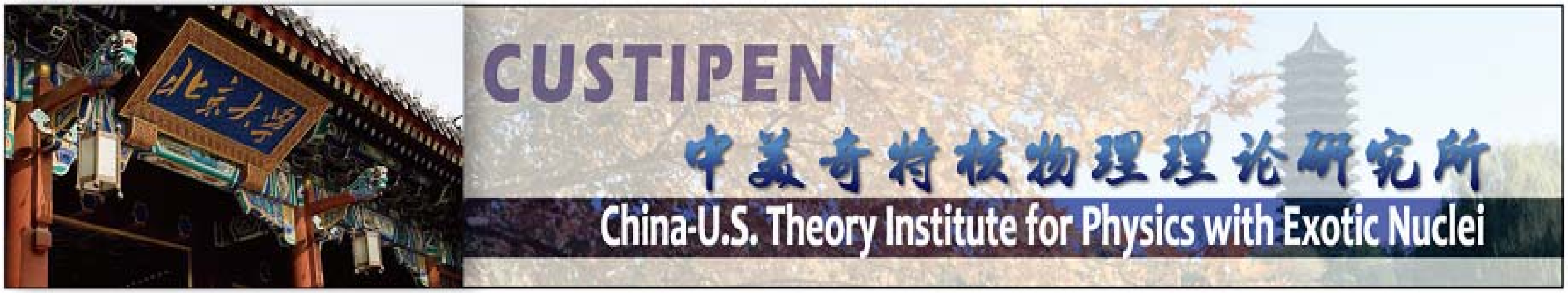

Trojan Horse Method and its application to nuclear astrophysics with stable and unstable

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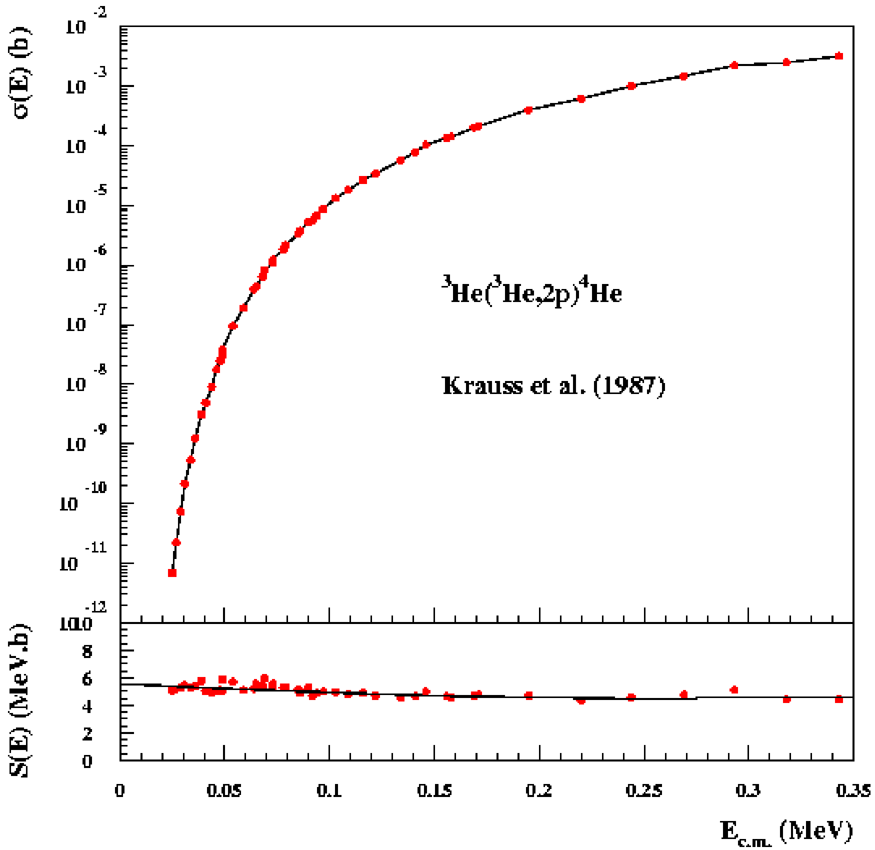


@ Gamow energies

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

The DANGER OF EXTRAPOLATION ...

large uncertainties in the extrapolation!

It is Necessary to Maximize the signal-to-noise ratio

SOLUTIONS

Even worse with RIB!!!!!!

- IMPROVEMENTS TO INCREASE NUMBER OF DETECTED PARTICLES

4 π 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

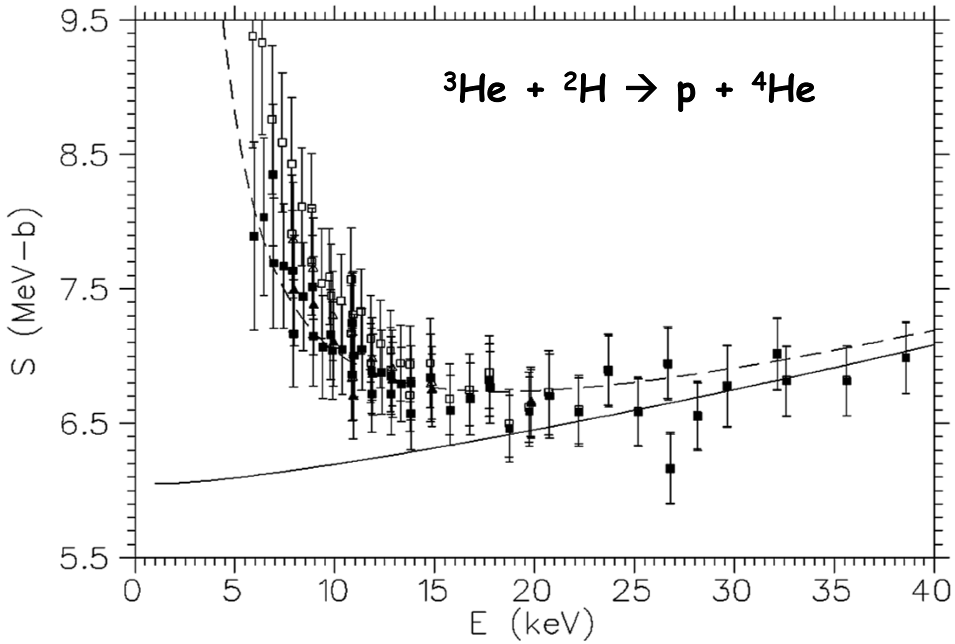
The electron screening effect must be taken into account

(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

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

S(E) (MeVb)



E(KeV)

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

NEW METHODS ARE NECESSARY

-to measure cross sections at never reached energies especially in the RIB case

-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

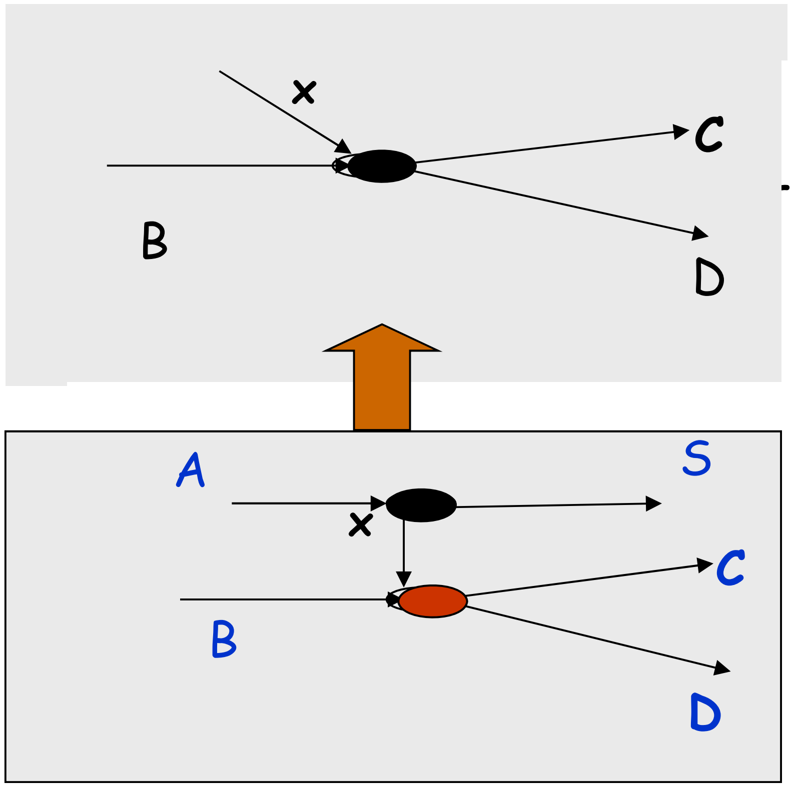
c) – Beta Delay decays studies and other methods

d) - The Trojan Horse Method (THM)

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

Trojan Horse Method (outlook)

Quasi-Free mechanism



Basic idea:

-The A nucleus present a strong cluster structure: $A = x \oplus S$ clusters

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

$B + x \rightarrow C + D$

-The S cluster acts as a spectator

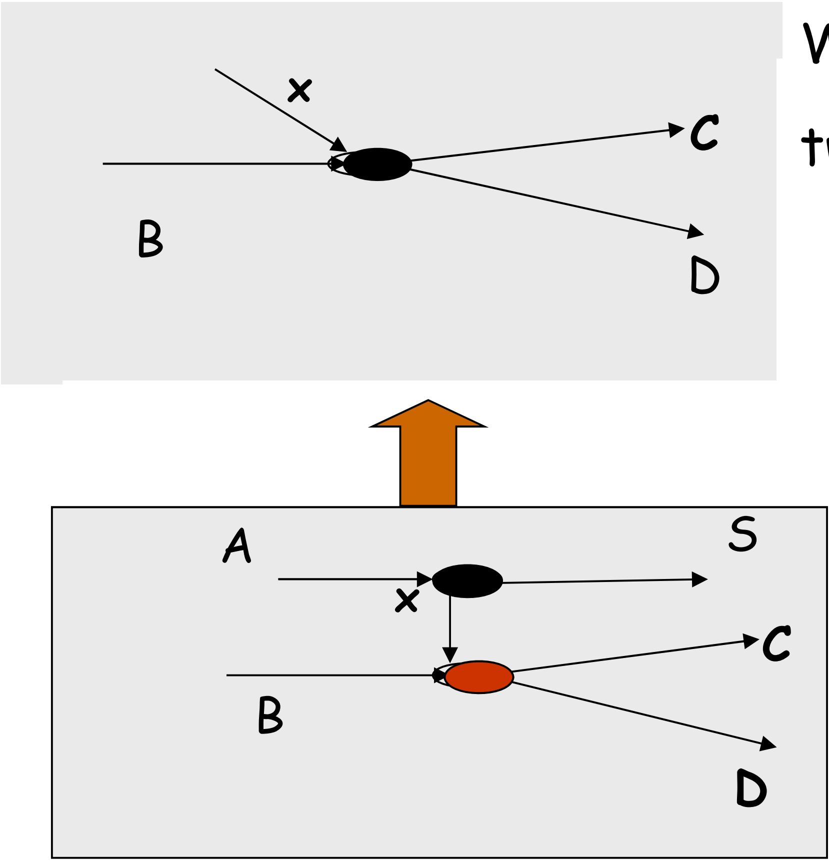
(it doesn' t take part to the reaction)

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

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



We can extract astrophysically relevant two-body cross section σ

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

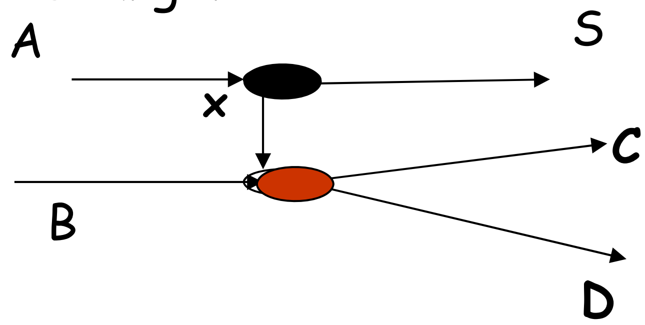
from quasi- free contribution of an appropriate three-body reaction

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

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

Quasi-Free mechanism → Trojan Horse Method

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



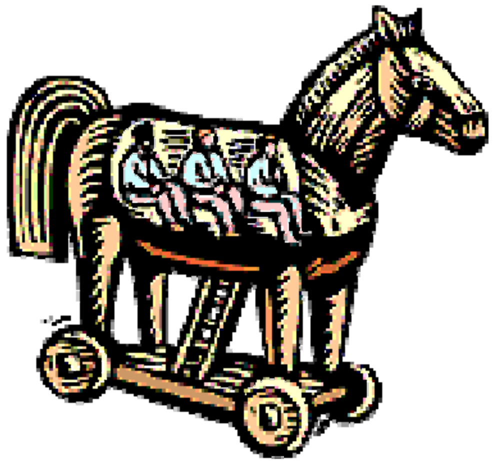
$$E_A > (E_{AB})_{Coulomb\ Barrier}$$

(This means that B and x have a non-negligible probability to be very close)

The nucleus A can be brought into nuclear field

of nucleus B and the cluster x induces the reaction

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



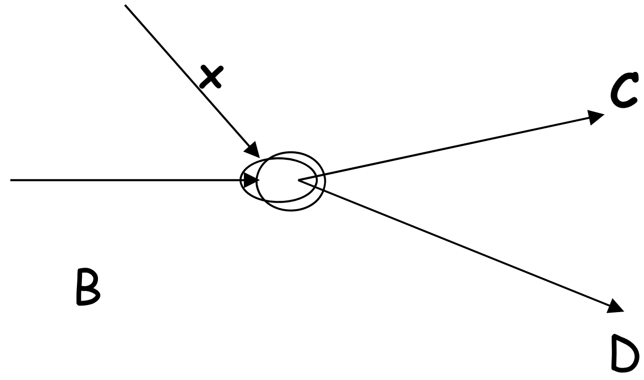
Coulomb effects and electron screening are negligible

Two body reaction takes place at:

$E_{qf.} = E_{Bx} - B_{x\text{-}S}$

Where

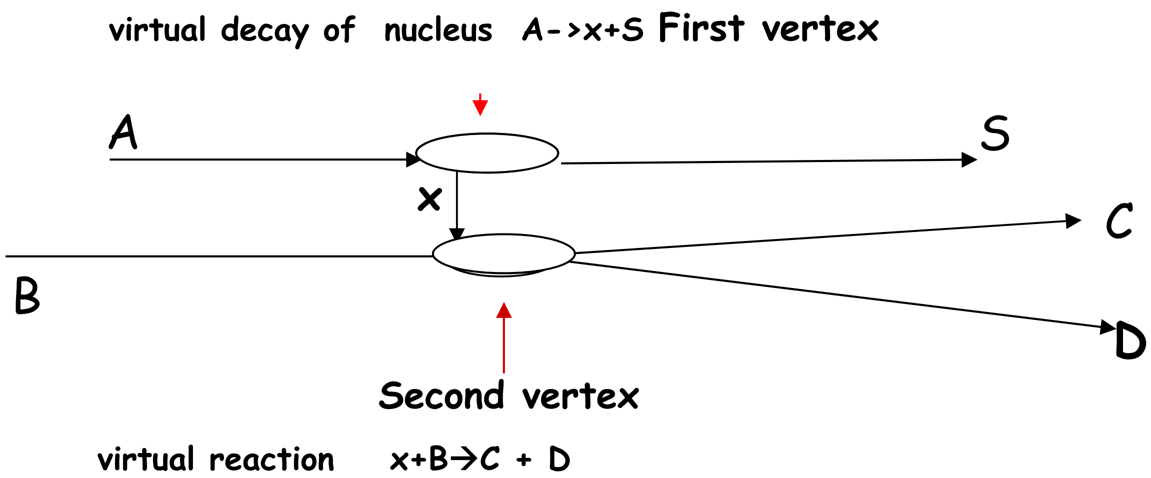
E_{Bx} is the beam energy in the center of mass of the two body reaction



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

(under proper kinematical conditions) **$E_{qf} \sim 0$**

In Plane
of the



corresponding to the two vertices

$$\frac{d^3\sigma}{dE_C \, d\Omega_c \, d\Omega_D} \propto KF \; [\Phi(q)_{xs}]^2 \left[\frac{d\sigma}{d\Omega}\right]_{x + B \to C + D}$$

First vertex

Second vertex

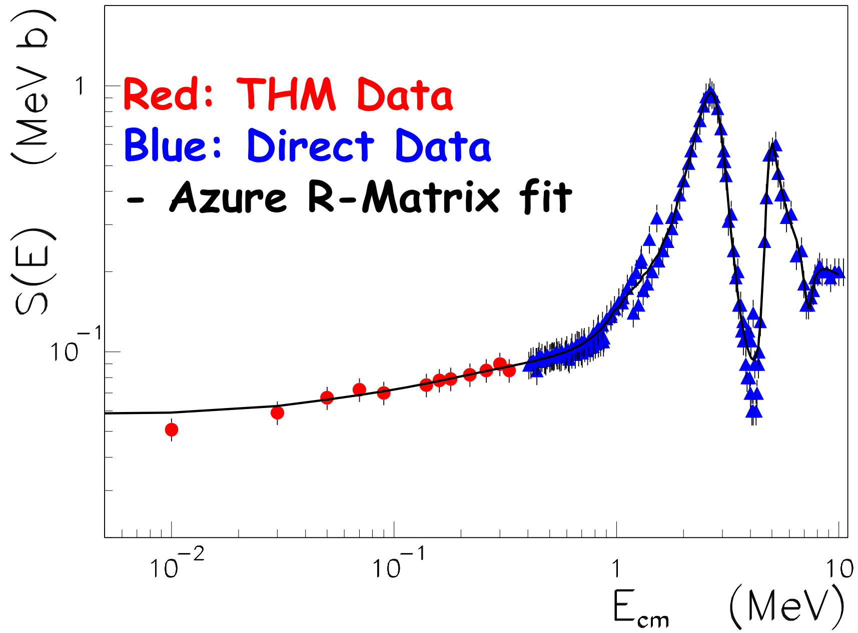
KF kinematical factor

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

$(d\sigma/d\Omega)$ two-body cross section of the virtual reaction **x + B→ C + D**

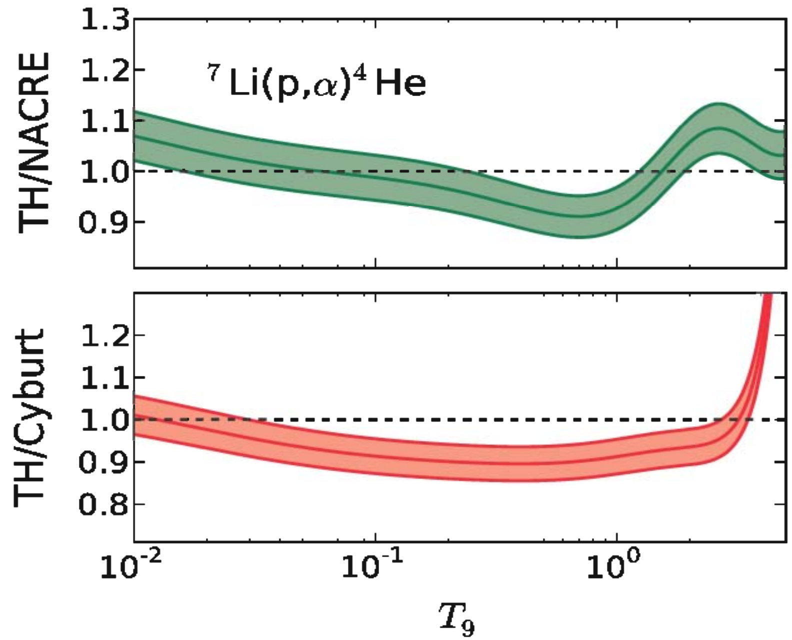
The $^7Li(p,\alpha)^4He$ reaction rate (RGP et al, APJ, 786, 2014)

For the rate both direct And THM data were taken into account

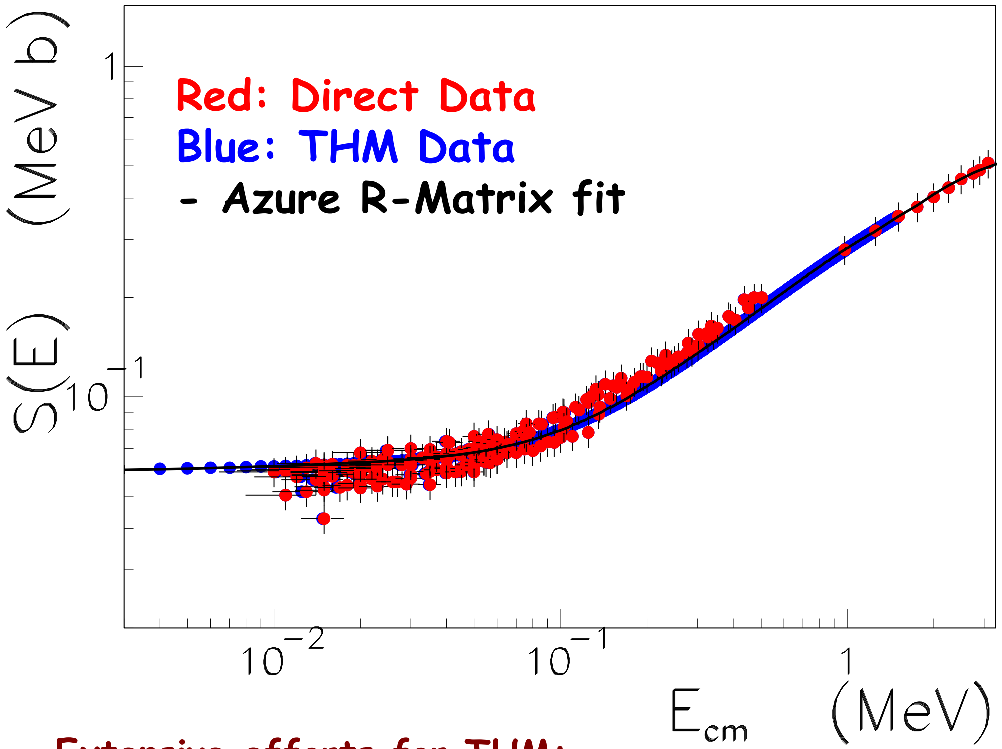


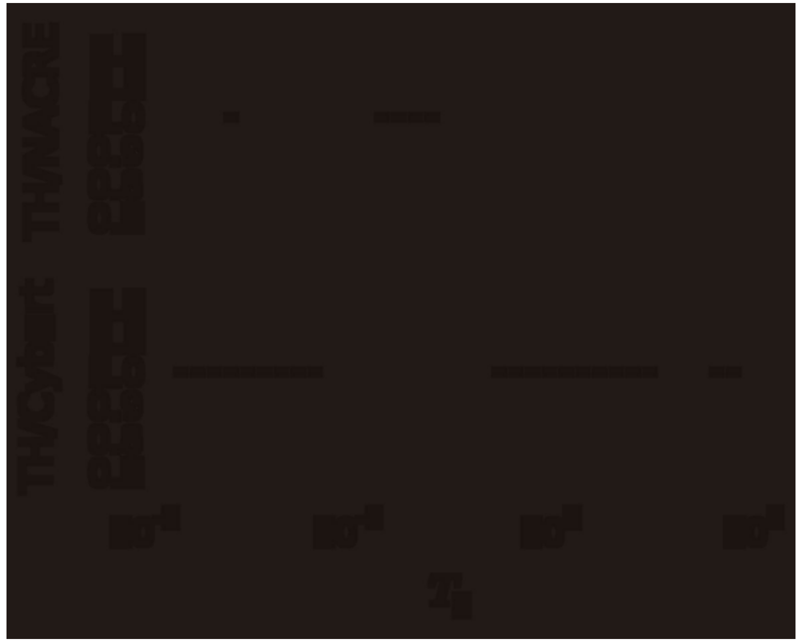
Extensive efforts for THM: Spitaleri et al.1999, Lattuada et al APJ 2001, RGP et al A&A 2003, Lamia et al., A&A 2012

RESULTS for the reaction rate



The updated d(d,n)^{3}He reaction rate





Extensive efforts for THM:
Tumino et al 2011, Pizzone et al 2013

For the rate both direct
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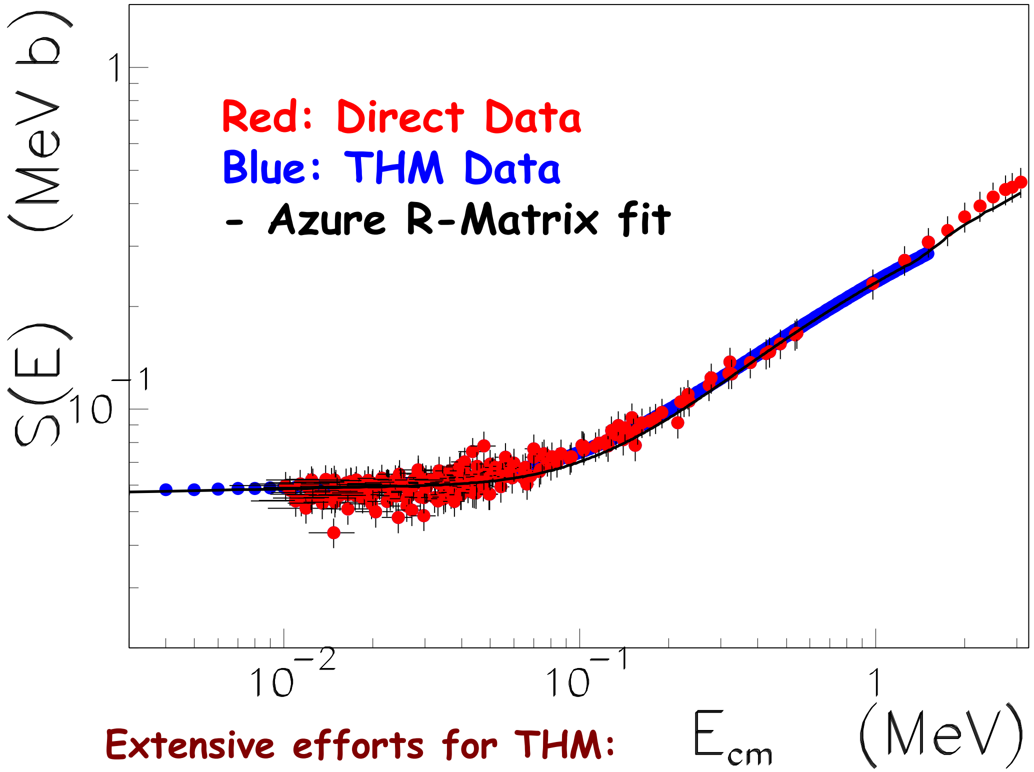
RESULTS
for the reaction rate
(RGP et al, APJ, 786, 2014)

The updated $d(d,p)^3H$ reaction rate



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RESULTS
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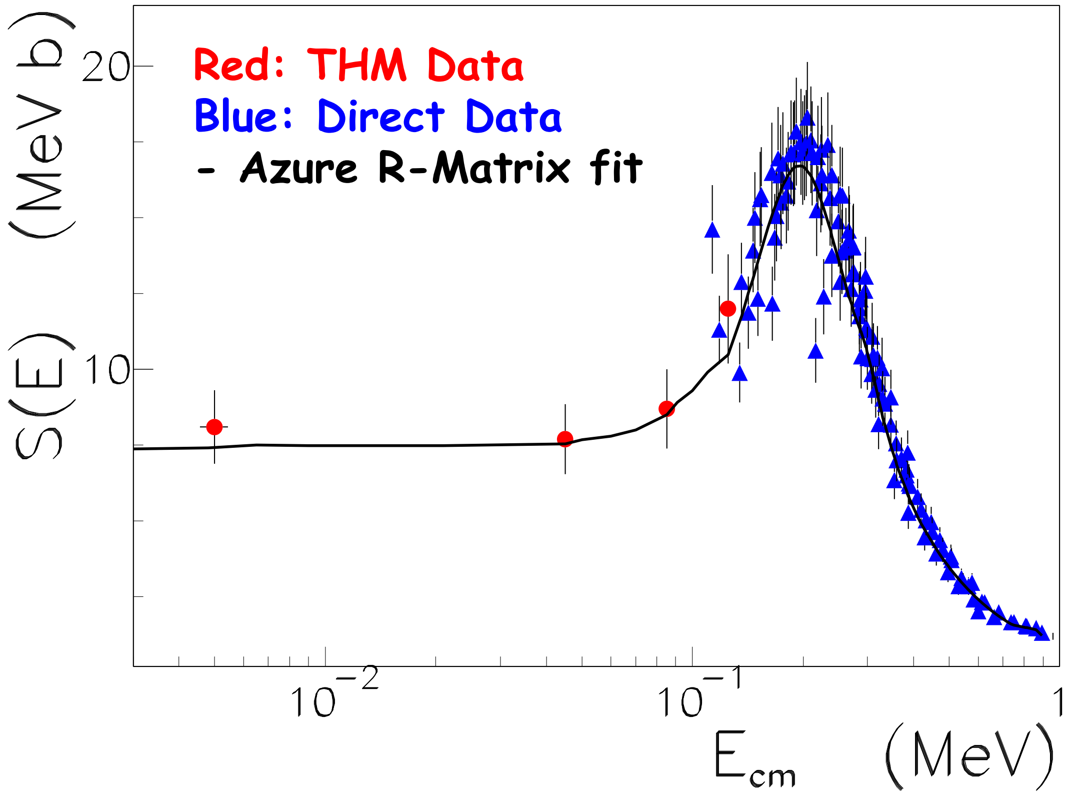
(RGP et al, APJ, 786, 2014)

The updated $^3He(d,p)^4He$ reaction rate



Extensive efforts for THM:
La Cognata et al. 2005

Future applications to $^6Li(p,a)^3He$??? Currently under investigation…

For the rate both direct And THM data were taken into account

Application to RIB

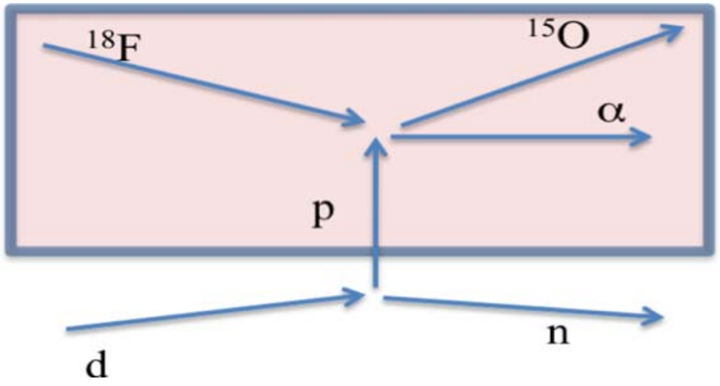
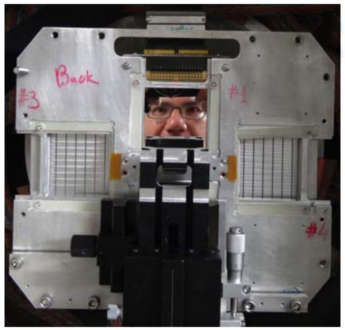


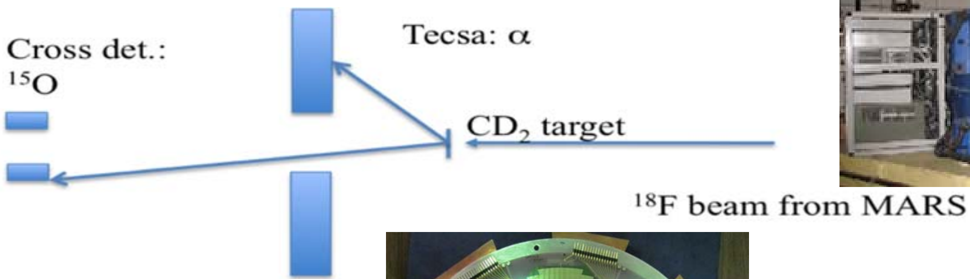
Figure 1: Schematic sketch of the $^{18}F(p,\alpha)^{15}O$ studied by means of the THM

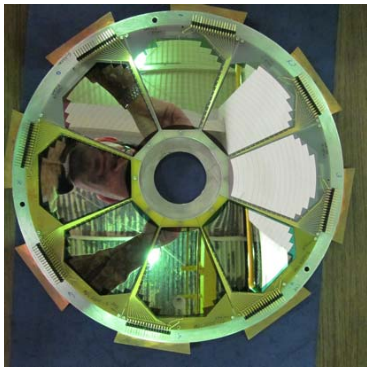
$^{18}F(p,\alpha)^{15}O$ studied via $^{18}F(d,\alpha^{15}O)n$

^{18}F beam produced via the MARS facility @TAMU

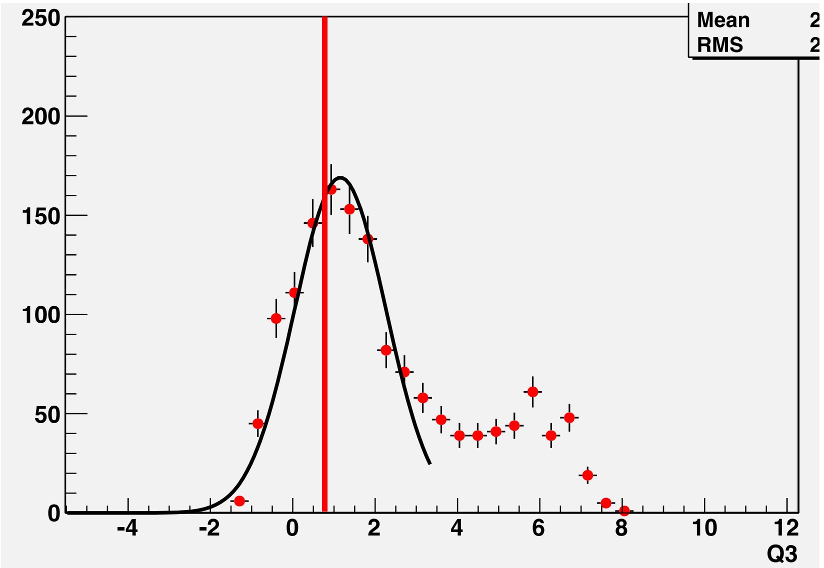
E=56 MeV, I=4x10^5 pps





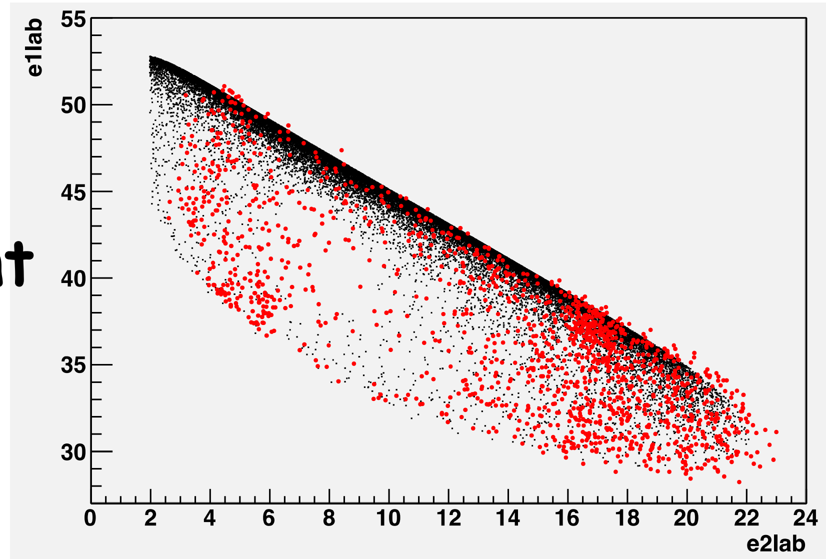


Preliminary results



Q-value Spectra and kinematic Locus used for gating on the Correct 3-body process
$^{18}F(d,a^{15}O)n$

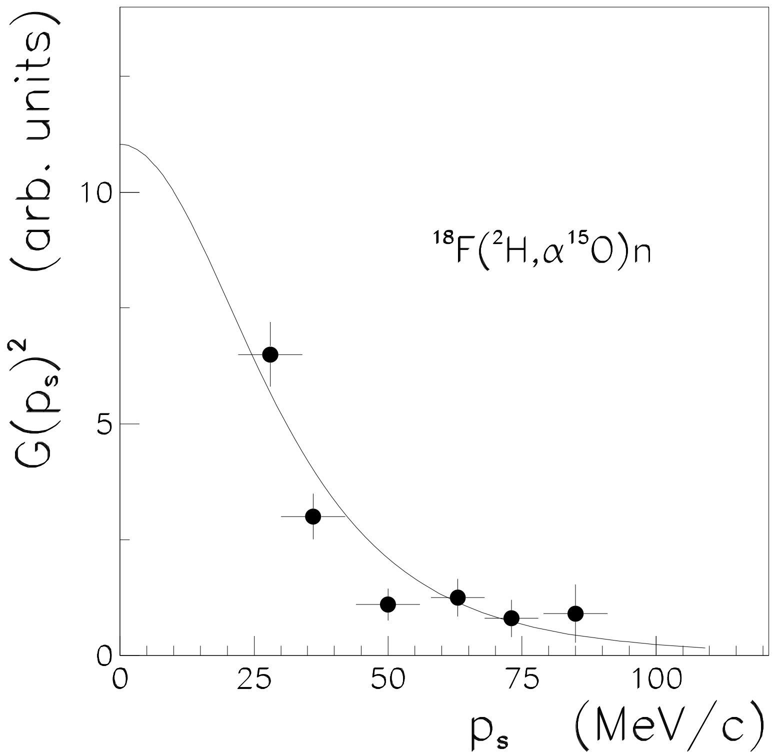
Kinematic locus in agreement With expected simulation

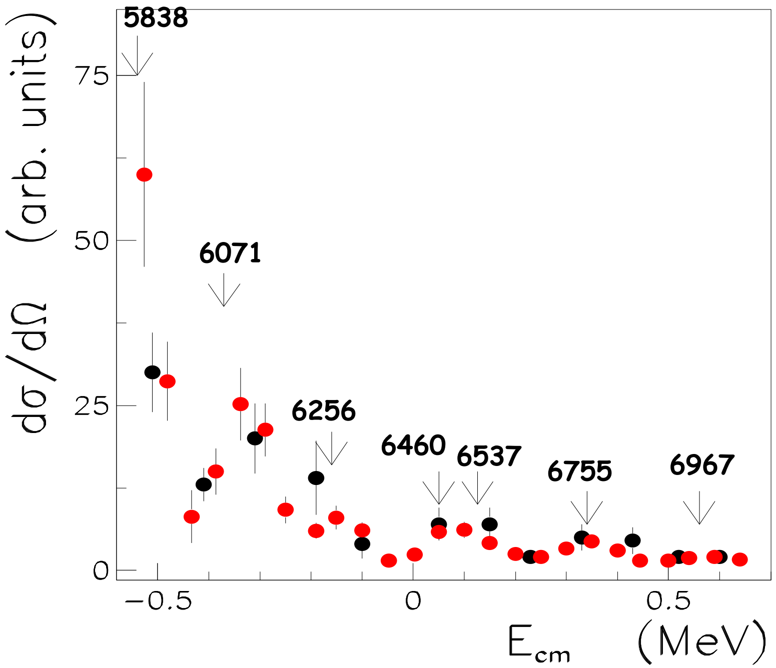


Preliminary results II

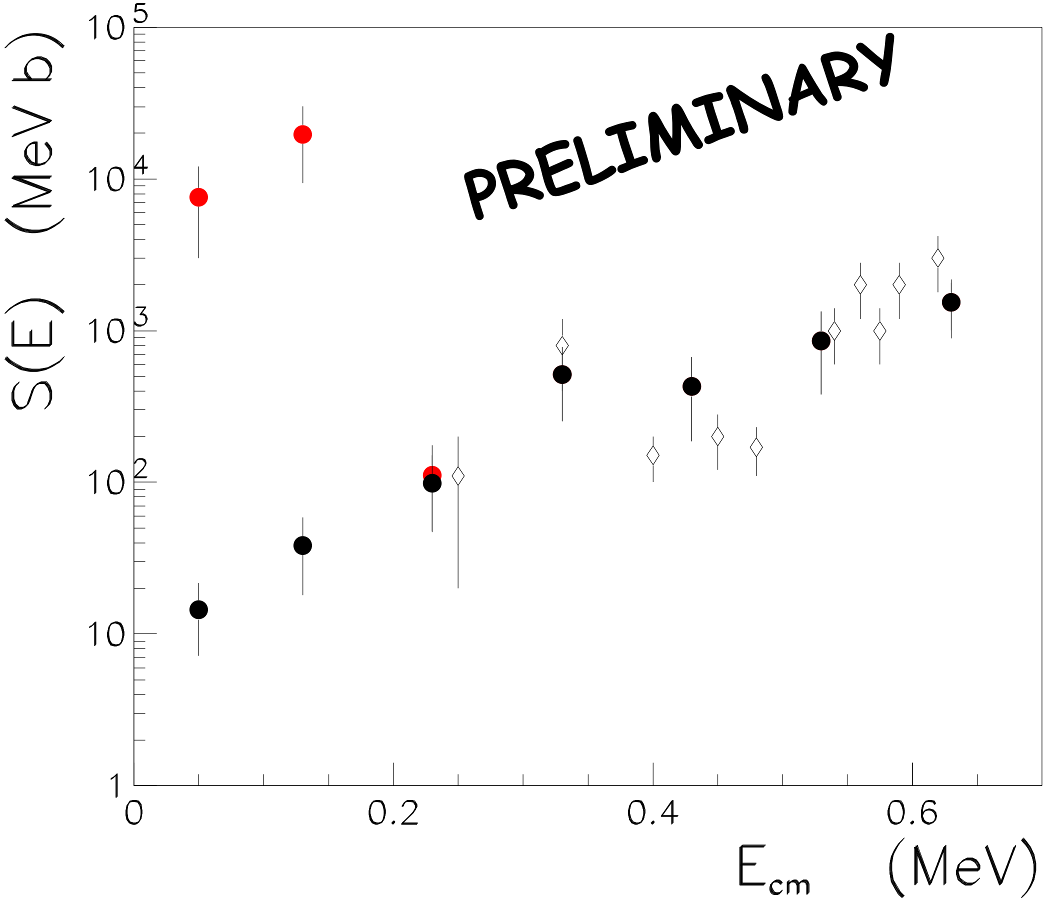
- Evidences of quasi-free break-up in the d momentum distribution

- Using the STD THM we extract the S(E)-factor for the $^{18}F(p,a)^{15}O$





Black: present work
Red: RIKEN THM run **Cherubini et al.**



- The S(E)-factor is measured in the astrophysical energy region
- Good agreement with direct data after normalization (Beers et al., Bardayan et al)
- THM suitable for RIB application
- PERSPECTIVES: reaction rate extraction & astrophysical applications

Lower limit (black): J^π= 1/2$^-$ or 5/2$^-$ E*=6460 keV.
Upper limit (red): J^π= 3/2$^+$ for resonance E*=6460 keV.

MARS uses a two-stage separation scheme to reduce the primary beam intensity and eliminate other unwanted reaction products. The first stage spatially separates ions based on their magnetic rigidity, equal to mv/q. The second stage uses a so-called Wien filter to separate ions based on their velocity. T