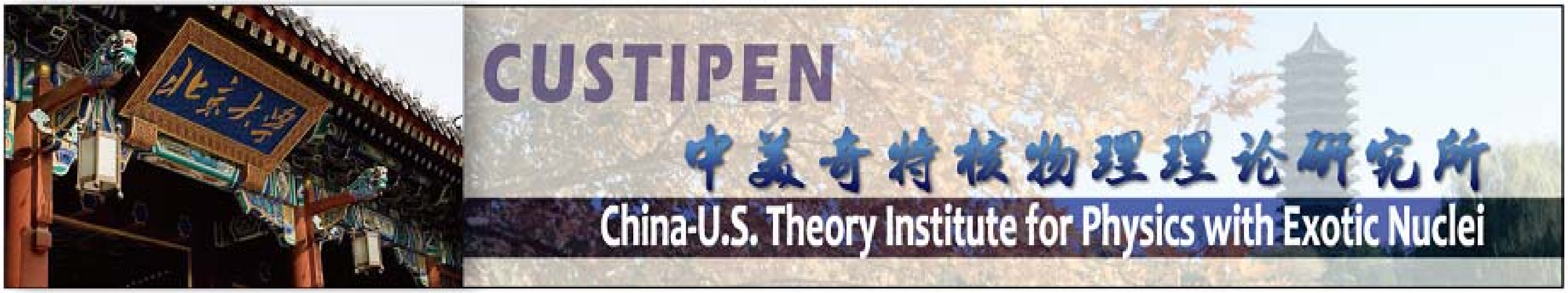

Trojan Horse Method and its application to nuclear astrophysics with stable and unstable

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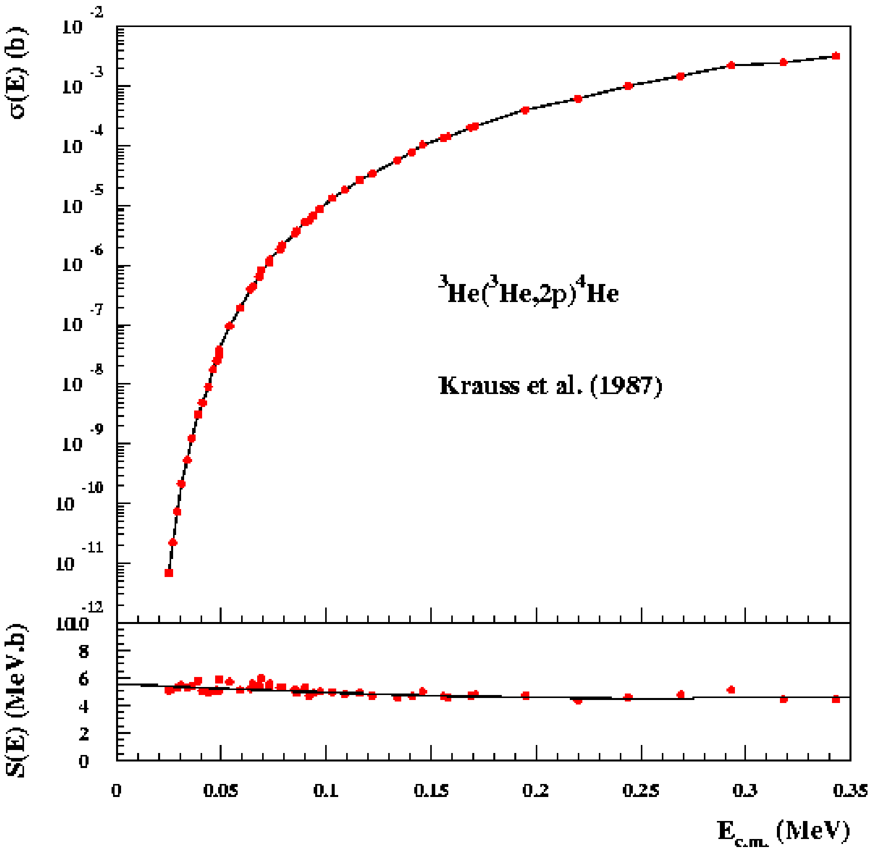


@ Gamow energies

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)

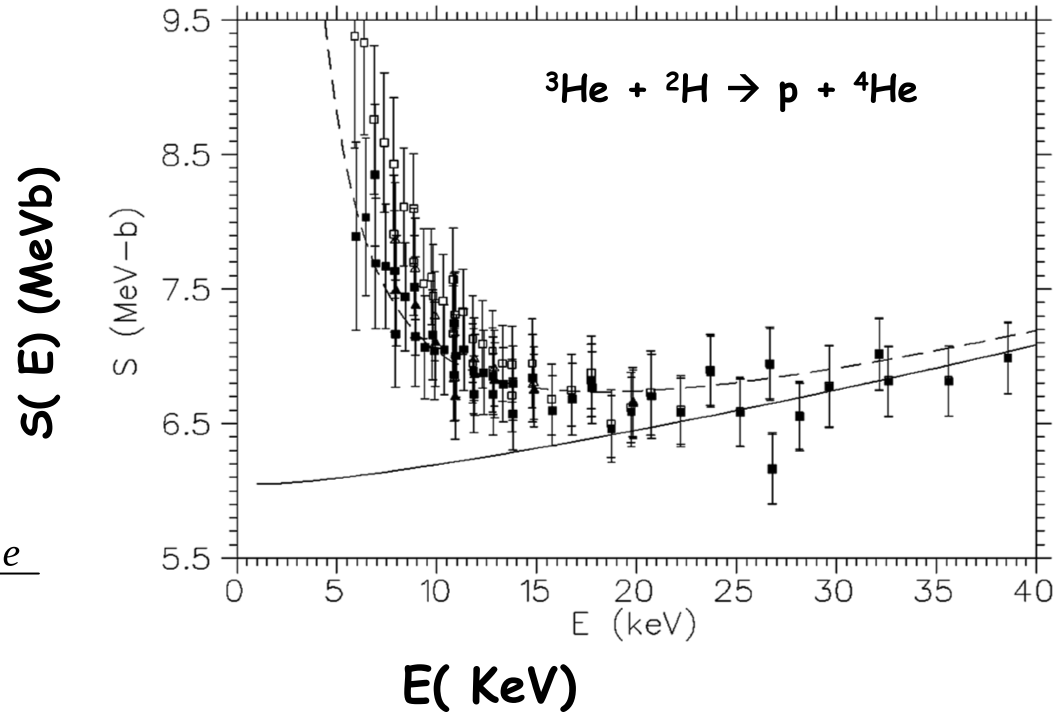
However

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

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



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

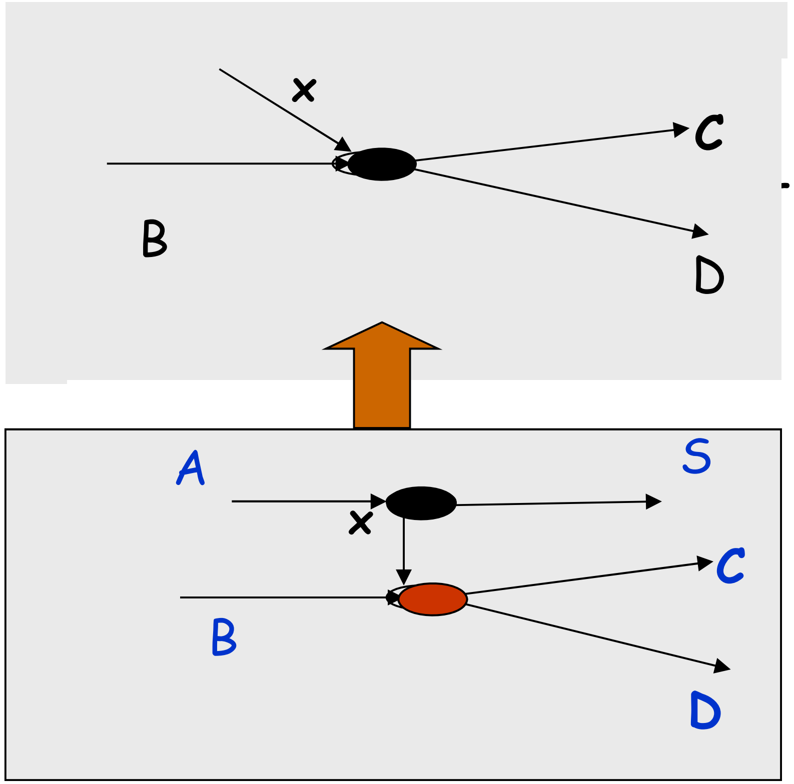
c) – Beta Delay decays studies and other methods

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:

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

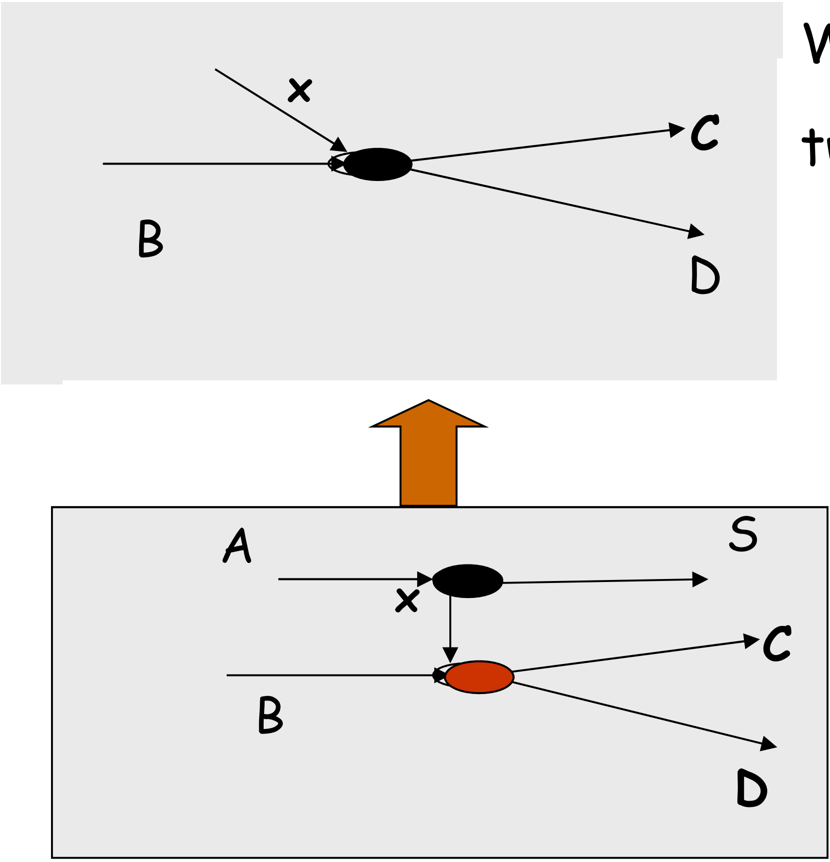
-The x cluster (participant) interacts with the nucleus B

B + x → C + D

-The S cluster acts as a spectator

(it doesn' t take part to the reaction)

A + B → C + D + S



We can extract astrophysically relevant

two-body cross section σ

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

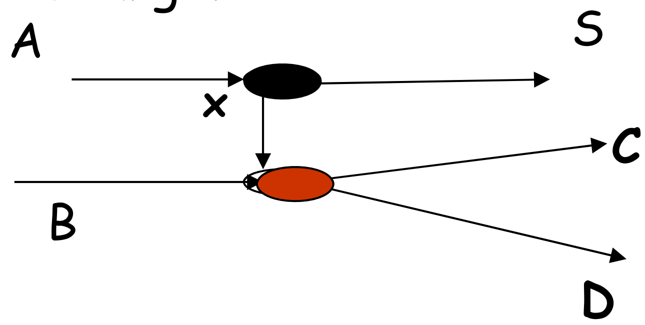
from quasi- free contribution of an appropriate three-body reaction

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

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

Quasi-Free mechanism → Trojan Horse Method

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



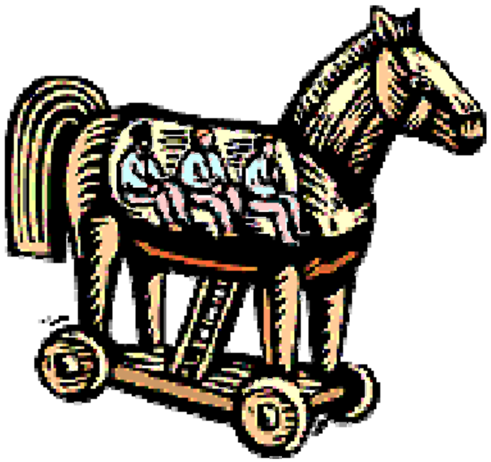
$$E_A > (E_{AB})_{Coulomb\ Barrier}$$

(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

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



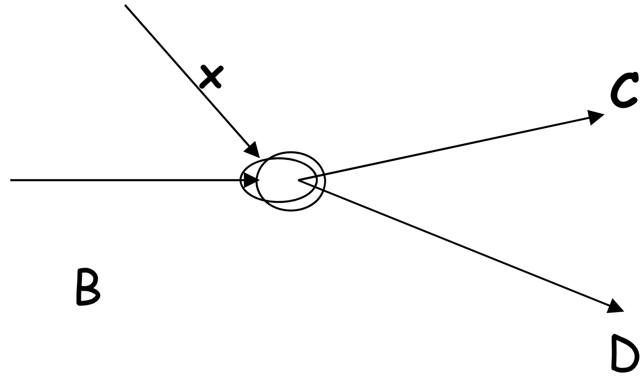
Coulomb effects and electron screening are negligible

Two body reaction takes place at:

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

Where

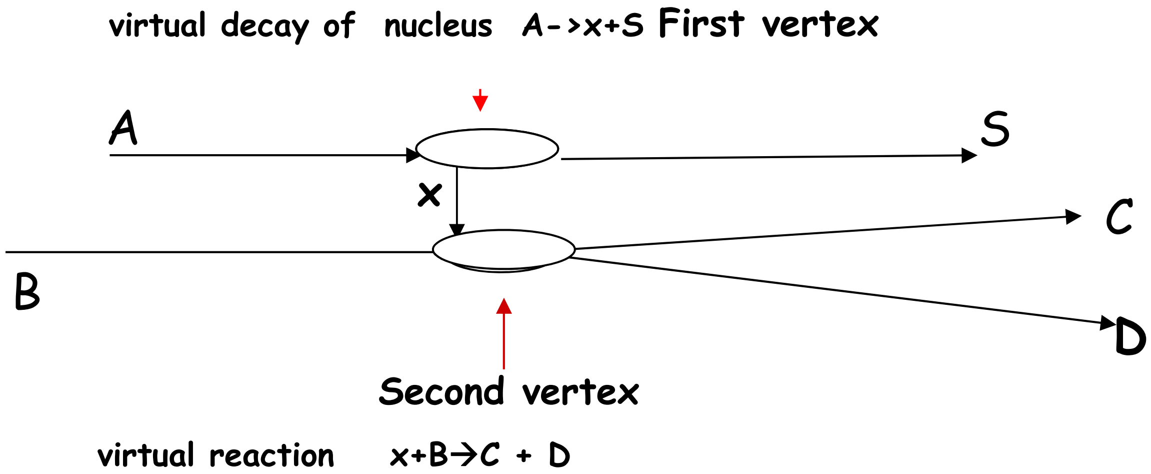
E_{Bx} is the beam energy in the center of mass of the two body reaction



$B_{x\text{-}S}$ 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

$$\frac{d^3\sigma}{dE_C \, d\Omega_c \, d\Omega_D} \propto KF \, [\Phi(q)_{xs}]^2 \left[\frac{d\sigma}{d\Omega}\right]$$

First vertex: $[\Phi(q)_{xs}]^2$

Second vertex: $\left[\frac{d\sigma}{d\Omega}\right]$ x + B→ C + D

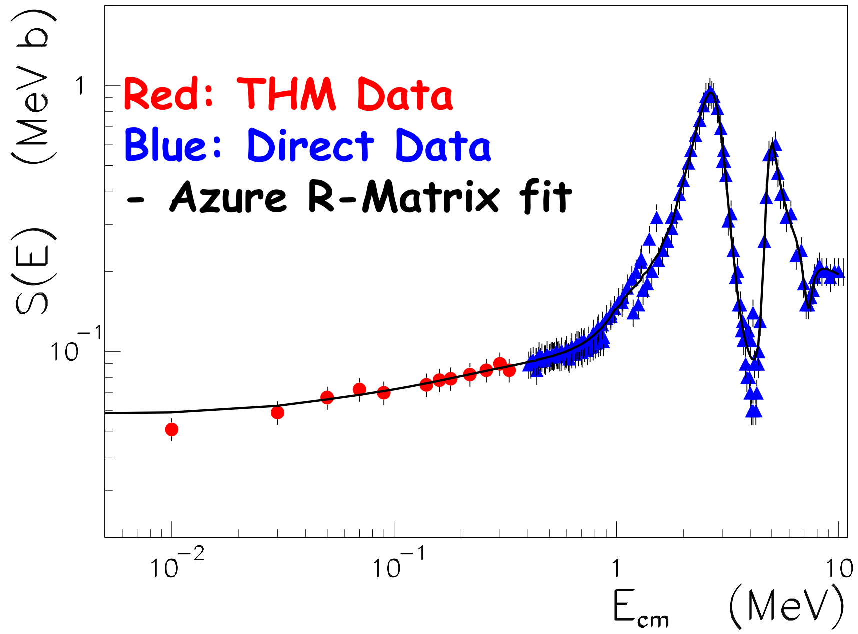
KF kinematical factor

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

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

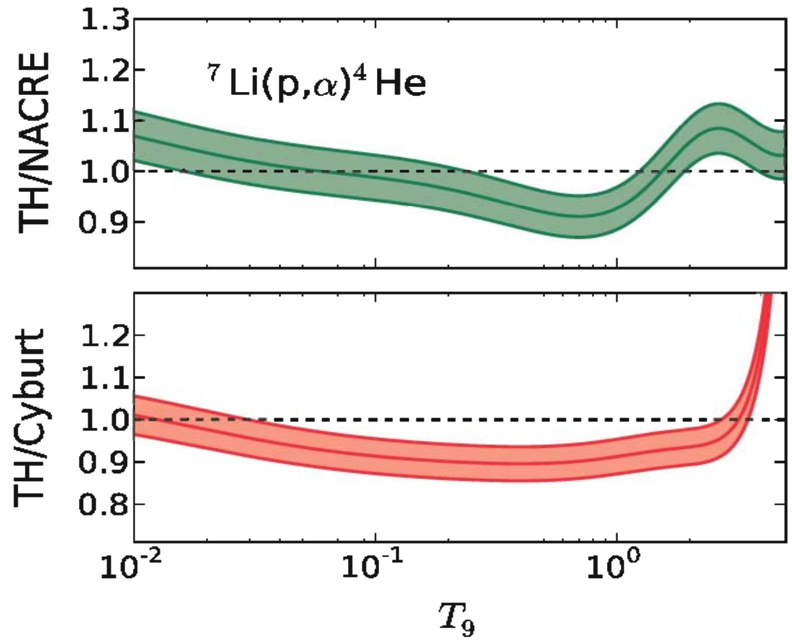
The $^7Li(p,\alpha)^4He$ reaction rate (RGP et al, APJ, 786, 2014)

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

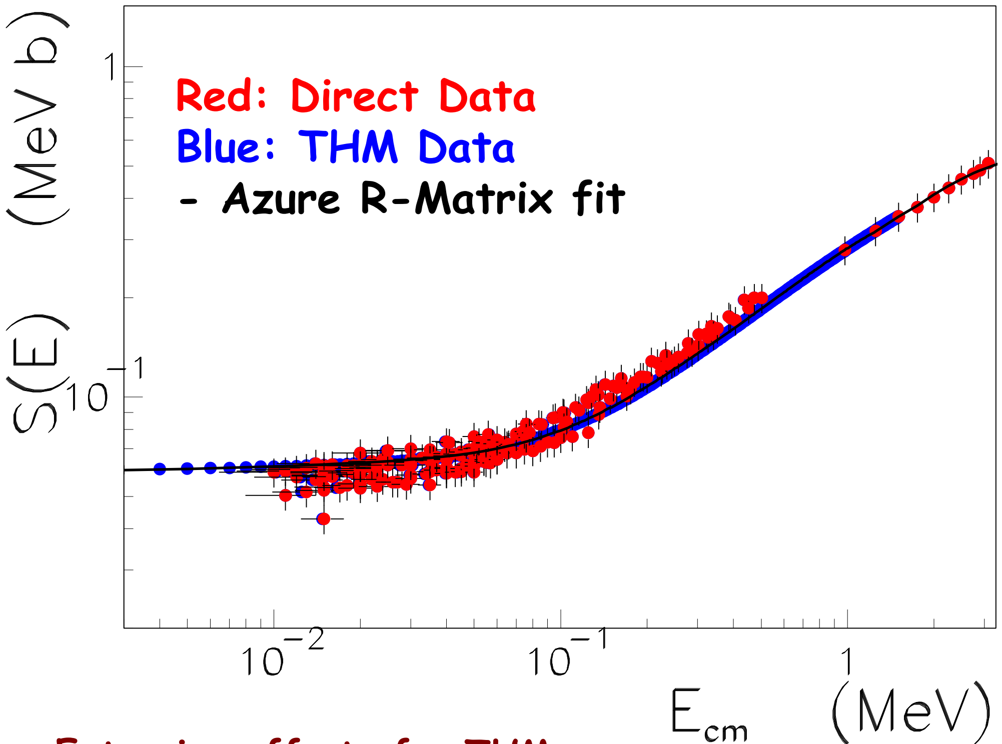


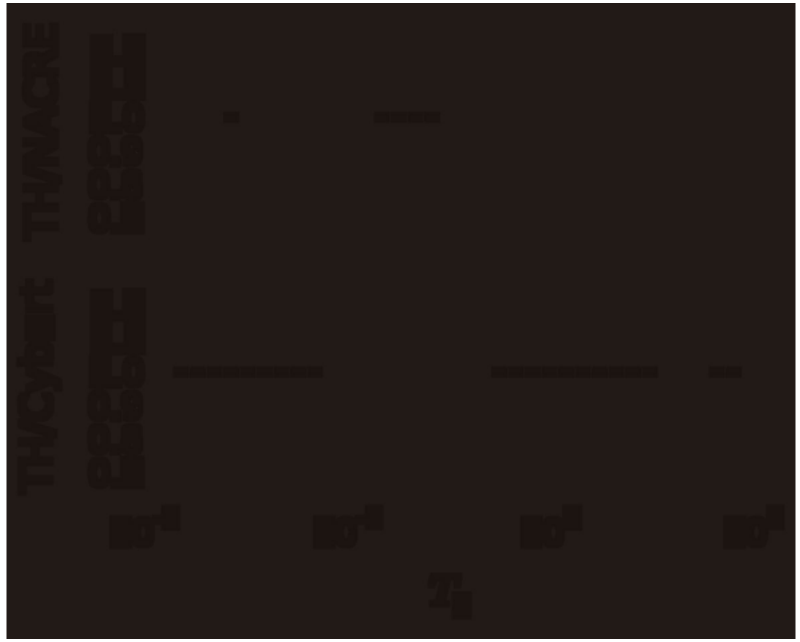
Extensive efforts for THM:
Spitaleri et al.1999, Lattuada et al
APJ 2001, RGP et al A&A 2003,
Lamia et al., A&A 2012

RESULTS
for the reaction rate



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



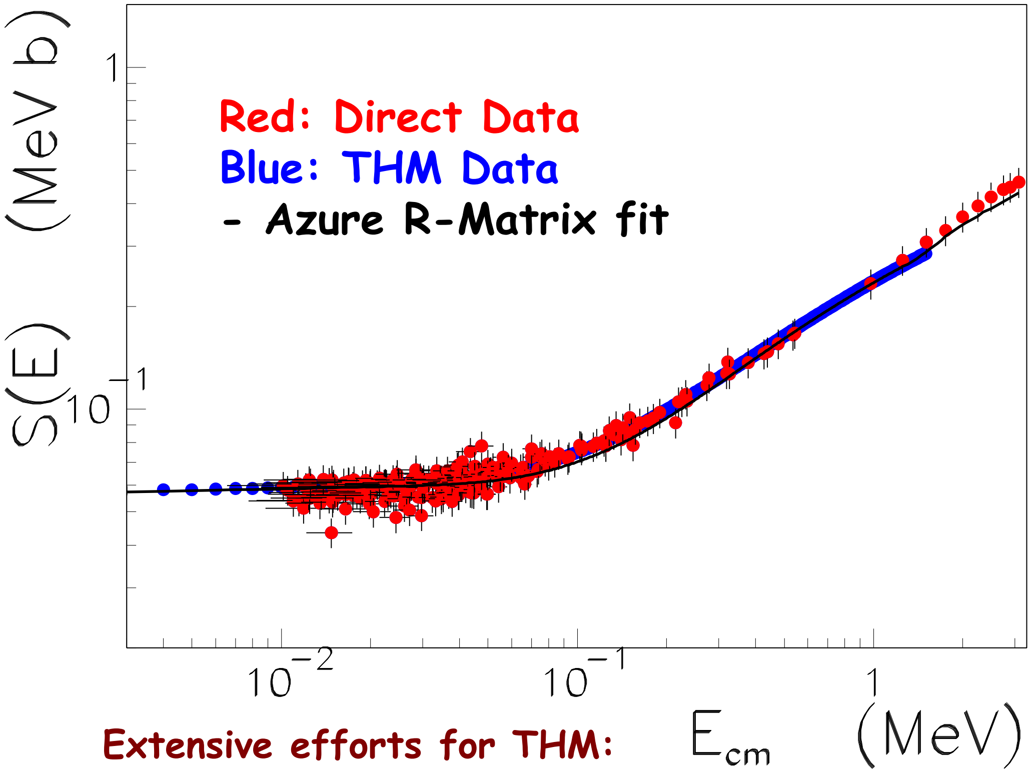


Extensive efforts for THM:
Tumino et al 2011, Pizzone et al 2013

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

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

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

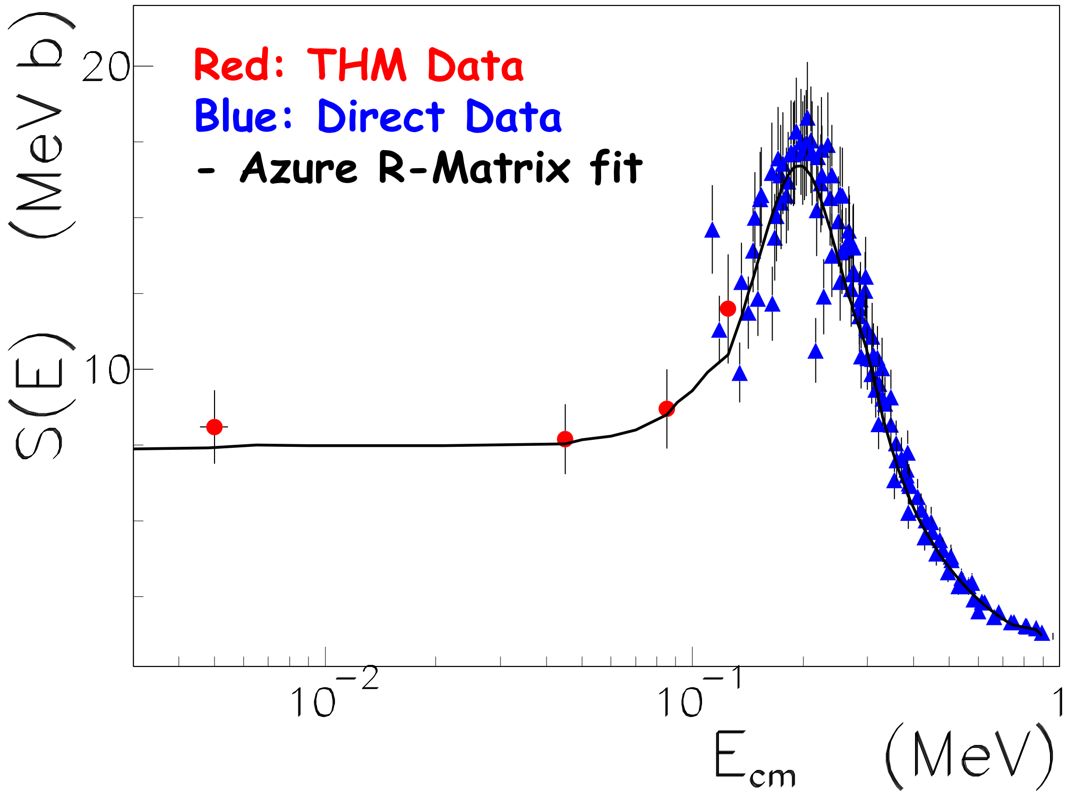


Extensive efforts for THM: Tumino et al 2011, Pizzone et al 2013

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

RESULTS
for the reaction rate
(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

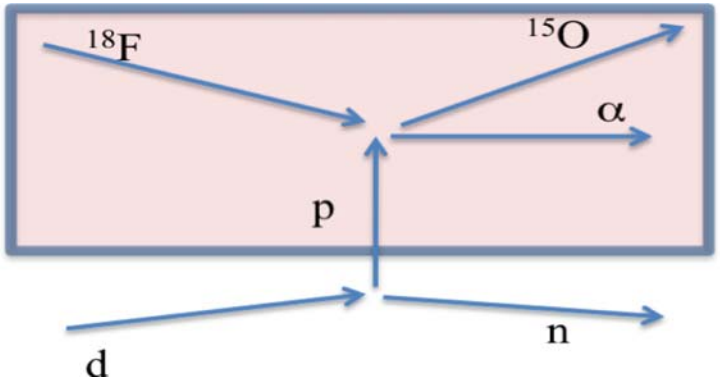
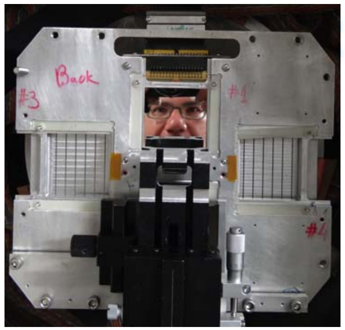


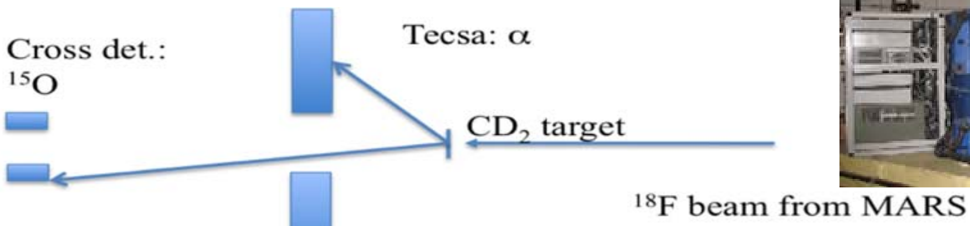
Figure 1: Schematic sketch of the $^{18}F(p,\alpha)^{15}O$ studied by means of the THM

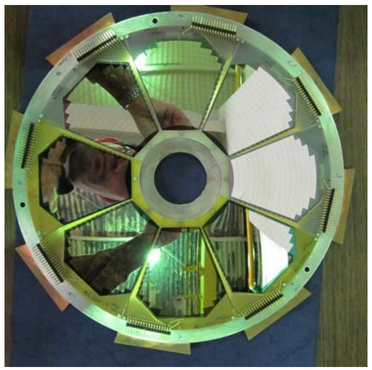
$^{18}F(p,\alpha)^{15}O$ studied via $^{18}F(d,\alpha^{15}O)n$

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

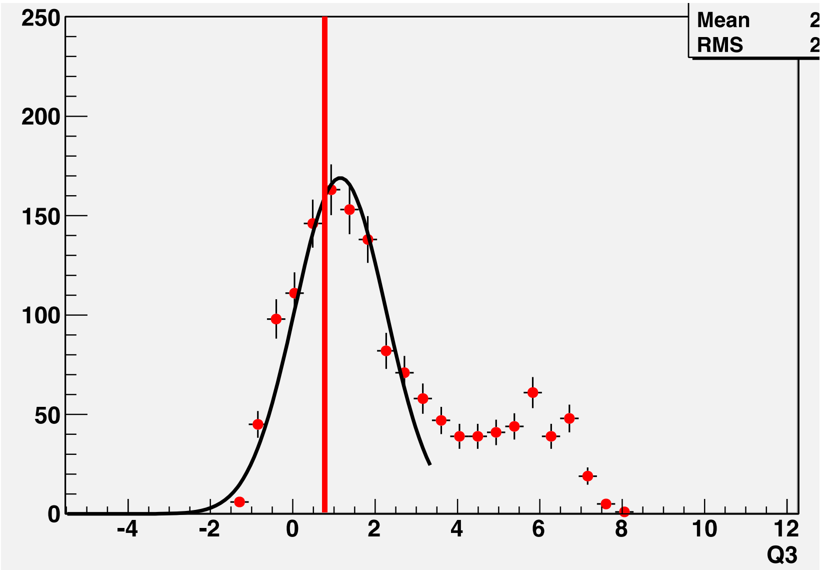
E=56 MeV, I=4×10^5 pps





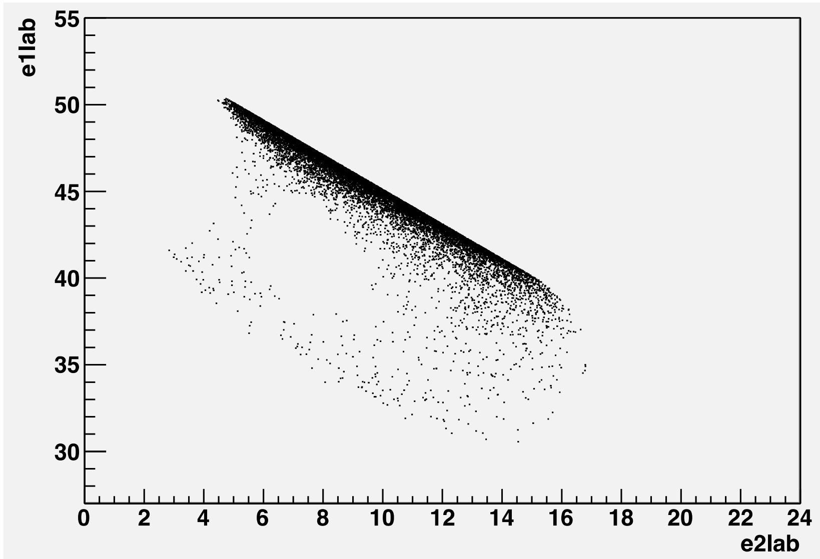


Preliminary results



Q-value Spectra and kinematic Locus used for gating on the Correct 3-body process

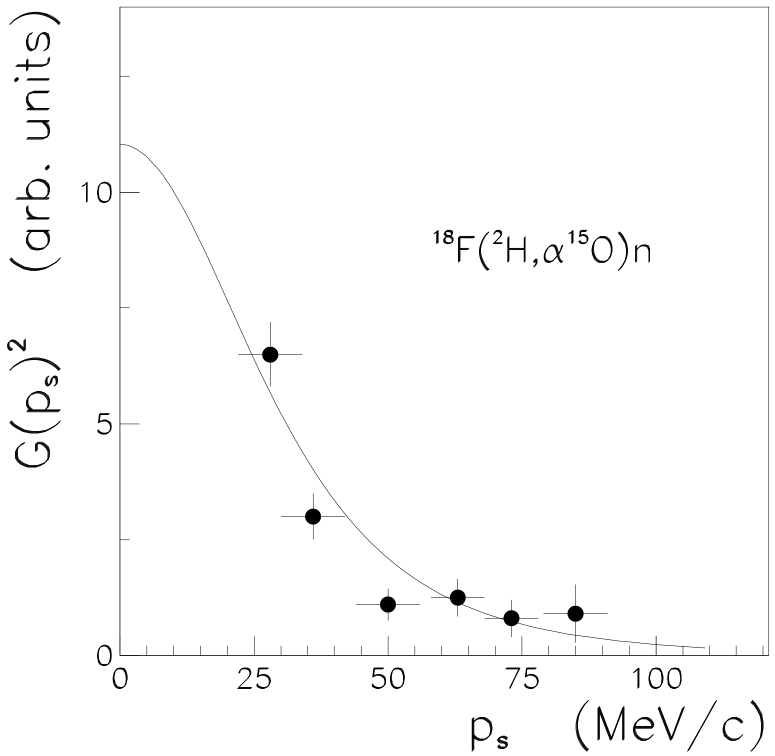
$^{18}F(d,a^{15}O)n$

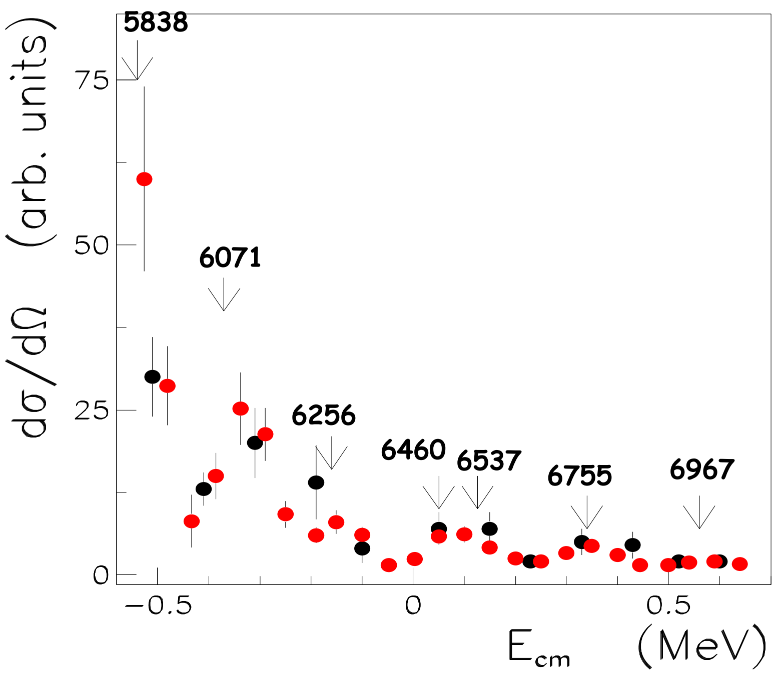


Preliminary results II

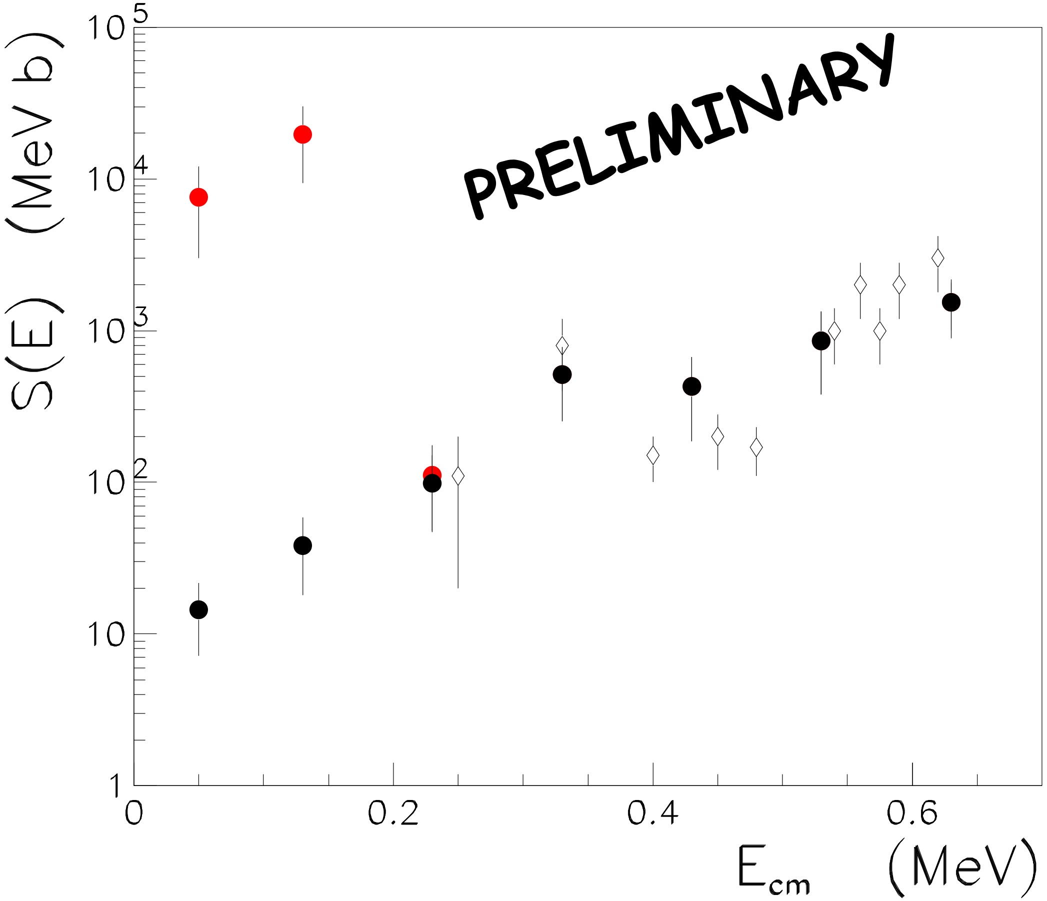
- Evidences of quasi-free break-up in the d momentum distribution

- 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