Few-body reactions investigated via the Trojan Horse Method

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

1) Extrapolation

DANGEROUS! large uncertainties
Nuclear astrophysics: troubles for measurements @ low energies

Solutions:

1) Extrapolation

2) Direct measure with high S/N

IMPROVEMENTS TO INCREASE THE NUMBER OF DETECTED PARTICLES

> 4π detectors

> New accelerators with high intensity beam

IMPROVEMENTS TO REDUCE THE BACKGROUND

> Laboratory with natural shield (underground physics)

\[ ^3\text{He}(^3\text{He},2p)^4\text{He} \]

At lowest energy: \( \sigma \sim 20\text{ fb} \rightarrow 1\text{ event/month} \)

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
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.

\[ x + B \rightarrow C + D \]

The binary reaction you’re interested in

\[ A + B \rightarrow C + D + S \]

The 3-body reaction you perform in the lab

A is the Trojan Horse nucleus

\[ x + S \]
The incoming energy $E_A$ of the incident particle is greater than the Coulomb barrier energy $(E_{AB})_{\text{Coul. Bar.}}$:

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

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.
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)

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

Where

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

$B_{x-S}$ binding energy of the two clusters inside the Trojan Horse plays a key role in compensating for the beam energy
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(under proper kinematical conditions)
In PWIA the cross section of the 3-body reaction can be factorized in two terms corresponding to the two vertices

\[ \frac{d^3\sigma}{dE_C d\Omega_C d\Omega_D} \propto KF \left| F(q)_{xS} \right|^2 \left[ \frac{d\sigma}{d\Omega} \right]_{TH} \]

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

\((ds/d\Omega)\) two-body cross section of the virtual reaction \(x + B \rightarrow C + D\)

THM: how can we overcome the Coulomb barrier?
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\[
\left[ \frac{d\sigma}{d\Omega} \right]_{x+B\rightarrow C+D}^{TH} \propto \frac{d^3\sigma}{dE_C d\Omega_C d\Omega_D} \frac{KF[F(q) x_S]^2}{K F \left[ F(\beta) \right]^2}
\]

Coulomb effects and electron screening are negligible

Measured and well above the Coulomb barrier
THM: how can we overcome the Coulomb barrier?

\[ ^7\text{Li} + p \rightarrow \alpha + \alpha \]

[Spitaleri et al. 1999]

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

Black line = OES pp cross section
Black triangles = TH data (HOES)

No Coulomb-nuclear interference deep experimentally observed

[Tumino et al. 2007 (PRL)]
[Tumino et al. 2008 (PRC)]
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[Tumino et al. 2007 (PRL)]
[Tumino et al. 2008 (PRC)]
Many astrophysical scenarios explored...i.e. the BBN

- $d(d,p)t$  
- $d(d,n)^3\text{He}$  
- $^3\text{He}(d,p)^4\text{He}$  
  [La Cognata et al. 2005 (PRC)]
- $^7\text{Li}(p,a)^4\text{He}$  

And using RIBs
- $^7\text{Be}(n,p)^7\text{Li}$ (in progress)
- $^7\text{Be}(n,\alpha)^4\text{He}$ (in progress)

& just done: $^3\text{He}(n,p)t$
Astrophysical motivation

The aim is the study of $^2\text{H}(d,p)^3\text{H}$ and $^2\text{H}(d,n)^3\text{He}$ (sensitivity!)
@energies relevant for the BBN scenario
(50-350 keV) $\rightarrow$ 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

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

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

$^3\text{He}=d+p$
The d-d reactions

d(d,p)³H

The graph shows the cross-section $(S(E))$ in units of (MeV b) as a function of the center-of-mass energy $(E_{cm})$ in MeV.

- **Direct Data (Updated comp.)**
- **THM Data**
- **Azure R-Matrix fit**

Data references:
The $d(d,n)^3He$ reaction

$^3He$ + $d$ → $^3He$ + $n$

(Tumino 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 independent 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

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[Graph showing polar invariance with Li, θHe, d, t, p.]

Present work: red triangles

[Rinollo et al. 2005]: black dots
Polar invariance

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

... and $^6\text{Li}(d,a)^4\text{He}$ result

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

[Spitaleri et al. 2001]

Within experimental errors good agreement
Conclusions

TH is based on \textit{TH-nucleus = 2 clusters}

\textbf{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 strength 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


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Thanks for your attention