

NUSDAF 2025 - 1st Collaboration Meeting on NUclear Structure, Dynamics and Astrophysics at FRIB

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Indirect methods: THM application to explosive nucleosynthesis

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for ASFIN collaboration



Università
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Nuclear reactions of astrophysical interest

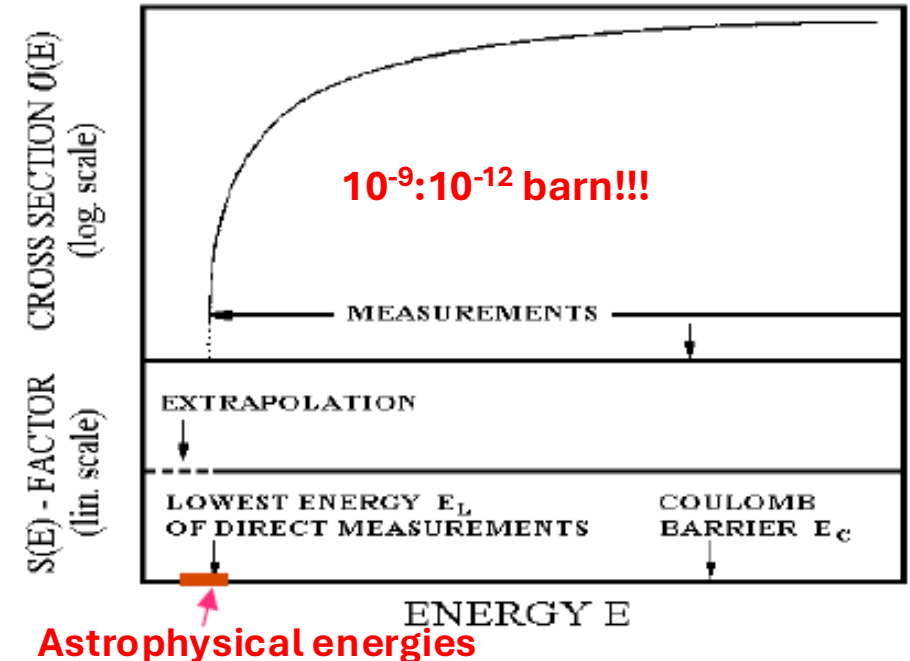
In astrophysical environment nuclear reactions take place at very low energies

Charged particles case: E_{cm} (keV) $\ll$ E_{CB} (MeV)

Tunnel effect $P \propto \exp(-2\pi\eta)$ $2\pi\eta$ = GAMOW factor

Exponential reduction of the cross section due to the Coulomb barrier

Experimental evaluation is severely hindered and in some cases, even beyond the technical possibilities



To increase signal/noise ratio

Improvements to increase the number of detected particles from the reaction of interest, i.e.

- increasing of the detection efficiency
- increasing of the beam intensity

Improvements to reduce the background

Nuclear reactions of astrophysical interest

Experimental approach is even more difficult for reactions involving RIBs

- Low beam currents for most isotopes (10^5 - 10^8 pps)
- Limited beam-energies are available → complicate to measure a whole excitation function, in the energy range of interest for astrophysics;

but ...

Important reactions induced by radioactive nuclei are involved in several explosive astrophysical scenarios:

Big Bang Nucleosynthesis

Novae explosive burning

X-Ray burst

Supernovae

Trojan Horse Method Approach

The **Trojan Horse Method (THM)** is an indirect technique for the measurement of cross sections at astrophysical energies of reaction between charged particles or neutron induced.

Basic idea:

It is possible to extract the two-body cross section relevant for the astrophysics,



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



- G.Baur: Phys. Lett.B178,(1986),135
- C. Spitaleri: 5th Winter School On Hadronic Physics. Folgaria, Italy, Feb 05-10, 1990
Problems Of Fundamental Modern Physics, li 21-36 (1991)
- R. E. Tribble, et al. Rep. Prog. Phy. 77 106901 2014
- C. Spitaleri et al. Eur. Phys. J. A (2016) 52: 77
- A. Tumino et al. *Annu. Rev. Nucl. Part. Sci.* 2021 71 1-33

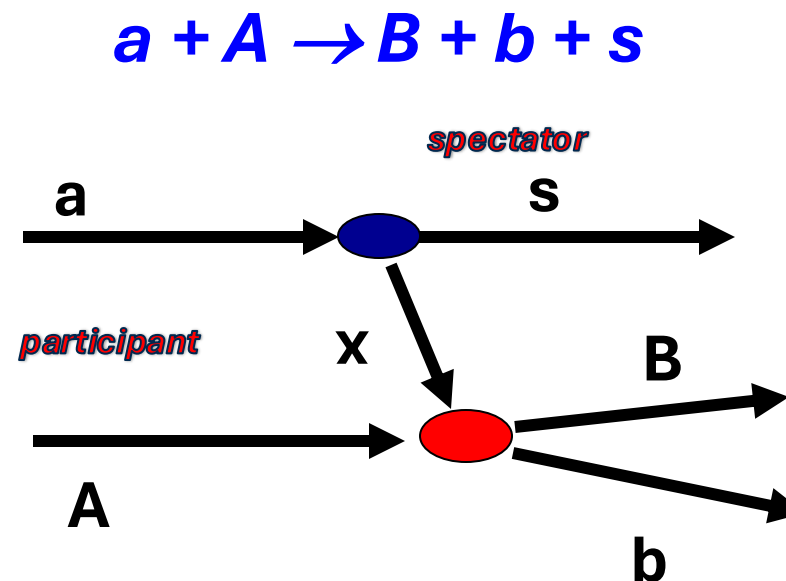
Trojan Horse Method Approach

THM is based on the quasi-free break-up mechanism

- a is the “TH nucleus” $a = x \oplus s$
- $a - A$ interaction $\rightarrow a$ break $\rightarrow$ the participant x interacts with $A \rightarrow$ two-body process
- Beam energy higher than $a - A$ Coulomb barrier $\rightarrow a$ break-up inside the nuclear field
- Coulomb effects and electron screening are negligible in the two-body process

$A + x \rightarrow B + b$ Half-Off-Energy-Shell (HOES)

- Cluster s acts as a spectator

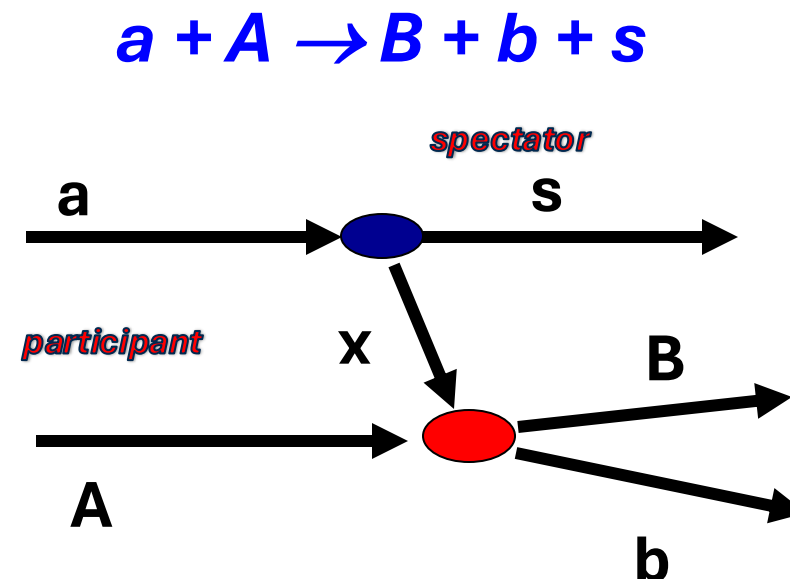


Trojan Horse Method Approach

The simplest theoretical approach is given by the **Plain Wave Impulse Approximation**:

$$\frac{d^3\sigma}{d\Omega_B d\Omega_b dE_B} \propto (KF) |\varphi(p_{xs})|^2 \left[\frac{d\sigma}{d\Omega} \right]^{HOES}$$

- kinematical factor
- square module of the Fourier transform of the radial wave function for the x-s inter-cluster motion
- the half-off-energy-shell differential cross section for the binary $A(x,b)B$ reaction at the center of mass energy E_{CM}



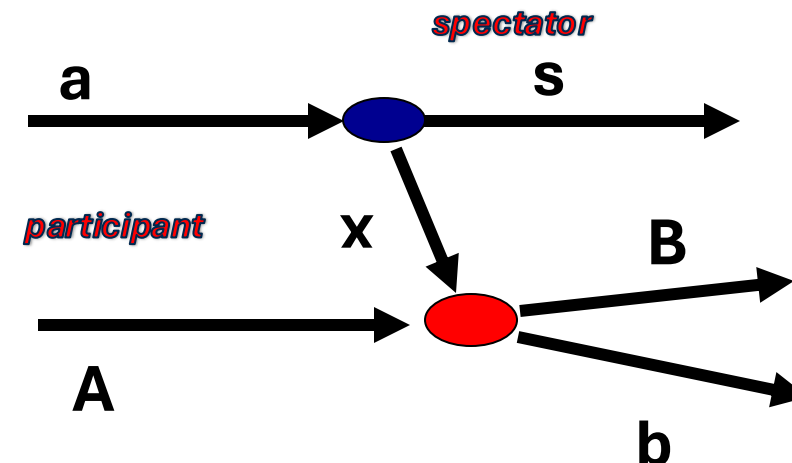
Trojan Horse Method Approach

The simplest theoretical approach is given by the **Plain Wave Impulse Approximation**:

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$$\left[\frac{d\sigma}{d\Omega} \right]^{\text{HOES}} \propto \frac{d^3\sigma}{d\Omega_B d\Omega_b dE_B} \frac{1}{KF |\varphi(p_{xs})|^2}$$



$$\left[\frac{d\sigma}{d\Omega} \right]^{\text{THM}} = \left[\frac{d\sigma}{d\Omega} \right]^{\text{HOES}} \times P_1 \propto \left[\frac{d\sigma}{d\Omega} \right]^{\text{Dir.}}$$

$P_1 \rightarrow$ Coulomb barrier penetrability

- No absolute cross section is measurable
- Normalization to direct measurements at higher energies
- THM is complementary to direct measurements

Trojan Horse Method: Resonant Case



Generic three-body reaction process is a transfer to the continuum where particle x is the transferred particle

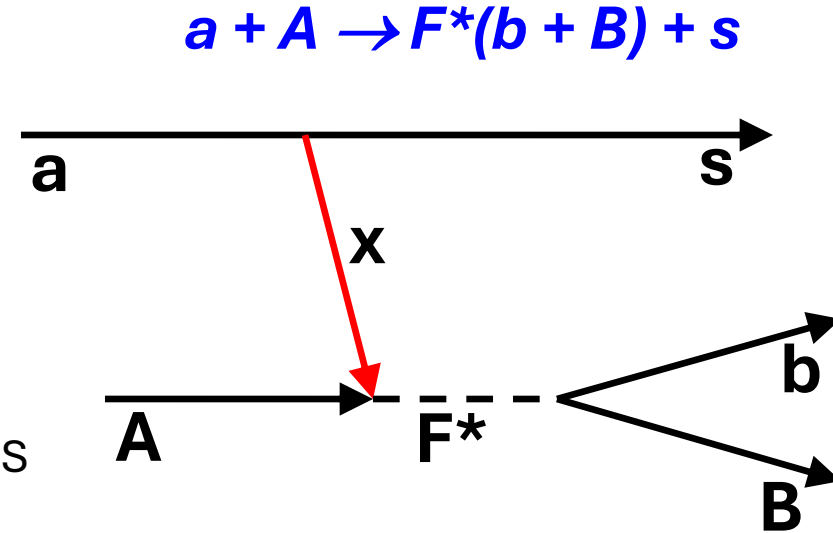
$$\frac{d^3\sigma}{d\Omega_B d\Omega_b dE_B} \propto (KF) |\phi(p_{xs})|^2 \left(\frac{d^2\sigma_{xA \rightarrow bB}}{dE_{xA} d\Omega} \right)^{\text{HOES}}$$

Modified R-Matrix is introduced to take into account the HOES nature of the two-body process.

The THM two body cross section takes the form:

$$\frac{d^2\sigma_{xA \rightarrow c'}}{dE_{xA} d\Omega_s} = NF \sum_i (2J_i + 1) \left| \sqrt{\frac{k_{c'}}{\mu_{c'}}} \frac{\sqrt{2P_{c'}} M_i(p_{xA} R_{xA}) \gamma_{xA}^i \gamma_{c'}^i}{D_i(E_{xA})} \right|^2$$

- $M_i(p_{xA} R_{xA})$ is the amplitude of the transfer reaction that replaces the entrance channel partial width.
- γ_c^i are the reduced widths for the i th resonance
- $D_i(E_{xA})$ is the standard R-Matrix denominator of one-level multi-channel



Mukhamedzhanov A.M. et al., J.Phys. G Nucl. Phys.
35, 014016 (2008)
La Cognata M. et al., Astrophysical J. 723, 1512 (2010)
La Cognata M. et al., Astrophysical J. 777, 143 (2013).

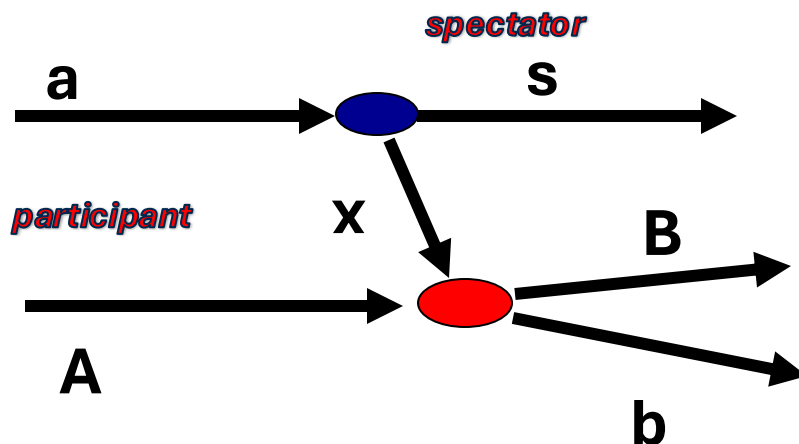
- Only one normalization coefficient.
- Same reduced widths as in the on-energy shell case.

Why Trojan Horse Method for RIB-induced reactions ?



- Because of the overcome of the Coulomb barrier suppression, THM experiments do not require very high intensity beams as in direct experiments
- Cross section measurement in a wide energy range with only one beam energy
 - In quasi-free conditions the two-body interaction takes place at:

$$E_{q.f.} = E_{xA} - B_{x-s}$$



E_{xA} 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 nucleus that **plays a key role in compensating for the beam energy**

Thanks to the **x-s inter-cluster motion** inside the TH nucleus, it is possible to **span a wider energy range with only one beam energy**

Why Trojan Horse Method for RIB-induced reactions ?



- TH nuclei as virtual source of target (or beam) nuclei

TH nucleus
$d = (p \oplus n)$
${}^3\text{He} = (d \oplus p)$
${}^6\text{Li} = (\alpha \oplus d)$
${}^3\text{He} = (d \oplus p)$
${}^{14}\text{N} = ({}^{12}\text{C} \oplus d)$

$$d = (p \oplus n)$$



neutron target, almost unique possibility to study RIB – neutron interaction

$${}^3\text{He} = (d \oplus p)$$

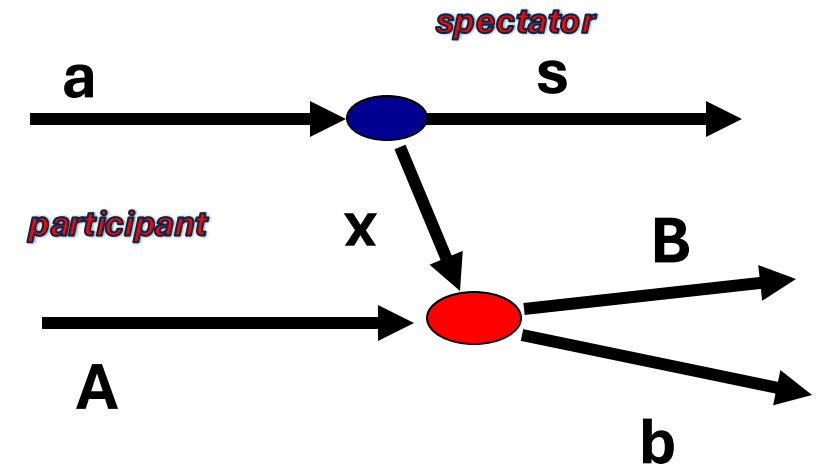
$${}^6\text{Li} = (\alpha \oplus d)$$



alpha particle target avoiding to use ${}^4\text{He}$ gas target

$${}^3\text{He} = (d \oplus p)$$

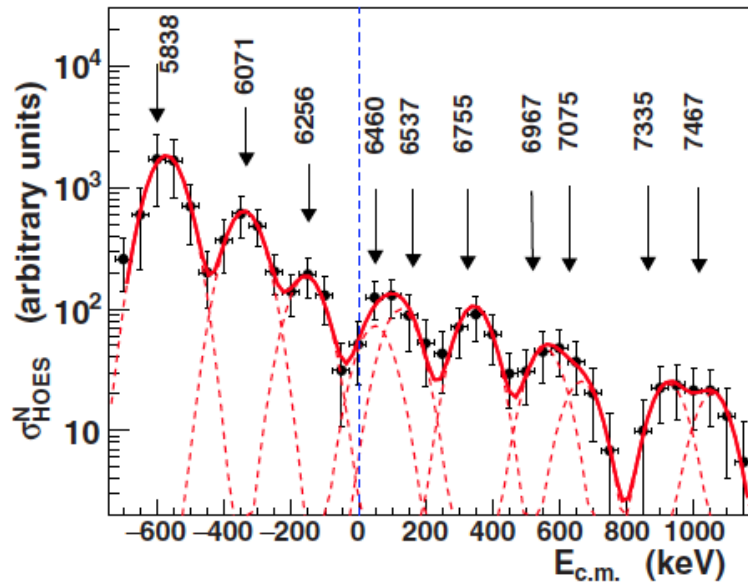
$${}^{14}\text{N} = ({}^{12}\text{C} \oplus d)$$



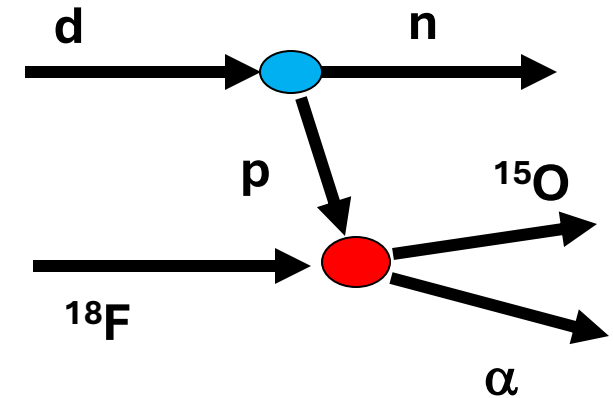
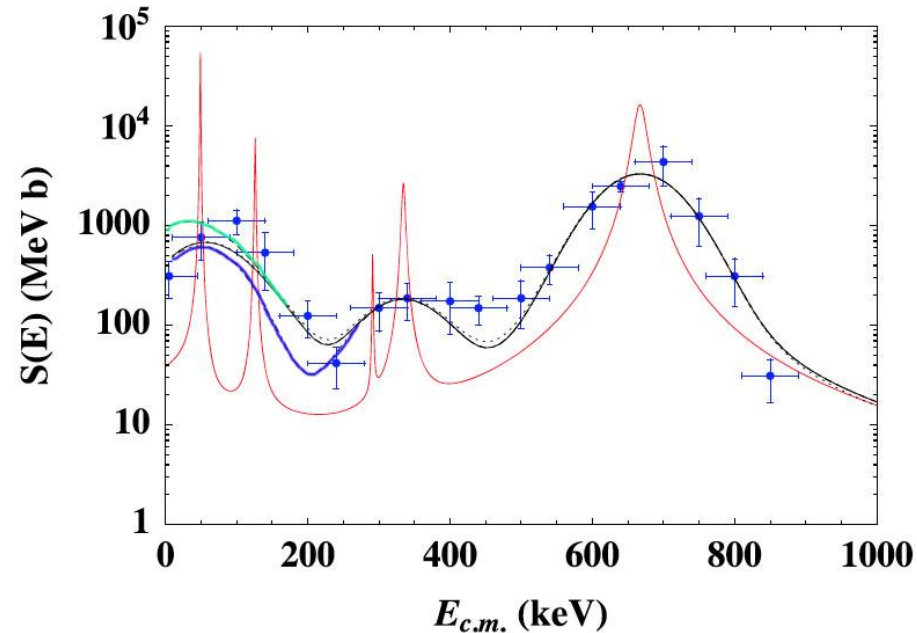
THM with RIB: some results



THM study of $^{18}\text{F}(p,\alpha)^{15}\text{O}$



$^2\text{H}(^{18}\text{F},\alpha\ ^{15}\text{O})n$
deuteron TH nucleus ($p \oplus n$)



@ CRIB Riken
@ MARSTAMU

S. Cherubini, et al., PRC, 92, 015805, 2015
R. G. Pizzone, et al. 2016, EPJA, 52, 24
M. La Cognata et al. APJ, 846:65 (6pp), 2017

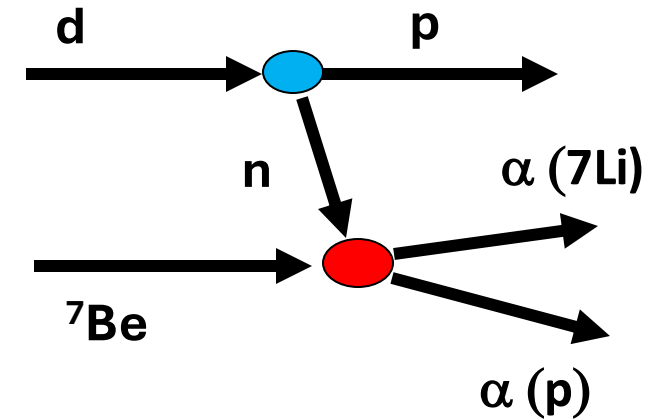
Beam intensity $\sim 5 \times 10^5$ pps

THM with RIB: some results



THM study of the
 ${}^7\text{Be}(n,\alpha)\alpha$ and ${}^7\text{Be}(n,p){}^7\text{Li}$

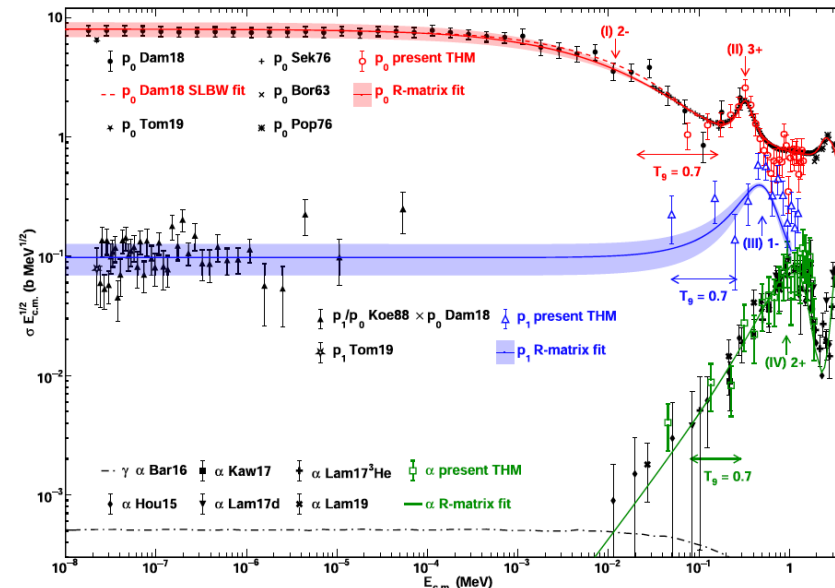
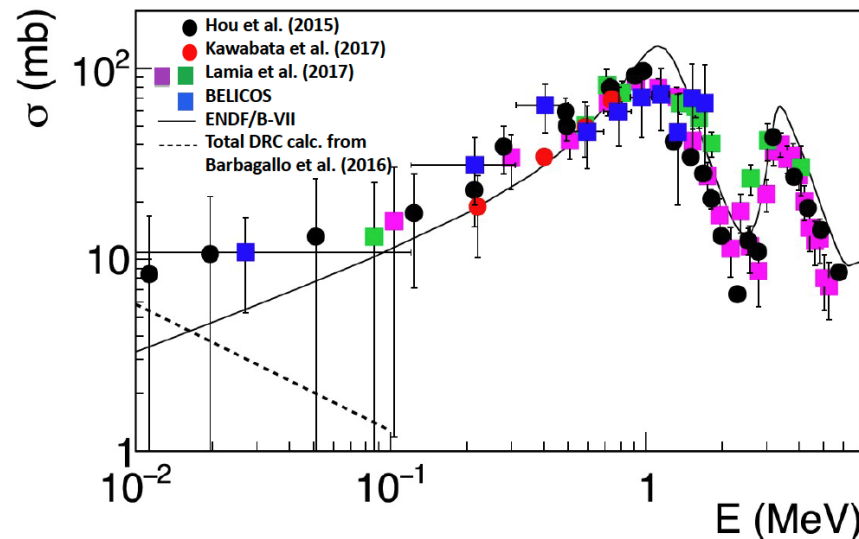
${}^2\text{H}({}^7\text{Be}, \alpha\alpha)\text{H}$
 ${}^2\text{H}({}^7\text{Be}, p {}^7\text{Li})\text{H}$
 deuteron TH nucleus ($p \oplus n$)
neutron target



@ EXOTIC LNL L. Lamia et al. APJ., 879:23, 2019

@ CRIB Riken Hayakawa et al. APJL, 915:L13 2021

Beam intensity : $5 \times 10^5 - 1 \times 10^6$ pps



THM with RIB: some results



THM measurement of :

$^{26}\text{Al}^{\text{gs}} (n,p)^{26}\text{Mg}$

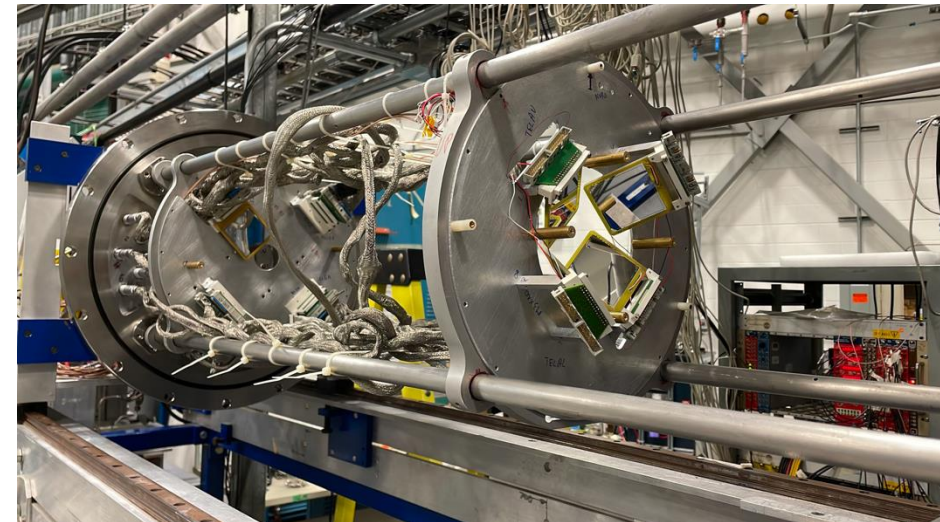
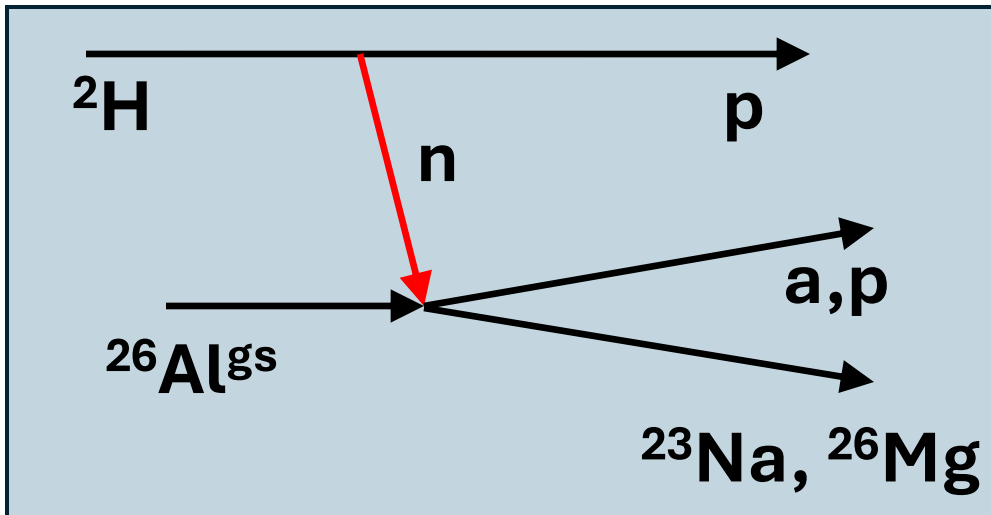
$^{26}\text{Al}^{\text{gs}} (n,\alpha)^{23}\text{Na}$

$^2\text{H}(^{26}\text{Al}^{\text{gs}},p\ ^{26}\text{Mg})p$

$^2\text{H}(^{26}\text{Al}^{\text{gs}},\alpha\ ^{23}\text{Na})p$

deuteron TH nucleus ($p \oplus n$)

neutron target



NEFASTA detector array
(NEar FAr Silicon Telescope Array),
8 telescopes arranged into two groups

Possible THM study at FRIB:

(α, p) reactions for X-Ray Bursts nucleosynthesis

X-ray bursts: thermonuclear explosions which take place on the surface of neutron stars in binary systems

The (α, p) reactions are expected to influence the shape and rise times of luminosity curves coming from X-ray bursts (XRBs).

Sensitivity studies for X-ray Burst include $^{14}\text{O}(\alpha, p)^{17}\text{F}$, $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ and $^{22}\text{Mg}(\alpha, p)^{25}\text{Al}$ reactions among the processes that have an influence on the burst light curve and on the composition of the burst ashes.

$^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$ reaction leads to breakout of the hot CNO cycle to the rp-process.

Data available in literature:

Few direct measurements (at the upper end of the Gamow window)

Reaction rate evaluation is based on :

time-inverse measurements and transfer reaction or elastic scattering measurements to evaluate the parameters of the involved resonances.

Table 2
Reactions that Impact the Burst Light Curve
in the Multi-zone X-ray Burst Model

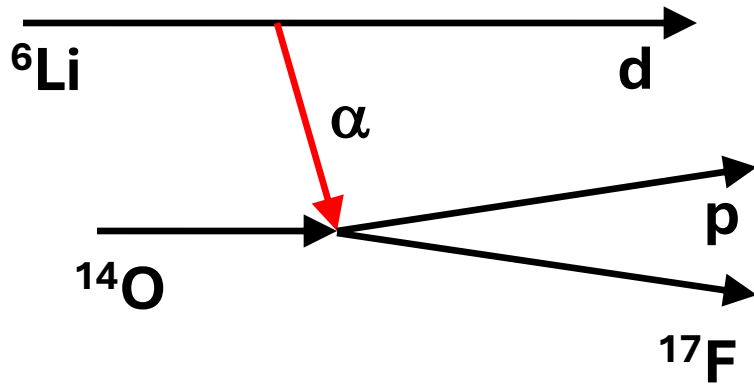
Rank	Reaction	Type ^a	Sensitivity ^b	Category
1	$^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$	D	16	1
2	$^{56}\text{Ni}(\alpha, p)^{59}\text{Cu}$	U	6.4	1
3	$^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$	D	5.1	1
4	$^{61}\text{Ga}(p, \gamma)^{62}\text{Ge}$	D	3.7	1
5	$^{22}\text{Mg}(\alpha, p)^{25}\text{Al}$	D	2.3	1
6	$^{14}\text{O}(\alpha, p)^{17}\text{F}$	D	5.8	1
7	$^{23}\text{Al}(p, \gamma)^{24}\text{Si}$	D	4.6	1
8	$^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$	U	1.8	1
9	$^{63}\text{Ga}(p, \gamma)^{64}\text{Ge}$	D	1.4	2
10	$^{19}\text{F}(p, \alpha)^{16}\text{O}$	U	1.3	2
11	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	U	2.1	2
12	$^{26}\text{Si}(\alpha, p)^{29}\text{P}$	U	1.8	2
13	$^{17}\text{F}(\alpha, p)^{20}\text{Ne}$	U	3.5	2
14	$^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$	U	1.2	2
15	$^{57}\text{Cu}(p, \gamma)^{58}\text{Zn}$	D	1.3	2
16	$^{60}\text{Zn}(\alpha, p)^{63}\text{Ga}$	U	1.1	2
17	$^{17}\text{F}(p, \gamma)^{18}\text{Ne}$	U	1.7	2
18	$^{40}\text{Sc}(p, \gamma)^{41}\text{Ti}$	D	1.1	2
19	$^{48}\text{Cr}(p, \gamma)^{49}\text{Mn}$	D	1.2	2

Notes.

^a Up (U) or down (D) variation that has the largest impact.

^b $M_{LC}^{(i)}$ in units of $10^{38} \text{ erg s}^{-1}$.

$^{14}\text{O}(\alpha, p)^{17}\text{F}$ via THM



^{14}O @ 15 MeV $\rightarrow E_{\text{cm}}$ 0 – 3 MeV
in quasi-free conditions

ReA3 provides energies ranging from 0.3 MeV
eV/u to up to 6 MeV/u

Beam	EG (T=0.35GK)	Ebeam (MeV)	Ebeam/A (MeV/u)	EG (T=1.5GK)	Ebeam (MeV)	Ebeam/A (MeV/u)
^{14}O	0.56	13.6	0.97	1.48	17.7	1.27
^{18}Ne	0.66	17.2	0.95	1.75	23.2	1.29
^{22}Mg	0.76	20.9	0.95	2.00	29.0	1.32

List of requested beam energies centered on the effective Gamow energy, spanning energies between breakout (T=0.35 GK) and a typical peak XRB temperature (T~1.5 GK).

CCSN nucleosynthesis



The ^{44}Ti ($t_{1/2} = 60$ y) is of great importance because allows a direct diagnostic of the CCSN explosion energy and timescale. Ryo Sawada and Keiichi Maeda 2019 ApJ 886 47

^{44}Ti abundance is evaluated by gamma-ray emission.

^{44}Ti produced in a supernova depends strongly on the cross section of the $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ reaction.

Direct measurements available in literature:

- at energies higher than the Gamow window.

A. Sonzogni et al., Phys. Rev. Lett. 84, 1651 (2000)

- upper limit on the cross section at an energy within the Gamow window.

V. Margerin et al., Phys. Lett. B 731, 358 (2014)

Conclusions

- THM is an experimental technique that can improve our knowledge of nuclear reactions of astrophysical interest induced by radioactive nuclei.
- The study of (α, p) reactions in X-ray bursts nucleosynthesis represents a physical case that can be studied with the THM at FRIB

AsFiN Collaboration

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Thank you for the attention