SNAQ January 2022

Schools on Nuclear Astrophysics Questions

Jan 12, 2022

Astrophysics and unstable nuclei: Indirect method for radioactive ion beam experiments

Giuseppe Gabriele Rapisarda

Overview

- ✓ Nuclear reactions of astrophysical interest
- ✓ Introduction to the Trojan Horse Method (THM)
- ✓ RIB induced reactions of astrophysical interest measured via THM:

  $^{18}F(p,\alpha)^{15}O$

  $^{7}Be(n,\alpha)^{4}He$

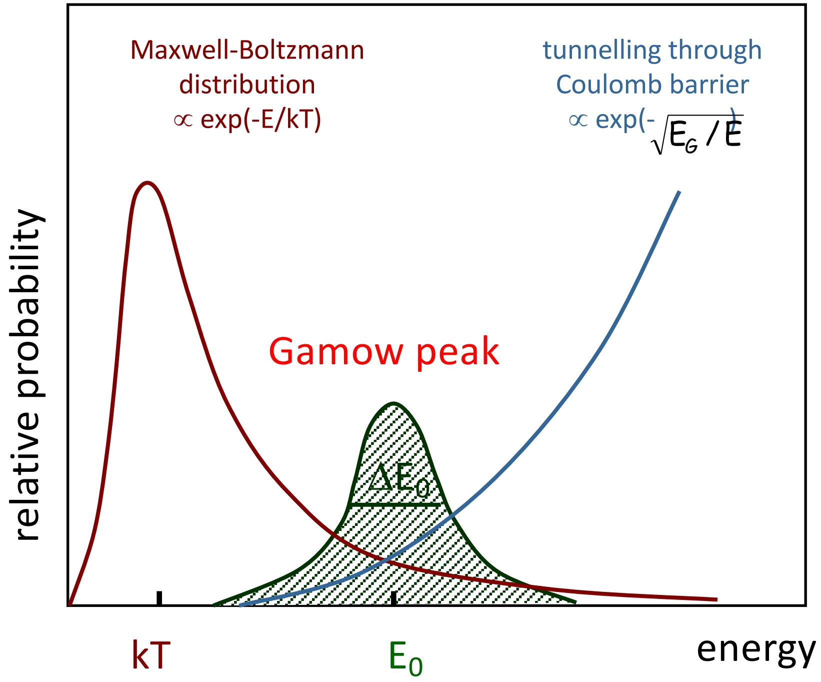
  $^{7}Be(n,p)^{7}Li$

Nuclear reactions of astrophysical interest

In astrophysical environments the energy required for particle interactions is taken from Thermal Energy.

In particular, **nuclear reactions take place** if particles approach each other with energy within the so-called **Gamow window**.

That is produced by the convolution of the probability for **penetrating the Coulomb barrier** that goes down rapidly with decreasing energy, and the **Maxwell-Boltzmann distribution** of the energy



In main-sequence stars T ~ 10^6 K then E=kT~ keV

In massive stars, stellar explosive scenarios or Big Bang nucleosynthesis T~ 10^9 K E~ 0.5-1 MeV

Charged particles interact well below the Coulomb Barrier

E_{cm} (keV) << E_{coul} (MeV)

Tunnel effect

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

Nuclear reactions of astrophysical interest

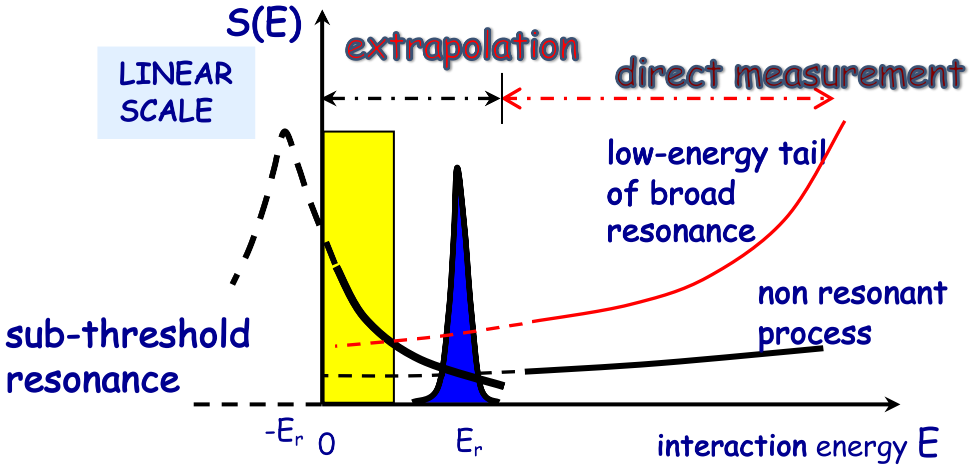
@ Gamow energies σ in the range nanobarn - picobarn

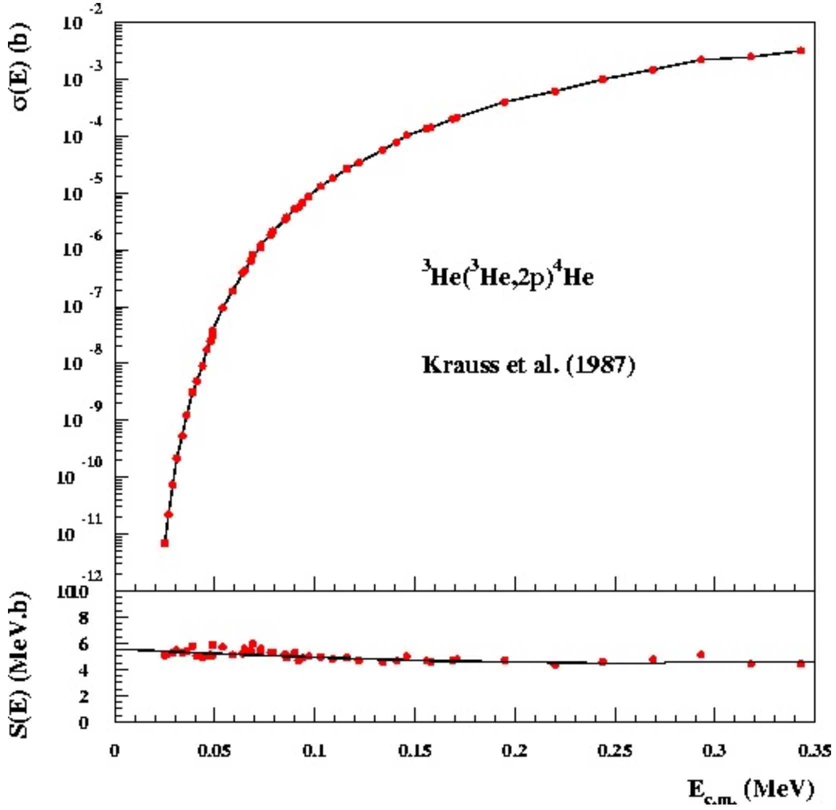
in general, cross section direct evaluation is

- severely hindered (1 ev/month)
- in some cases even beyond present technical possibilities.

A possible solution to evaluate these cross sections consist in using the **EXTRAPOLATION** from data at higher energies

through the Astrophysical S(E)-factor $S(E) = \sigma(E)e^{2\pi\eta}E$





The extrapolation could introduce systematic uncertainties!!!

No possibility to properly take into account the effects of possible resonances

Nuclear reactions of astrophysical interest induced by RIB

Experimental approach is even more difficult for reactions involving RIBs

- Low beam currents for most isotopes (10^5 -10^8 pps)
- Limited beam-energies available → complicate to measure a whole excitation function, especially at astrophysical energies;

but …

Important reaction induced by RIB are involved is several astrophysical scenarios some examples …

Big Bang Nucleosinthesys: $^{8}Li(\boldsymbol{\alpha},n)^{11}B$
$^{7}Be(n, p)^{7}Li$
$^{7}Be(n, \alpha)^{4}He$

Novae explosive burning: $^{14}O(\alpha,p)^{17}F$
$^{18}F(p,\alpha)^{15}O$

Supernovae: $^{26}Al(n,p)^{26}Mg$
$^{26}Al(n, \alpha)^{2}Na$

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,

$$A + x \rightarrow B + b$$

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

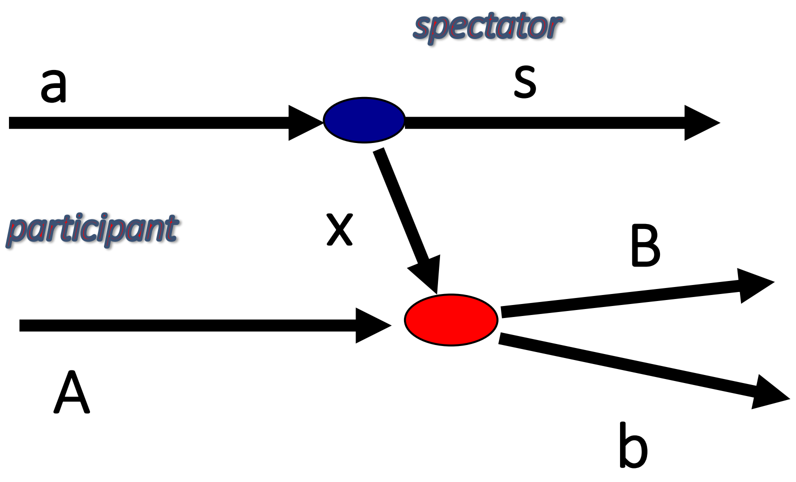
$$a + A \rightarrow B + b + s$$

- 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, Ii 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

$$a + A \rightarrow B + b + s$$



- **a** is the "TH nucleus" **a = x ⊕ s**
- Beam energy higher that **a - A** Coulomb barrier
- **a – A** interaction → **a** break-up inside the nuclear field
  - The participant **x** interacts with **A**→ two body process
- **Coulomb effects and electron screening are negligible**

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

- Cluster **s** acts as a spectator

- In quasi-free conditions the two body interaction takes place at:

$$E_{cm} = E_{xA} - B_{x\text{-}s}$$

A key feature for RIBs application!!

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

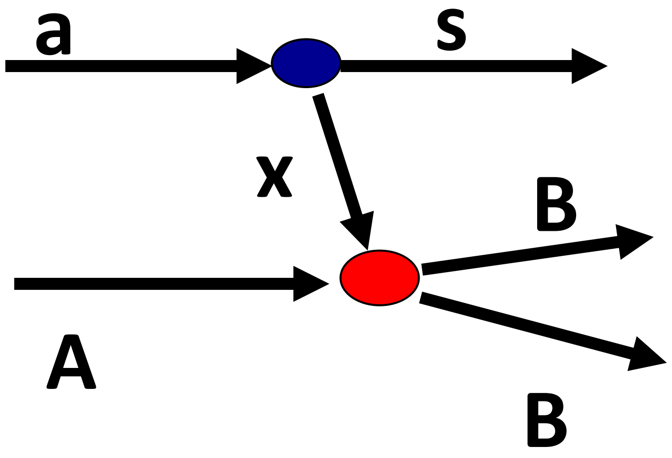
Thanks to the **x-s inter-cluster motion** inside a, it is possible to **span a wider energy range with only one beam energy**

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
- 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}



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

$\mathbf{P_l}$ Coulomb barrier penetrability

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

THM applied for studying RIB induced reactions

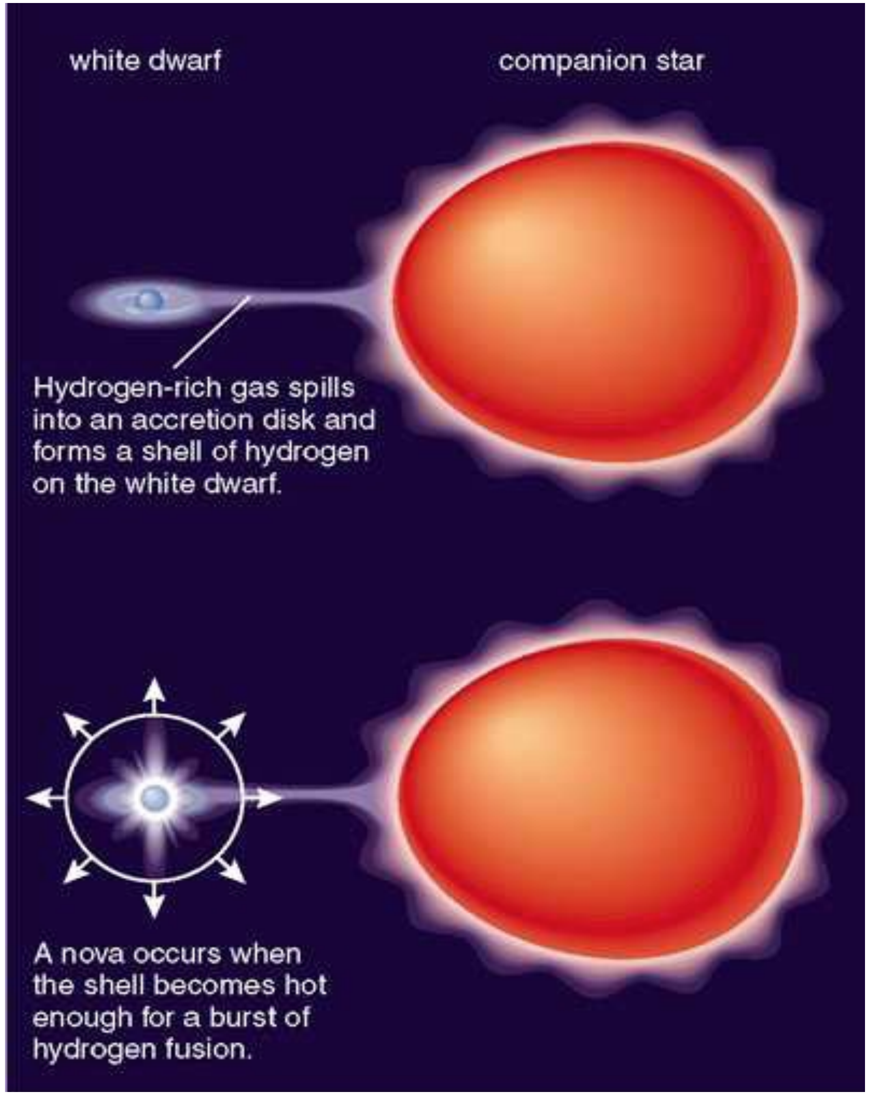
$^{18}F(p,\alpha)^{15}O$

$^{7}Be(n,\alpha)^{4}He$

$^{7}Be(n,p)^{7}Li$

at the low energies of astrophysical interest

Astrophysical scenario



Classical Nova

- In a binary system the companion star transfers hydrogen-rich material onto the surface white dwarf
- The temperature and density of the accumulated layers increase with time until it undergoes runaway fusion.

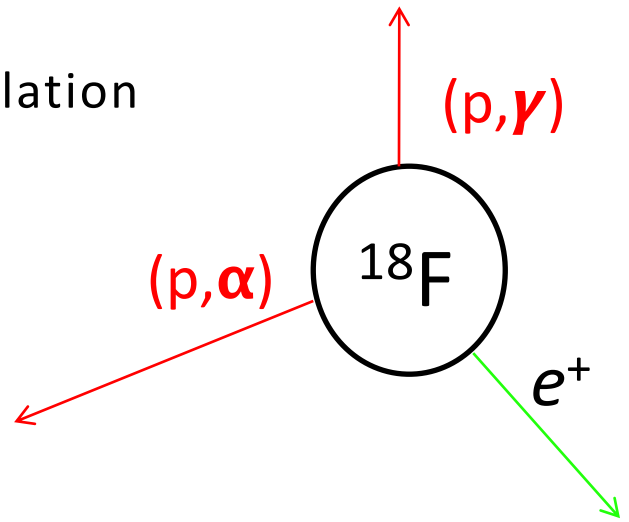
γ-ray emission

Astrophysical scenario
The role of the ^{18}F

γ - ray emission → 511 keV line from e^+-e^- annihilation

e^+ mostly comes from β decay of ^{18}F

^{18}F lifetime of ~158 min is well matched
to the timescale for nova envelope to become
transparent to γ -ray emission



^{18}F is produced relatively abundantly via the Hot-CNO cycle

Production reactions

$^{16}O(p, \gamma)^{17}F$ →
- $^{17}F(p, \gamma)^{18}Ne(\beta^+)^{18}F$
- $^{17}F(\beta^+)^{17}O(p, \gamma)^{18}F$

Burning reactions

$^{18}F(p,\alpha)^{15}O$

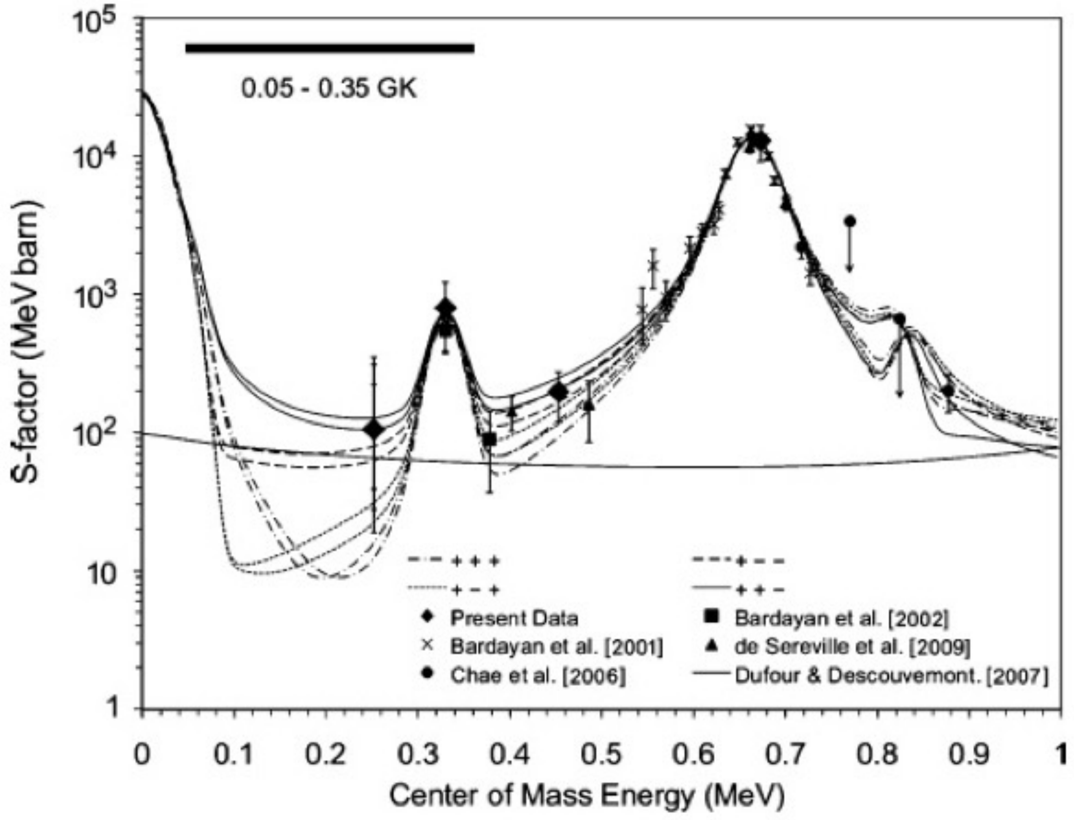
$^{18}F(p, \gamma)^{19}Ne$

Energy region of astrophysical interest

100 – 400 keV

$0.05 < T_9 < 0.5$

Study of the $^{18}F(p,\alpha)^{15}O$ reaction: direct data



C. E. Beer et al. PRC 83, 042801(R) (2011)

Direct data down to 250 keV

indirect measurements dedicated to the study of the involved 19Ne levels

recent works *D. Kahl et al.* Eur. Phys. J. A (2019) 55: 4
J. E. Riley et al. PHYSICAL REVIEW C 103, 015807 (2021)

S- factor and Reaction rate uncertainties
are due to the unknown properties of the low energy levels and the possible interference effects

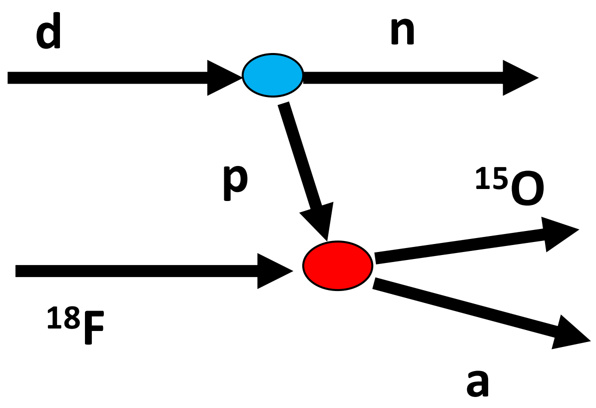
Extrapolation via R-matrix calculations

New data in the extrapolation region could improve our knowledge

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

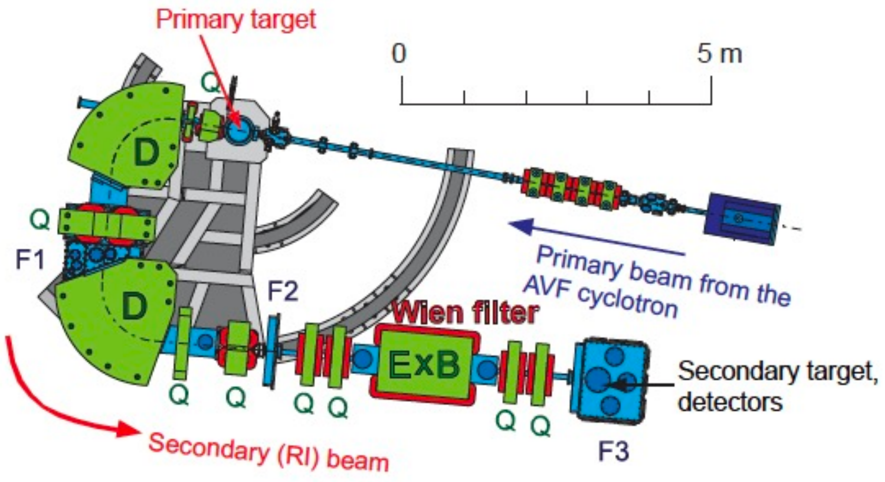
$^{2}H(^{18}F,a\ ^{15}O)n$

deuteron TH nucleus (p ⊕ n)



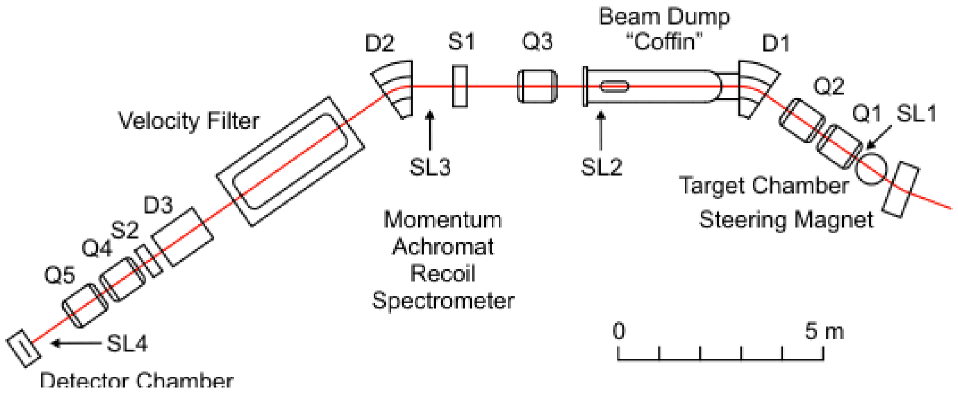
^{18}F @ CRIB

Y. Yamaguchi et al. NIM A 589, 150 (2008).



^{18}F from MARS spectrometer

R.E. Tribble et al. NIM A285, 441 (1989)



Basic scheme for in-flight RIBs production

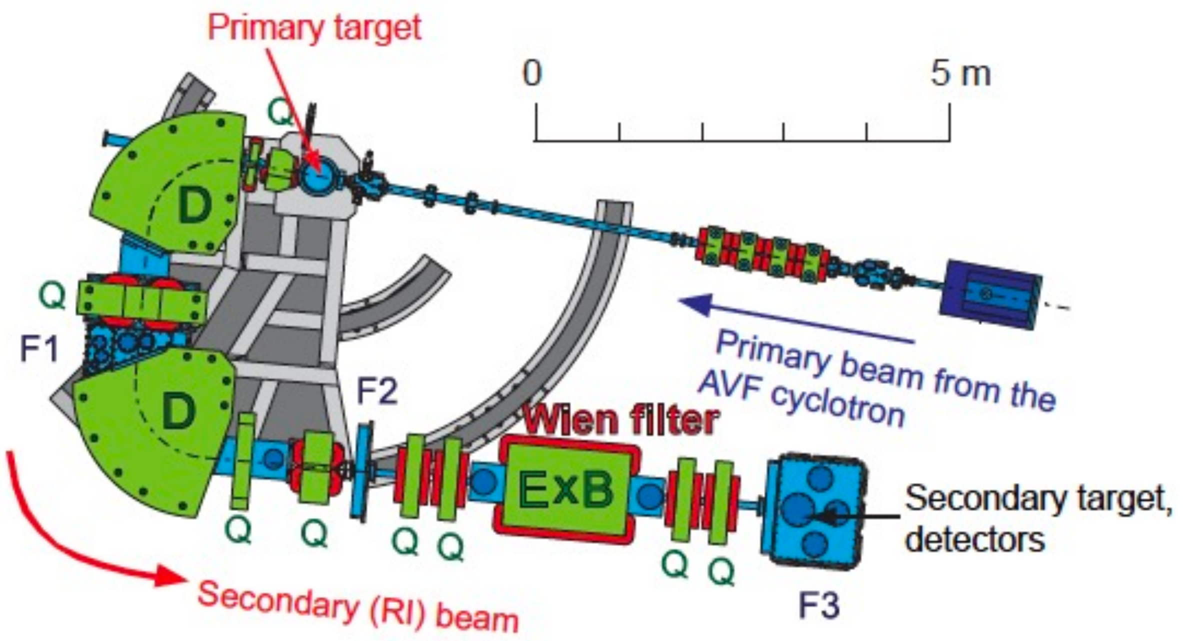
- Primary beam X
- Primary target (H) gas target

→ to induce a X(p,n)Y

- A system of ion-optical devices :

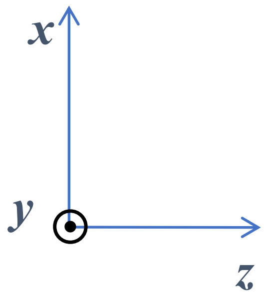
- Quadrupoles for beam focusing
- Dipole bending magnet
- Wien filter

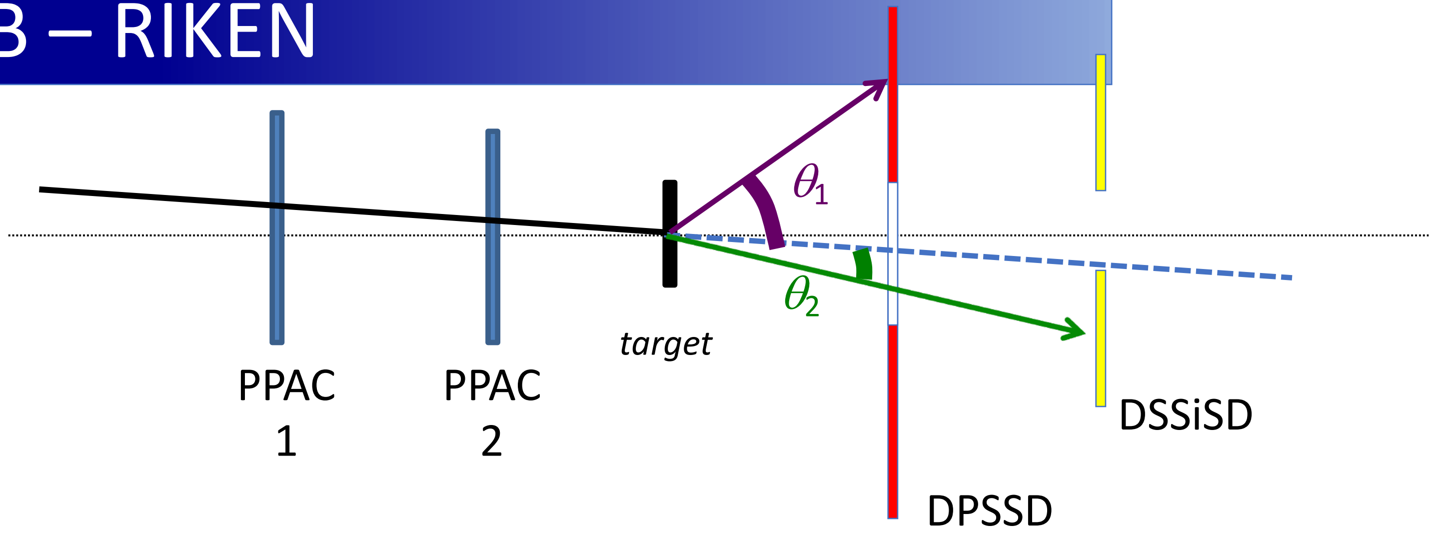
- Slit sets and collimator
- PPACs for beam tracking



CRIB

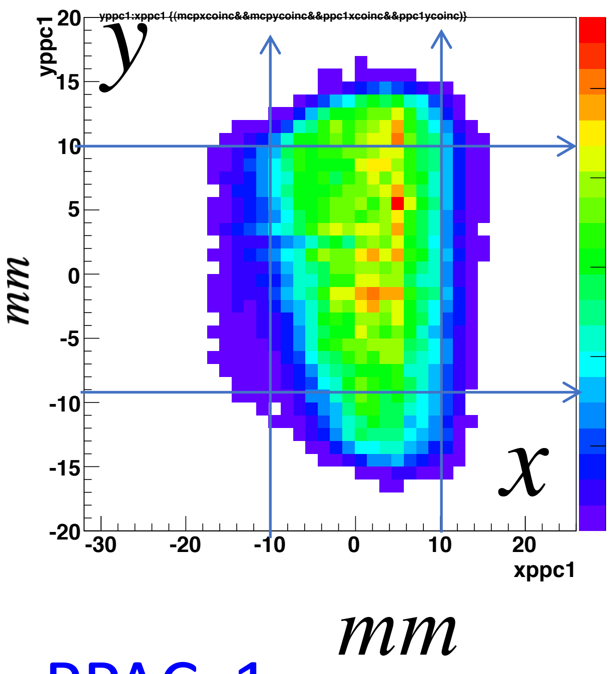
BEAM TRACKER @ CRIB – RIKEN



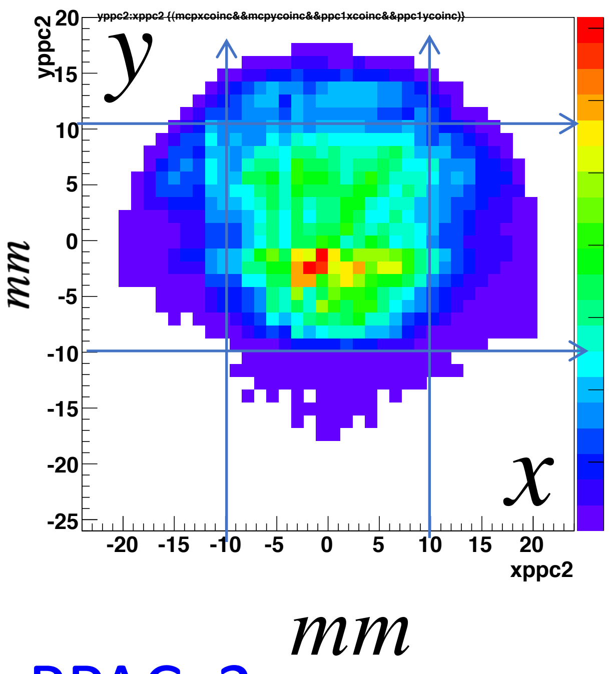


BEAM TRACKED EVENT- BY -EVENT

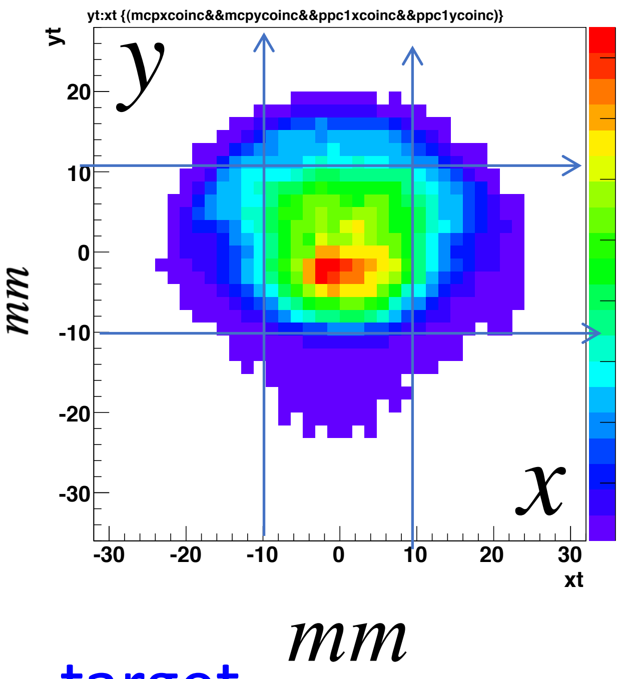
Beam track reconstruction event by event



PPAC 1



PPAC 2

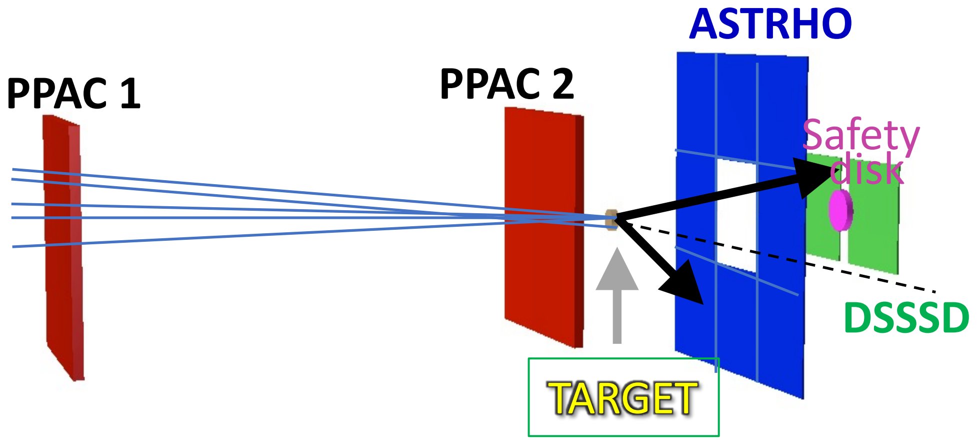


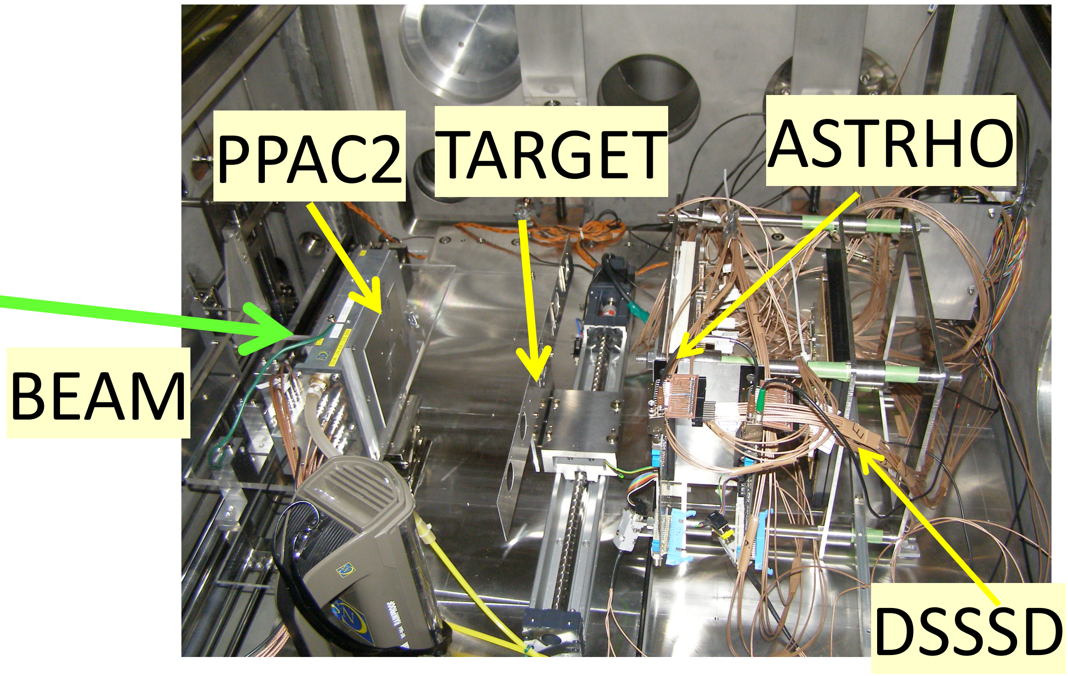
target

^{18}F beam features

	@ CRIB – RIKEN -JP	@ TAMU -TEXAS
Primary reaction	$H(^{18}O,^{18}F)n$	$H(^{18}O,^{18}F)n$
Beam energy	47.9 MeV (FWHM 1.9 MeV)	52 MeV (FWHM 2.6 MeV)
Beam spot	2cm x 2cm with tracking system	3 mm x 5 mm (non tracking system)
Beam purity	98%	94%
Beam intensity	$5 \times 10^5 – 2 \times 10^6$ pps	$3 - 4 \times 10^5$ pps

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





CD_2 TARGET 150-200 μg/cm^2

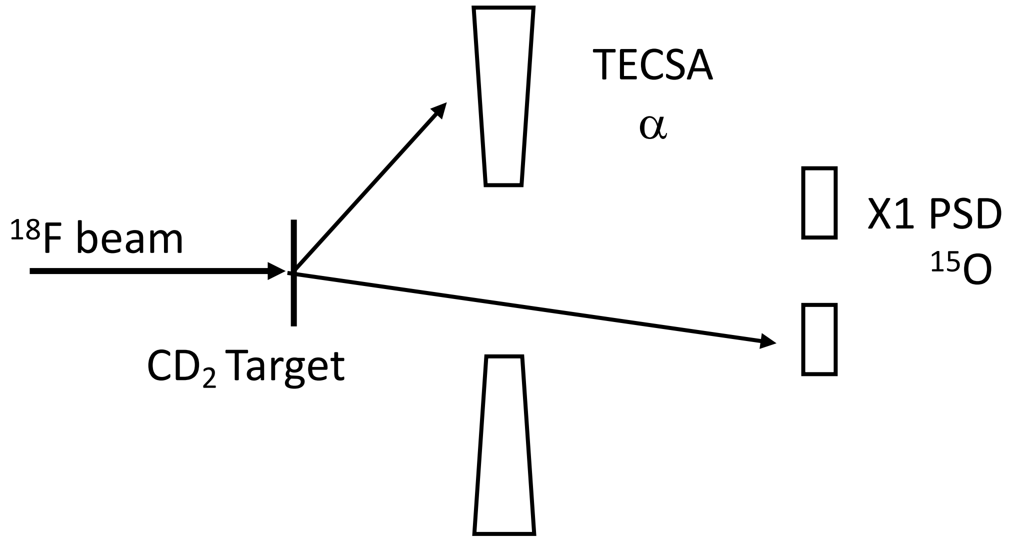
ASTRHO → α
n. 8 bidimensional position-sensitive detectors (BPSD, 45 x 45 mm², 500 μm thick

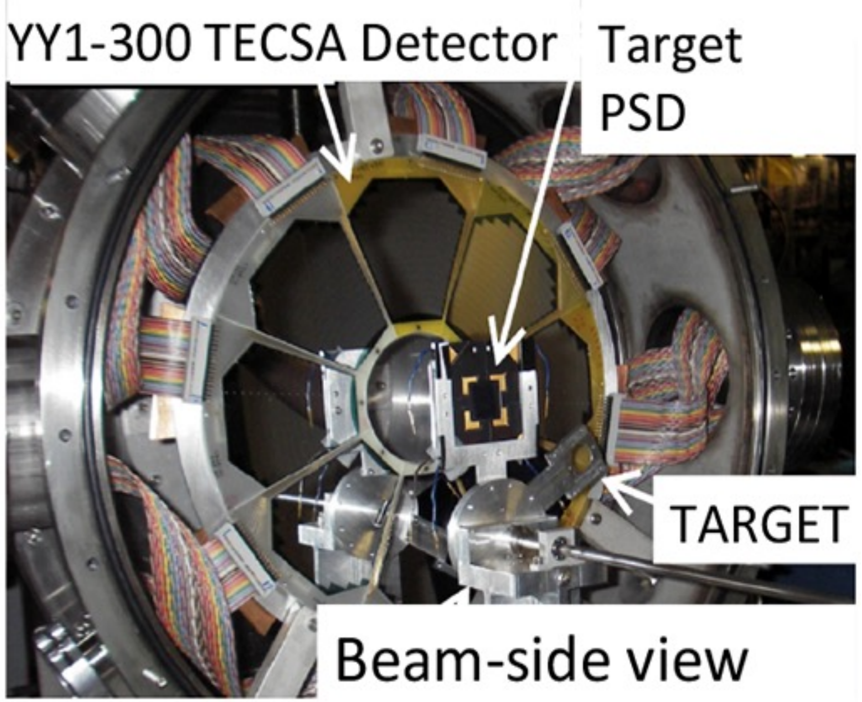
DSSSD → ^{15}O
n. 2 Double Sided Silicon Strip Detectors (16 strips x-y)

Trigger: total or, off-line multiplicity 2 fixed

	DSSSD	ASTRHO
Angular range	2° - 11°	11° - 31°
Angular resolution	0.5° (tracking+ detectors)	0.5° (tracking+ detectors)
Energy resolution	0.8%	0.8%

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





CD_2 TARGET 400-800 μg/cm^2

TECSA → α
n. 8 16 arch strip YY1-300 um
B.T. Roeder et al. NIM A634, 71 (2011)

X1-PSD → ^{15}O
n. 2 16 strips each, position sensitive

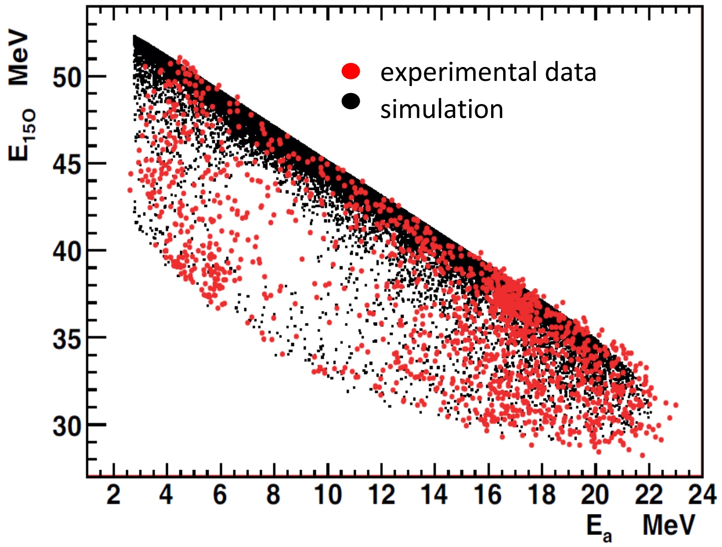
Trigger: TECSA X1-PSD coincidence

	X1-PSD	TECSA
Angular range	3° - 12°	15° - 40°
Angular resolution	0.7°	1.1°
Energy resolution	0.8%	0.8%

Selection of the reaction channel

$^{18}F + d \rightarrow ^{15}O + \alpha + n$

Kinematic locus
in agreement with simulation

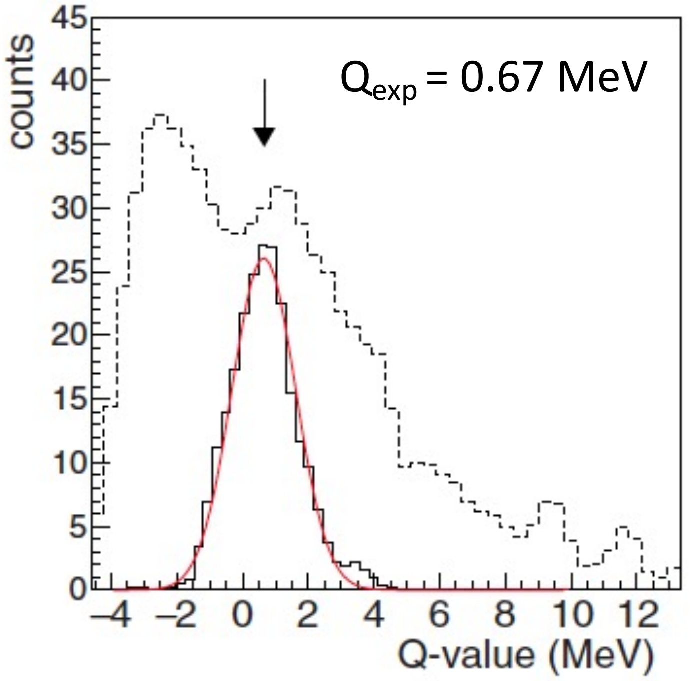


R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

Experimental three-body Q-value spectra

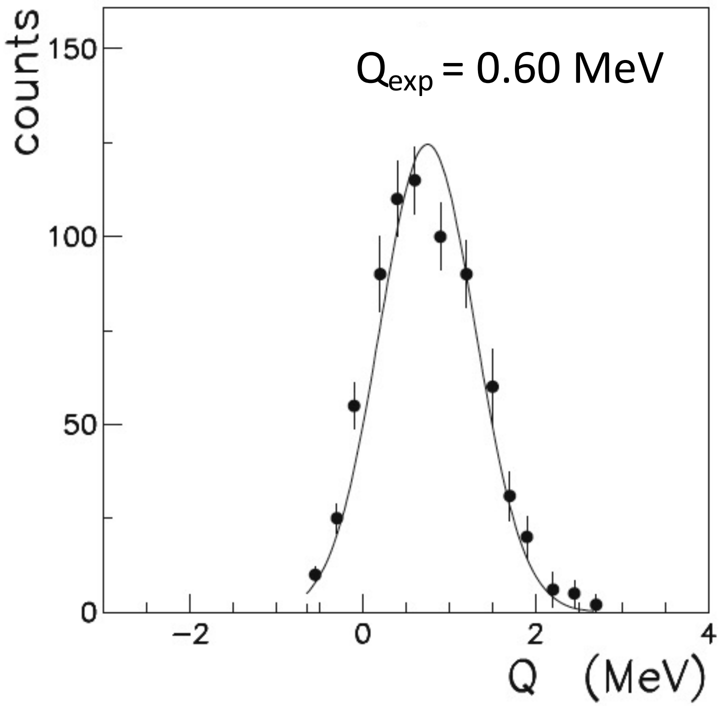
Q_{th} – value = 0.66 MeV (indicated by arrow)

@ CRIB – RIKEN



Cherubini et al. PRC 92, 015805 (2015)

@ TAMU



R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

Analysis of the reaction mechanism

Check for quasi-free mechanism

Comparison between the experimental momentum distribution and the theoretical one

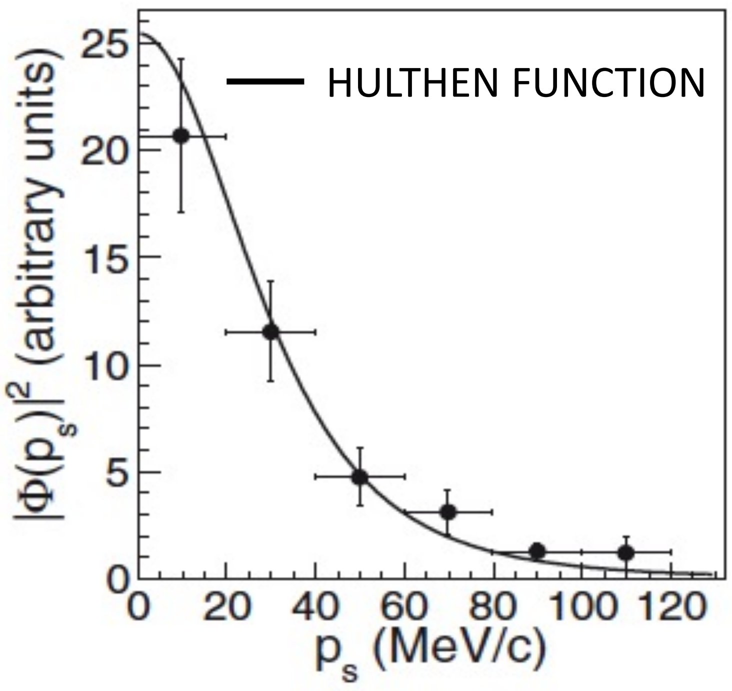
$$\frac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_\alpha\, dE_{^{15}O}} \propto KF\, |\varphi(\vec{p_d})|^2 \left(\frac{d\sigma_{^{18}F-p}}{d\Omega}\right)^{HOES}$$

Cut on E_{cm} and ϑ_{cm}

$$\left(\frac{d\sigma_{^{18}F-p}}{d\Omega}\right)^{HOES} \cong const$$

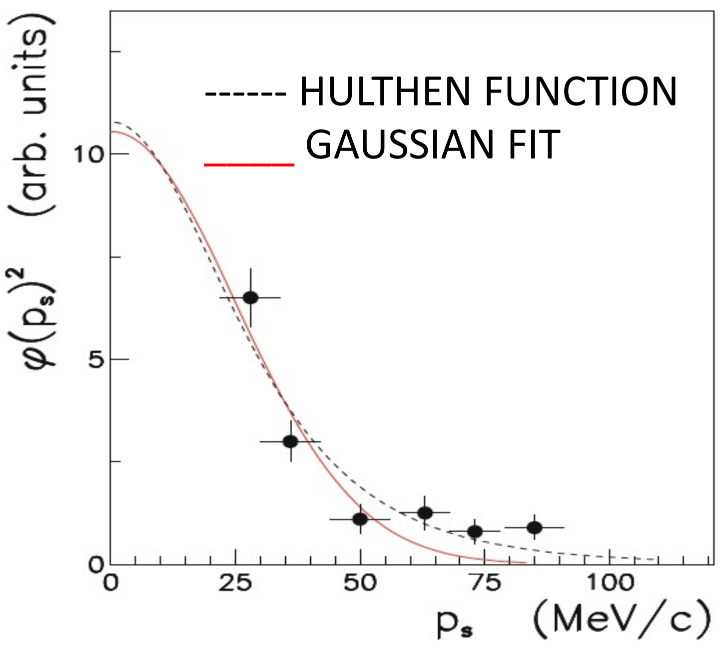
$$|\varphi(\vec{p_d})|^2 \propto \frac{\frac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_\alpha\, dE_{^{15}O}}}{KF}$$

@ CRIB – RIKEN



Cherubini et al. PRC 92, 015805 (2015)

@ TAMU



R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

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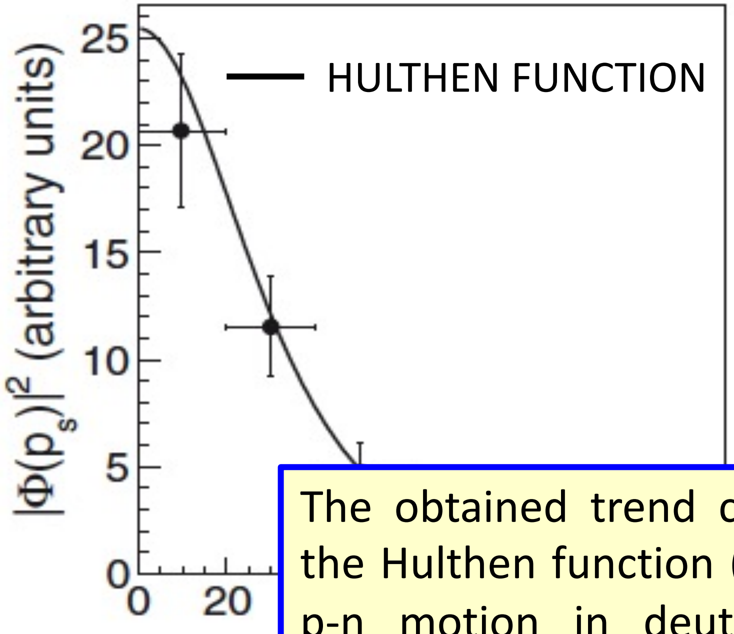
Cut on E_{cm} and ϑ_{cm}

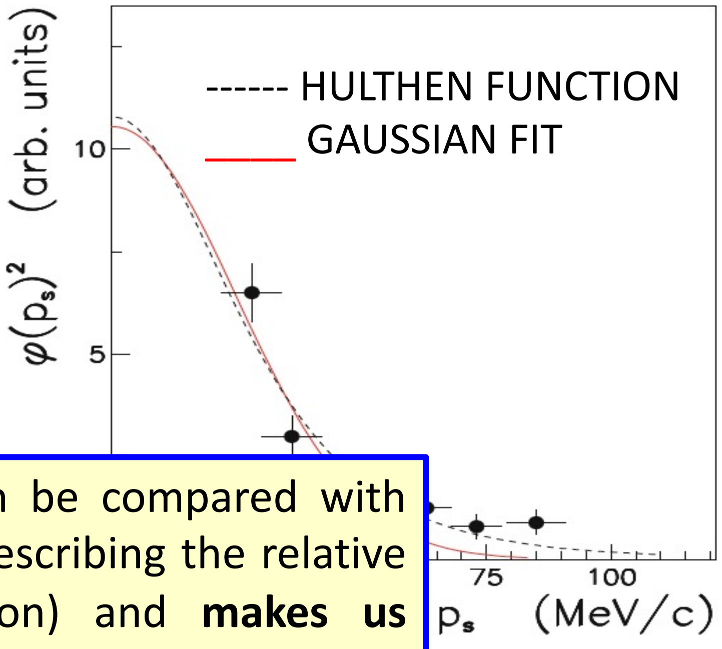
$$\left(\frac{d\sigma_{^{18}F-p}}{d\Omega}\right)^{HOES} \cong \text{const}$$

$$|\varphi(\vec{p_d})|^2 \propto \frac{\frac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_\alpha\, dE_{^{15}O}}}{KF}$$

@ CRIB – RIKEN



@ TAMU



The obtained trend can be compared with the Hulthen function (describing the relative p-n motion in deuteron) and **makes us confident that the process is "mostly" QF.**

Cherubini et al. PRC 92, 015805 (2015)

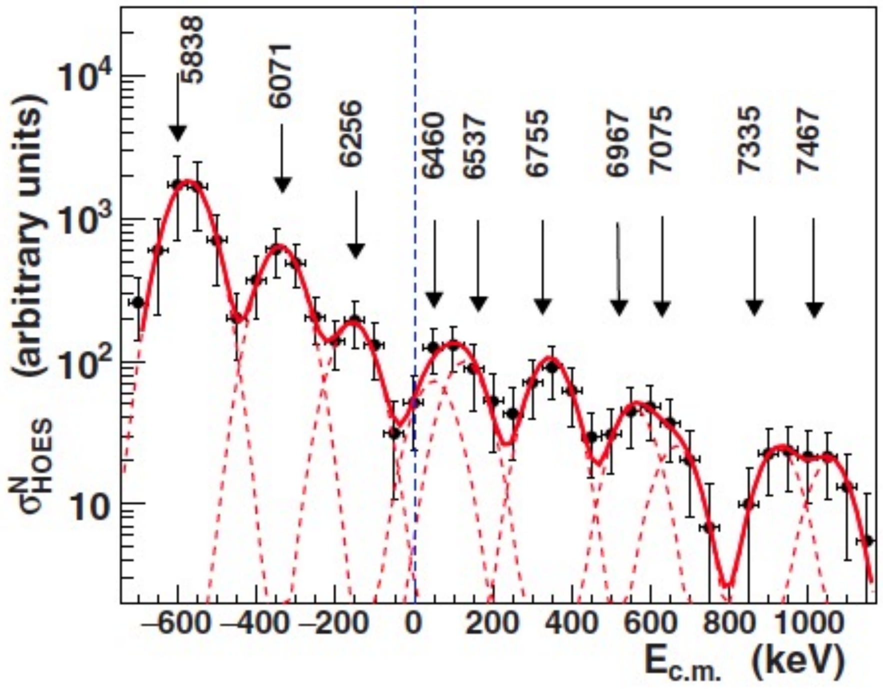
R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

Extraction of the two-body cross section

$$\left(\frac{d\sigma_{^{18}F-p}}{d\Omega}\right)^{HOES} \propto \frac{\dfrac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_{\alpha}\, dE_{^{15}O}}}{KF\, \left|\varphi_{exp}(\overrightarrow{p_d})\right|^2}$$

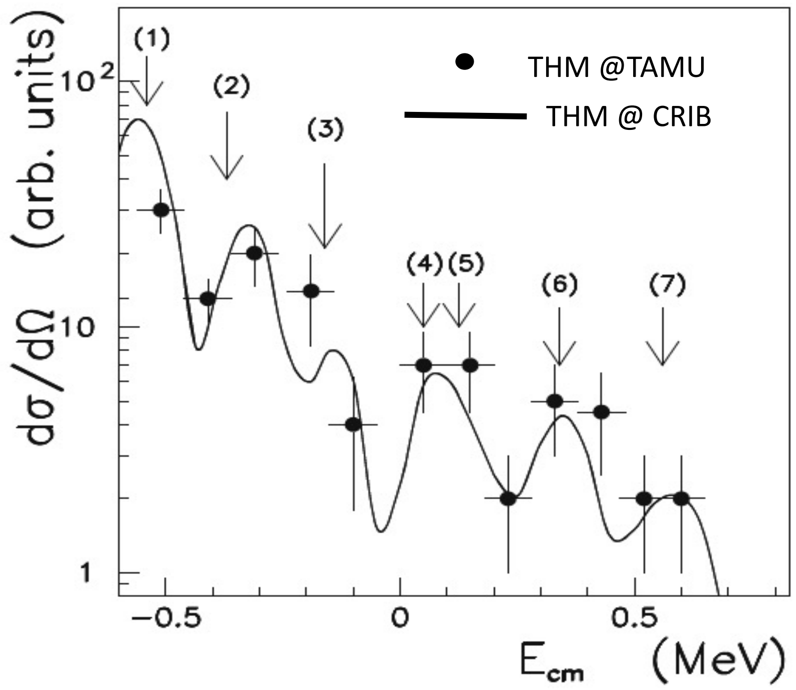
$$E_{cm} = E_{^{15}O-\alpha} - Q_{^{18}F+p\rightarrow {}^{15}O+\alpha}$$

@ CRIB – RIKEN - JP



Cherubini et al. PRC 92, 015805 (2015)

@ TAMU - TEXAS



R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

Number	E_{cm} (MeV)	Energy $^{19}Ne^*$ (keV)	$J^{(\pi)}$	Ref.
1	−0.57	5837	–	[41]
2	−0.34	6070	$3/2^+, 5/2^-$	[10]
3	−0.16	6255	$11/2^-$	[10]
4	0.05	6460	$3/2^+, 5/2^-$	[10, 40]
5	0.13	6537	$7/2^+, 9/2^+$	[40]
6	0.33	6755	$3/2^-$	[10, 12, 40]
7	0.56	6967	$5/2^+$	[40]
	0.66	7075	$3/2^+$	

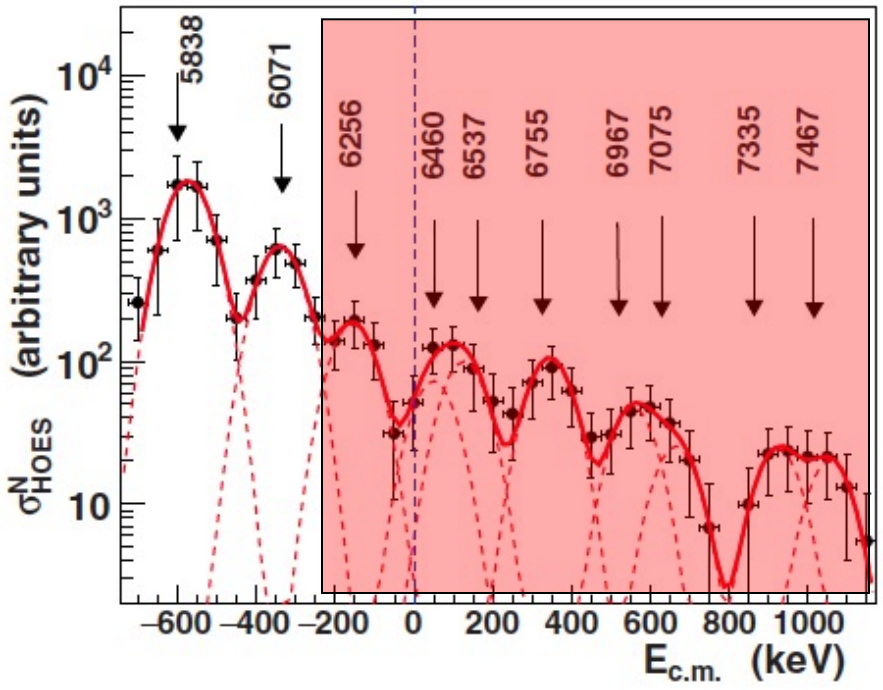
Extraction of the two-body cross section

$$\left(\frac{d\sigma_{^{18}F-p}}{d\Omega}\right)^{HOES} \propto \frac{\frac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_{\alpha}\, dE_{^{15}O}}}{KF\left|\varphi_{exp}(\overrightarrow{p_d})\right|^2}$$

$$E_{cm} = E_{^{15}O-\alpha} - Q_{^{18}F+p\rightarrow {^{15}O}+\alpha}$$

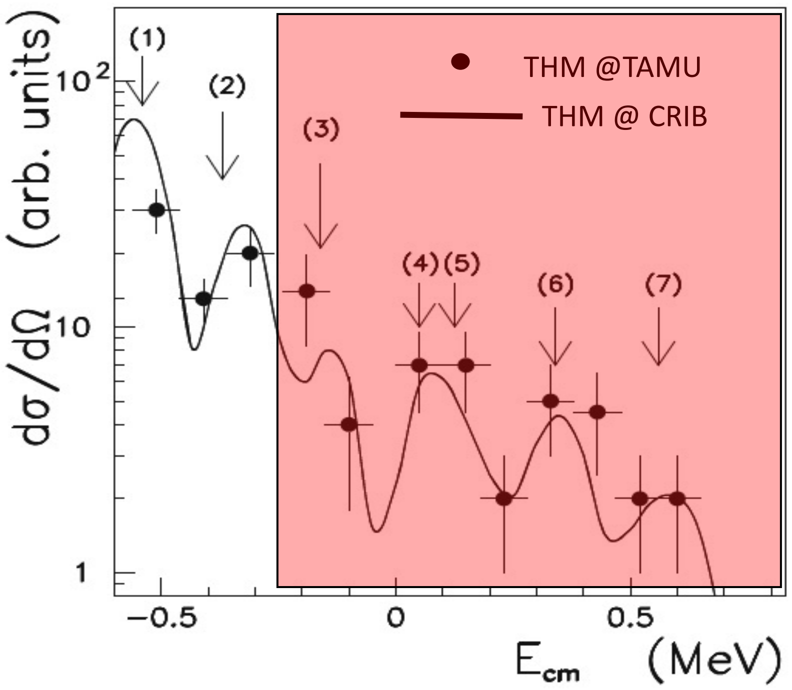
Energy region of astrophysical interest

@ CRIB – RIKEN - JP



Cherubini et al. PRC 92, 015805 (2015)

@ TAMU - TEXAS



R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

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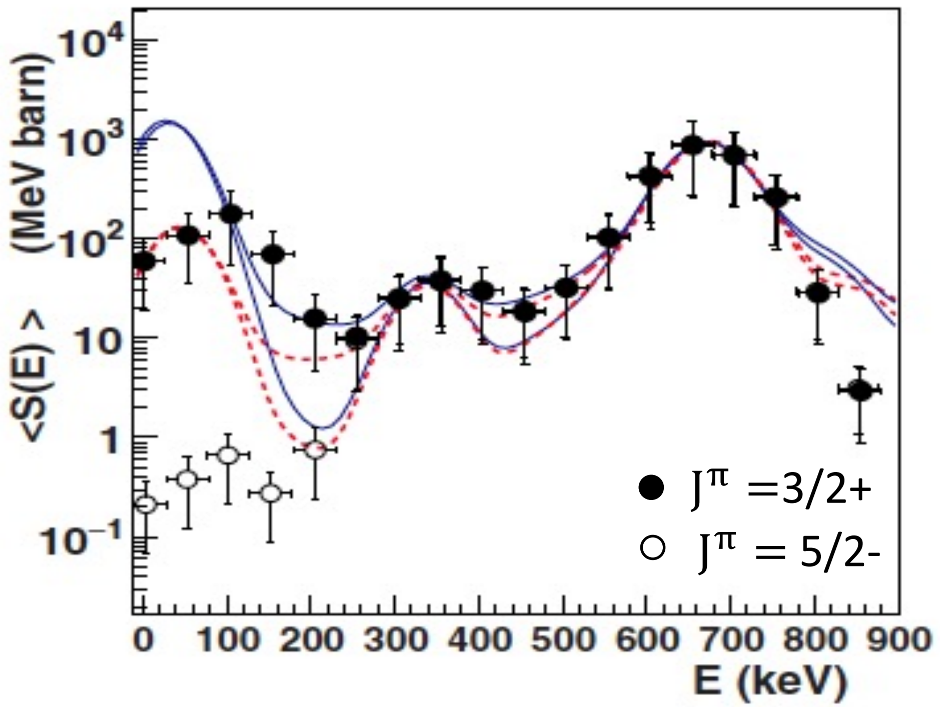
THM S(E) – factor

The S(E)-factor is measured in the astrophysical energy Region

THM suitable for RIB application



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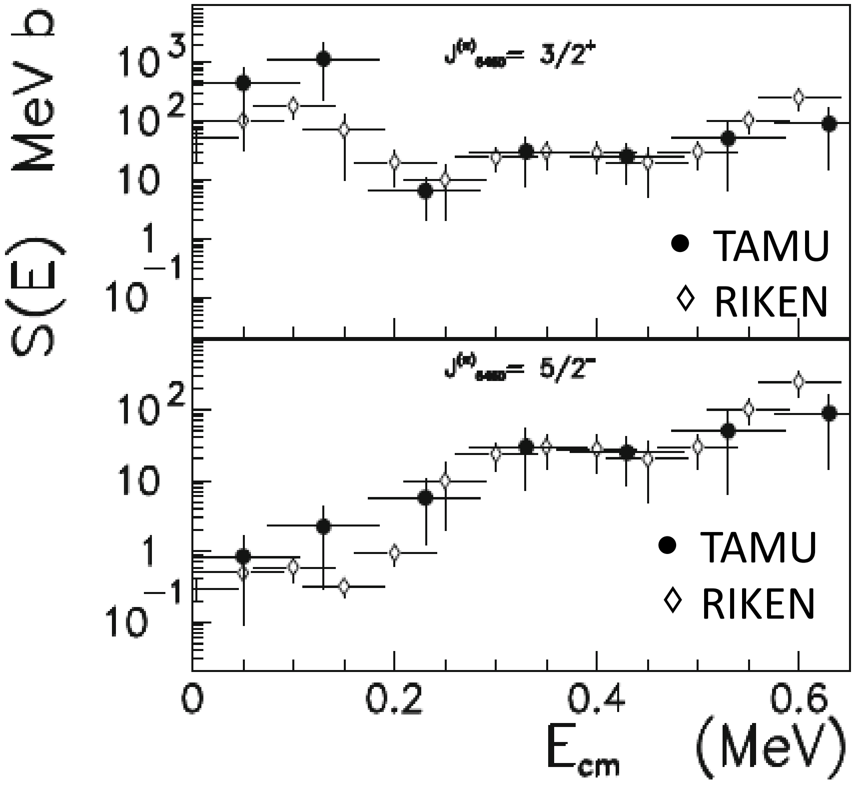
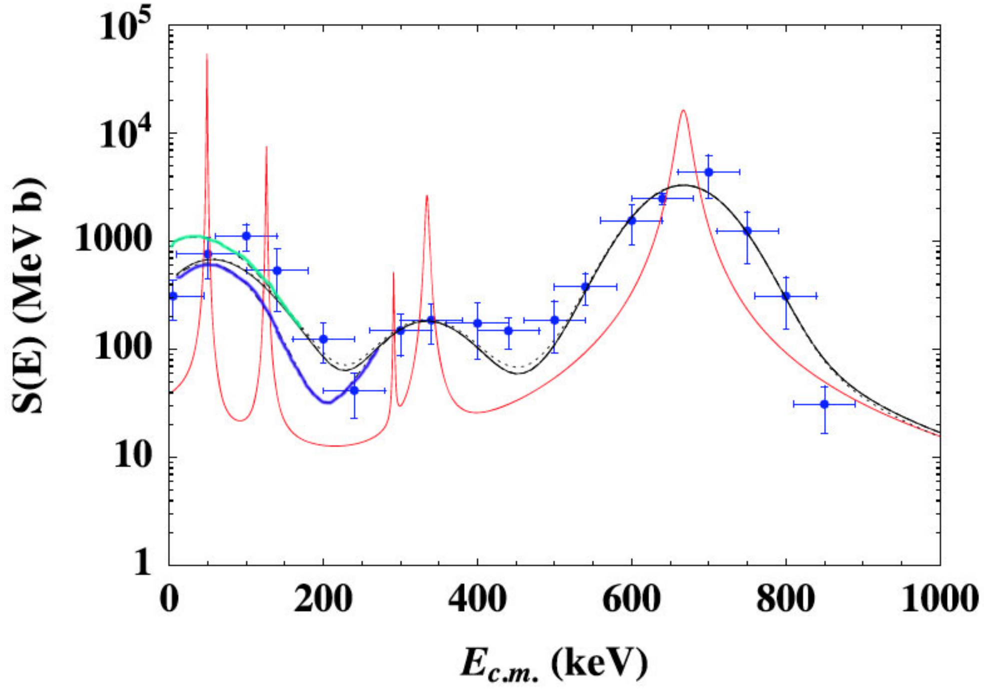


Resonance E*=6460 keV
(E_{cm}= 50 keV)
Lower limit : J^{π}= 5/2⁻
Upper limit : J^{π}= 3/2⁺

R-Matrix calculations by Beer et al. Phys. Rev. C 83, 042801 (2011)

R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24

R-matrix calculations



- TAMU –RIKEN THM data average **assuming J^π= 3/2⁺ for resonance at 50 keV**

— Best fit curve. Smoothed R-matrix calculation accounting for a 53 keV energy spread

— Deconvoluted calculation

[19]Ne levels as in **Bardayan et al PLB 751 (2015) 311**

with some changes according to THM results:

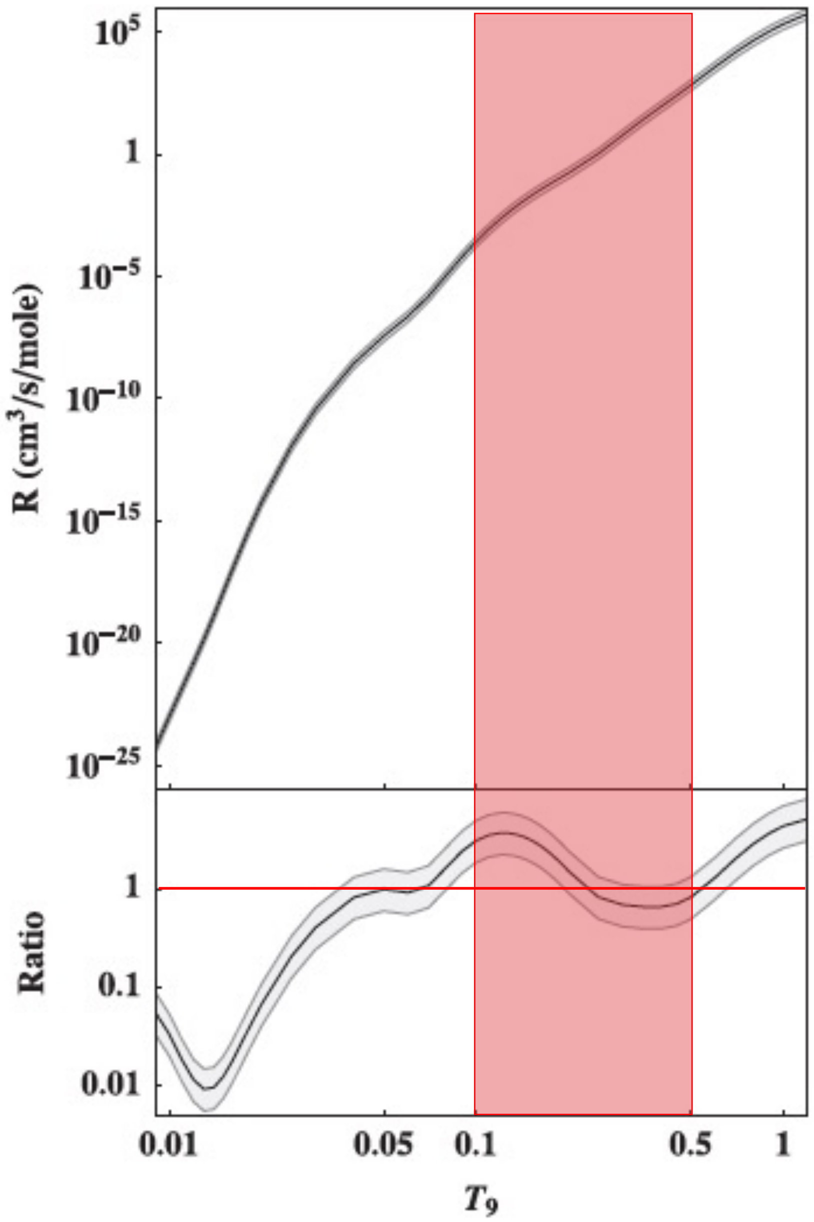
- without 7 keV level
- with 126 keV level

Table 1
Parameters of the R-matrix Calculation (Red Line) in Figure 1

E_{res} (keV)	E_x (keV)	J^π	Γ_p (keV)	Γ_α (keV)
−124	6286	$1/2^+$	83.5[a]	11.6
7	6417	$3/2^-$	$1.6\ 10^{-41}$	0.5
29	6440	$1/2^-$	$3.8\ 10^{-19}$	220
49	6460	$3/2^+$	$2.3\ 10^{-13}$	0.9
126	6537	$7/2^+$	$7.1\ 10^{-8}$	1.5
291	6702	$5/2^+$	$2.4\ 10^{-5}$	1.2
334	6745	$3/2^-$	$2.2\ 10^{-3}$	5.2
665	7075	$3/2^+$	15.2	23.8
1461	7872	$1/2^+$	55	347

La Cognata et al. the APJ 846:65 2017

New THM reaction rate



$$R_{ij} = \frac{N_i N_j}{1+\delta_{ij}} \langle \sigma v \rangle = \frac{N_i N_j}{1+\delta_{ij}} \left(\frac{8}{\pi A}\right)^{\frac{1}{2}} \left(\frac{1}{k_B T}\right)^{\frac{3}{2}} \cdot \int_0^\infty S(E) \exp\left[-\left(\frac{E}{k_B T} + 2\pi\eta(E)\right)\right] \mathrm{d}E$$

Higher reaction rate

$\downarrow$

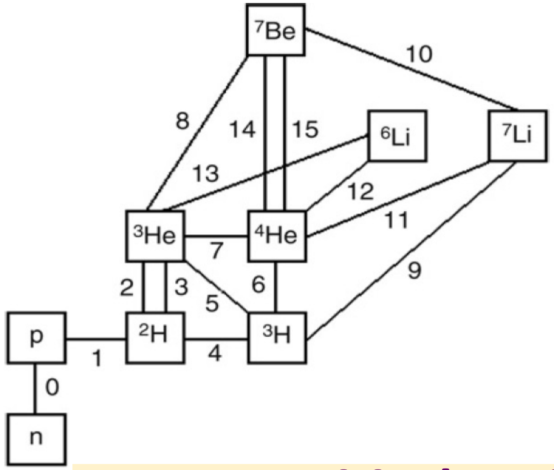
^{18}F content in Novae reduced by a factor 2

Ratio between THM Reaction rate and R.H. Cyburt ApjS 189, (2010) 240

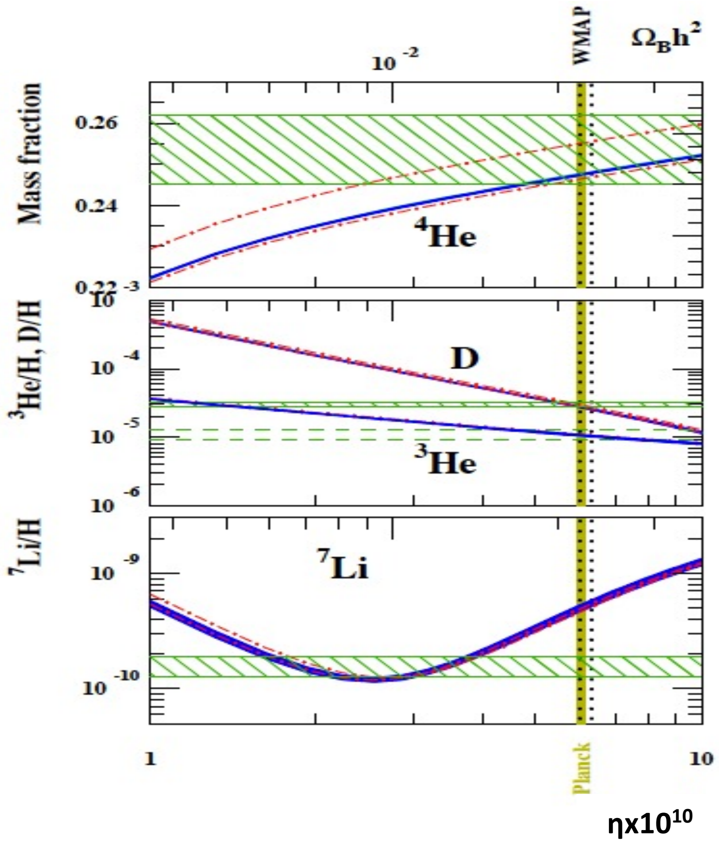
THM investigation of the neutron induced ^{7}Be burning

Cosmological Lithium Problem: discrepancy between observation and BBN prediction

- **$(Li/H)^{Stellar} \sim (1.3\text{-}2.3) \cdot 10^{-10}$ (Fields2005+Hernandez2010)**
- **$(Li/H)^{CMB} \sim (4.56\text{-}5.34) \cdot 10^{-10}$ (Coc et al., JCAP, 2014)**



0. τ_n
1. p(n,γ)d
2. $^{2}H(p,\gamma)^{3}He$
3. $^{2}H(d,n)^{3}He$
4. $^{2}H(d,p)^{3}H$
5. $^{3}He(n,p)^{3}H$
6. $^{3}H(d,n)^{4}He$
7. $^{3}He(d,p)^{4}He$
8. $^{3}He(\alpha,\gamma)^{7}Be$
9. $^{3}H(\alpha,\gamma)^{7}Li$
10. $^{7}Be(n,p)^{7}Li$
11. $^{7}Li(p,\alpha)^{4}He$
12. $^{4}He(d,\gamma)^{6}Li$
13. $^{6}Li(p,\alpha)^{3}He$
14. **$^{7}Be(n,\alpha)^{4}He$**
15. $^{7}Be(d,p)2^{4}He$



Possible (nuclear physics) solutions…

Nuclear Physics Inputs: Cross section measurements at BBN energies for ^{7}Li formation/destruction

$^{3}He(\alpha,\gamma)^{7}Be(e^{-},\nu_e)^{7}Li(p,\alpha)\alpha$

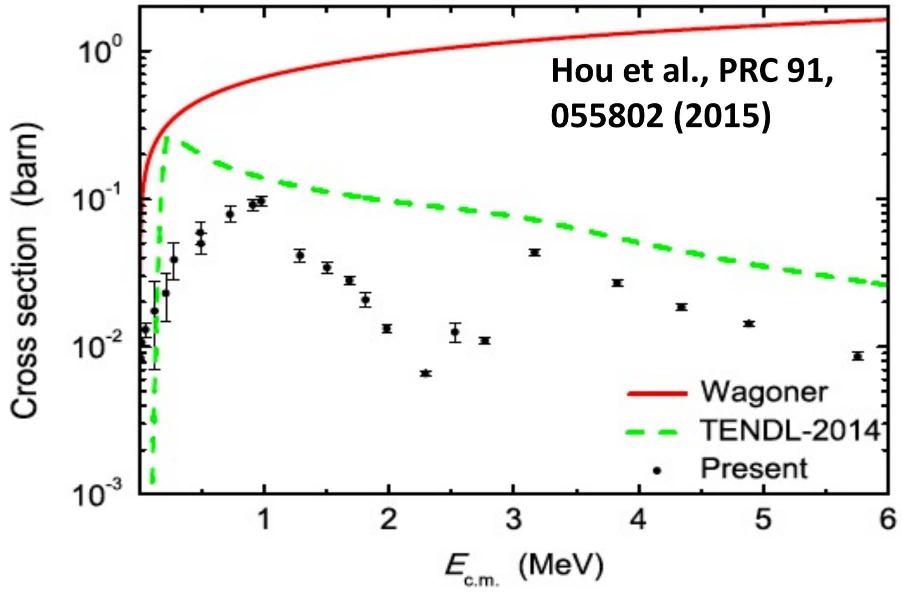
and for the ones involving ^{7}Be

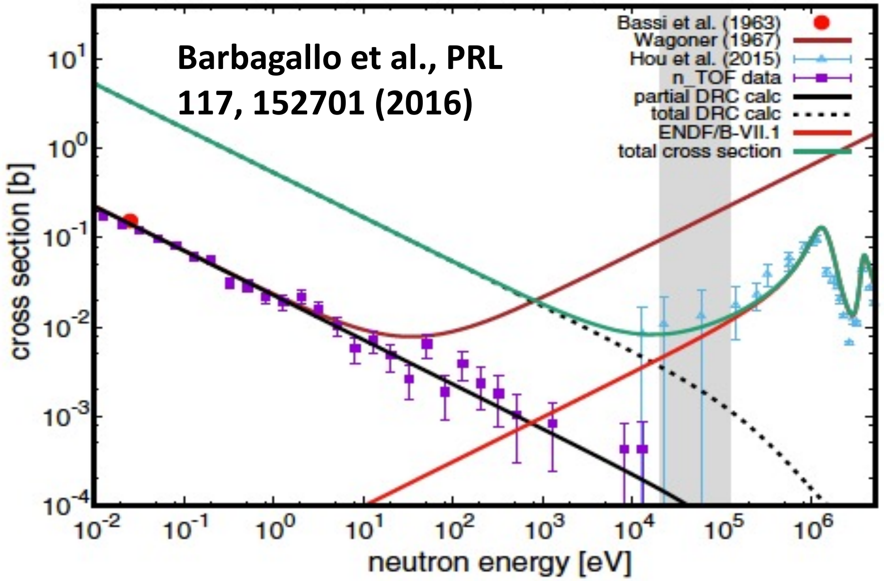
$^{7}Be(n,p)^{7}Li$ $\quad$ $^{7}Be(n,\alpha)^{4}He$

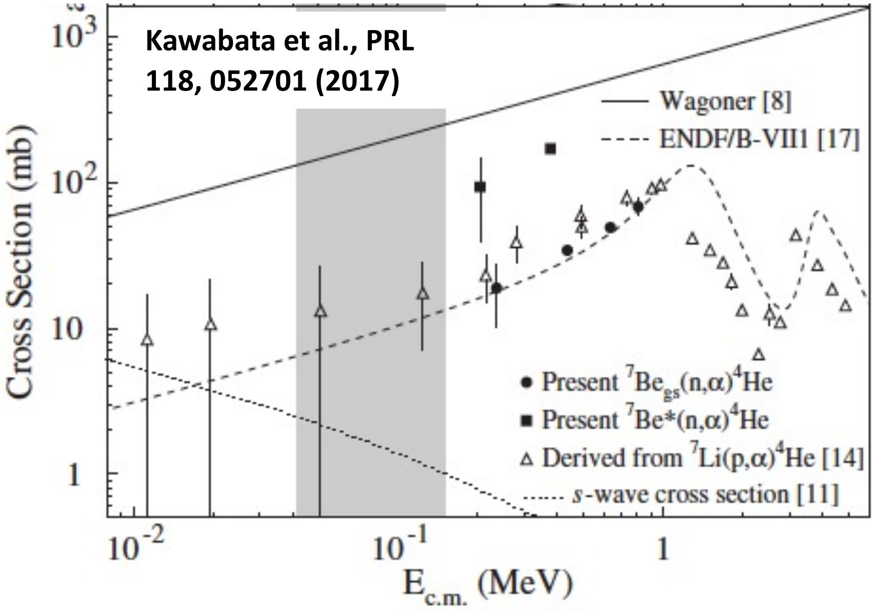
- Due to the large uncertainty assigned, these reactions provide one of the dominant contributions to theoretical errors in the ^{7}Li abundance evaluations (Serpico et al., 2004)

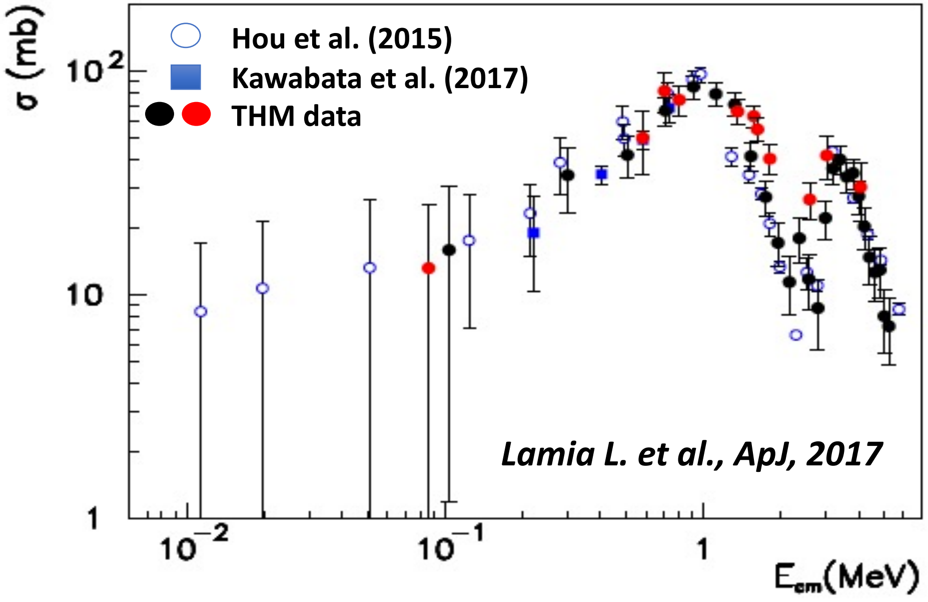
Reactions involving RIB and neutrons
Very challenge !!

$^7Be(n,\alpha)^4He$ cross section - direct measurement

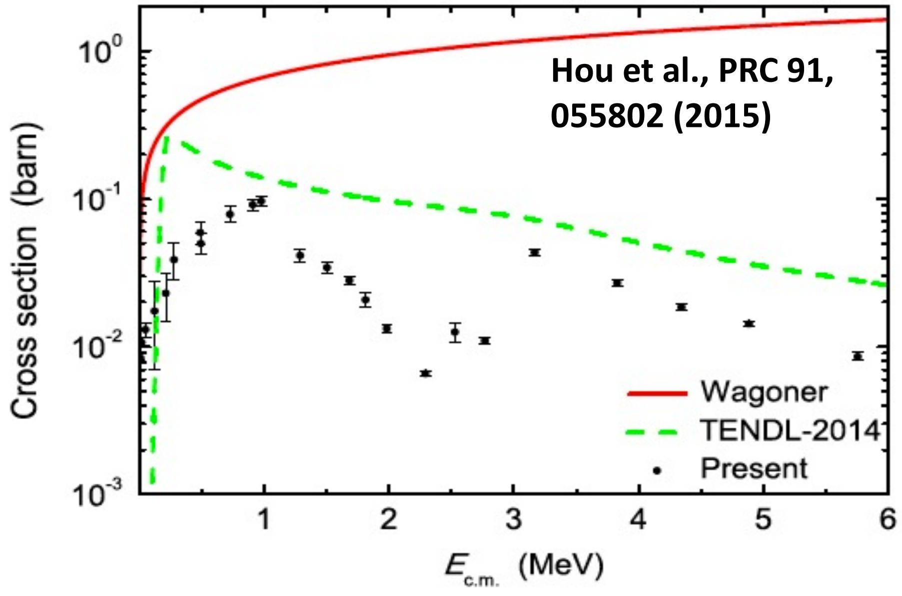


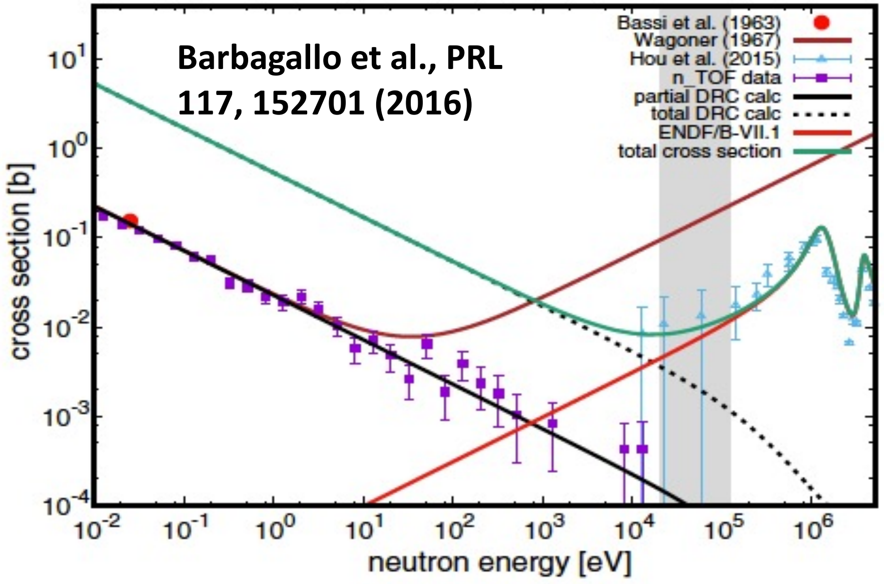


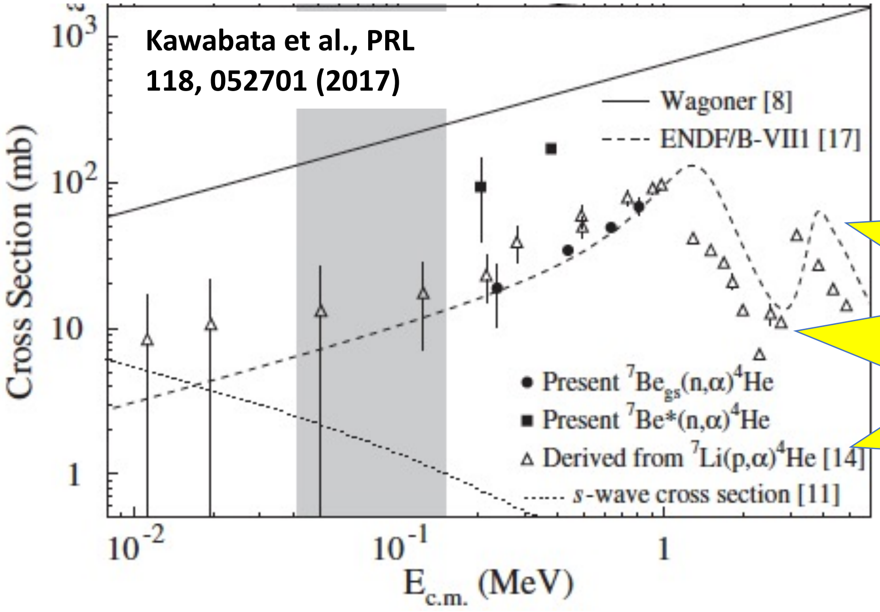


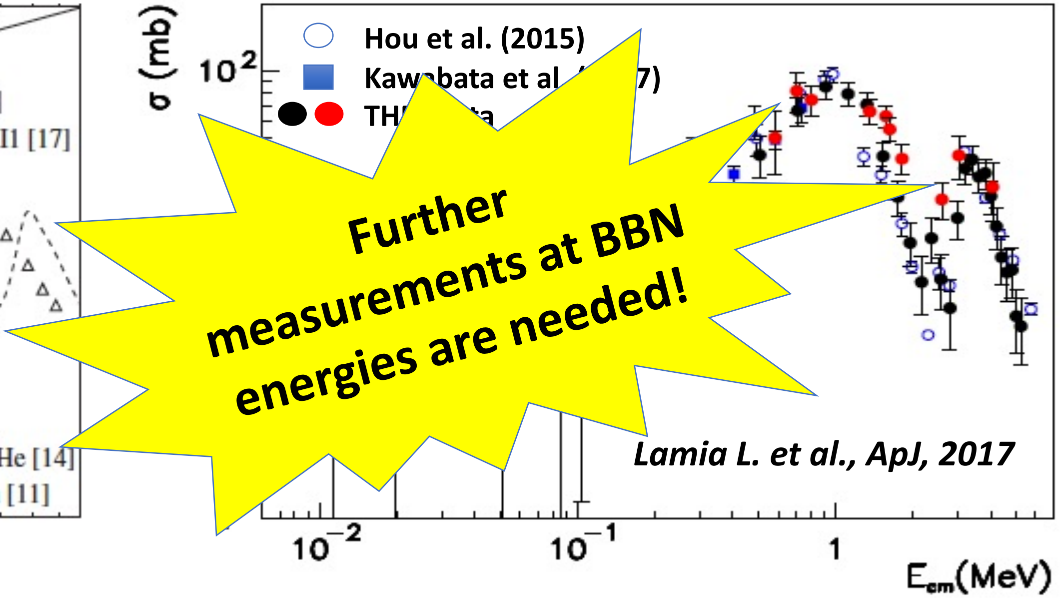


$^7Be(n,\alpha)^4He$ cross section - direct measurement





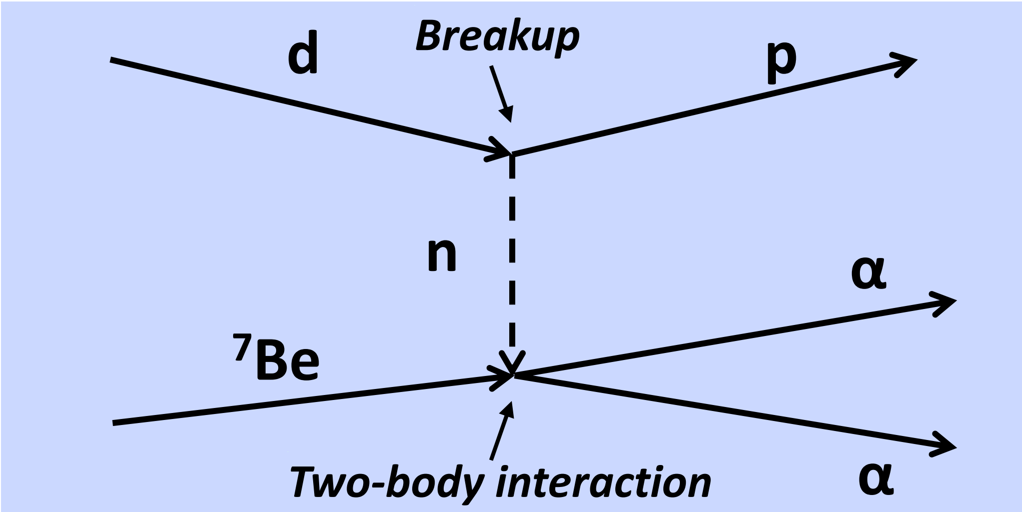




The $^{7}Be(n,\alpha)\alpha$ reaction via THM
BELICOS

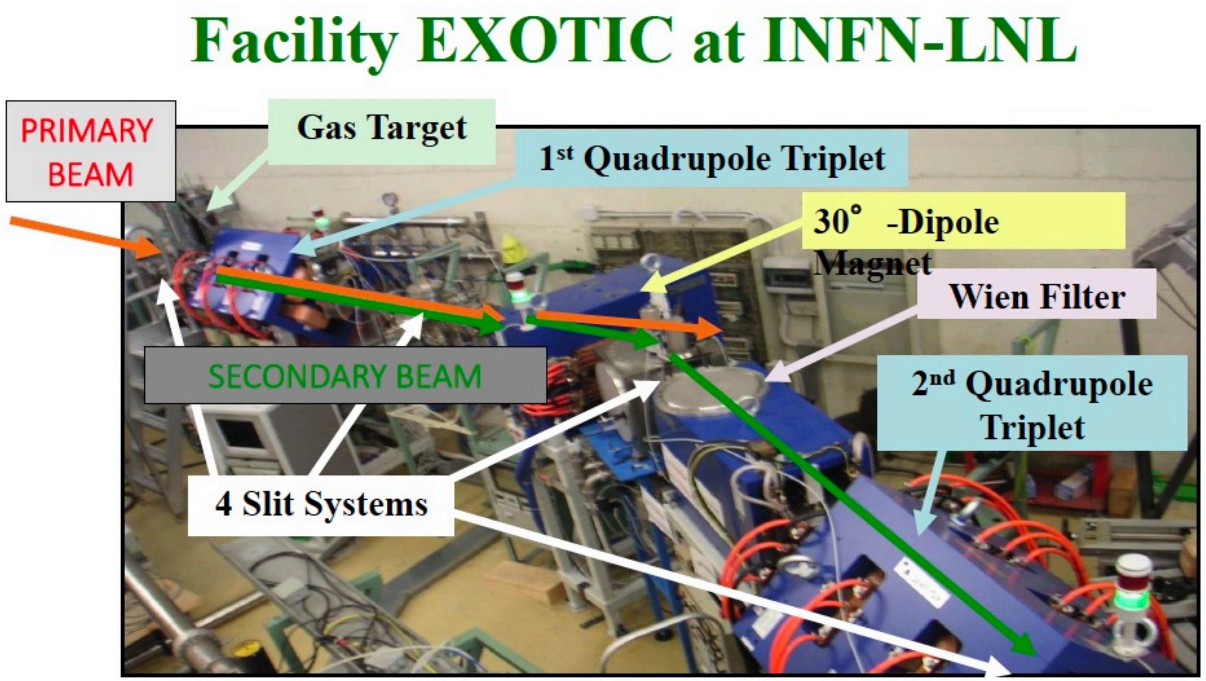
$^{7}Be(n,\alpha)^{4}He$ $^{2}H(^{7}Be, \alpha\alpha)H$ ⟵ THM reactions

First THM measurement of a reaction involving both a radioactive beam and neutrons



- ✓ **quasi-free breakup mechanism**
- ✓ ***d*** **as TH nucleus (p ⊕ n)**
- ✓ ***^{7}Be + n interaction***
- ✓ ***p is spectator***

^{7}Be production @ EXOTIC via $p(^{7}Li,^{7}Be)n$



Courtesy of M. Mazzocco and C. Parascandolo

^{7}Li primary beam

Energy: 31 MeV

Intensity 150-200 pnA

$^{1}H_2$ gas target

Pressure: 1 bar

Temperature: 90 K

^{7}Be secondary beam

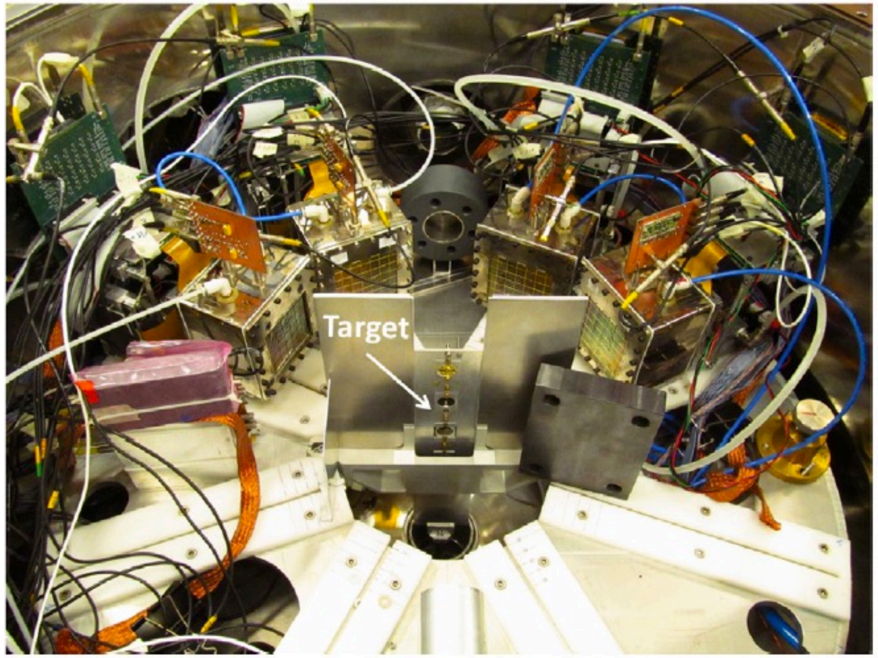
E_{lab}: (20.4 ± 0.5) MeV

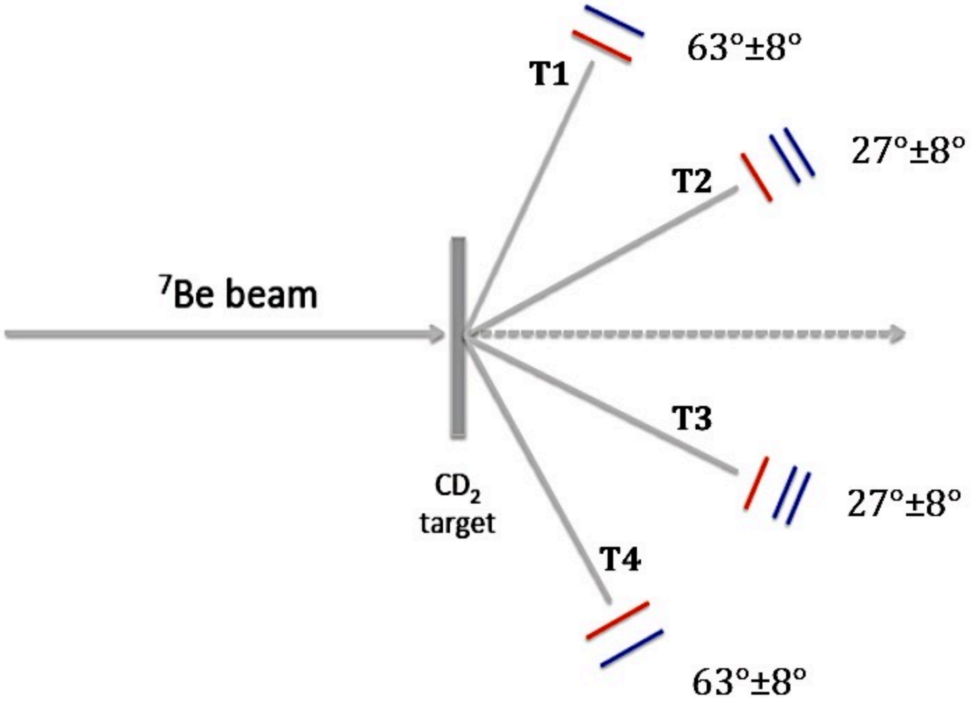
Intensity (average): $5*10^5$ pps

Purity: > 99 %

Beam spot: 9 mm (FWHM)

The BELICOS experimental setup





- 400 μg/cm^2 CD_2 target;
- EXPADES detection system

  Pierroutsakou, D. et al. 2016, NIMPA, 834, 46

T2(T3)→ IC + DSSSD (300 μm) **+ SPad** (300 μm)
T1(T4)→ IC + DSSSD (300 μm)

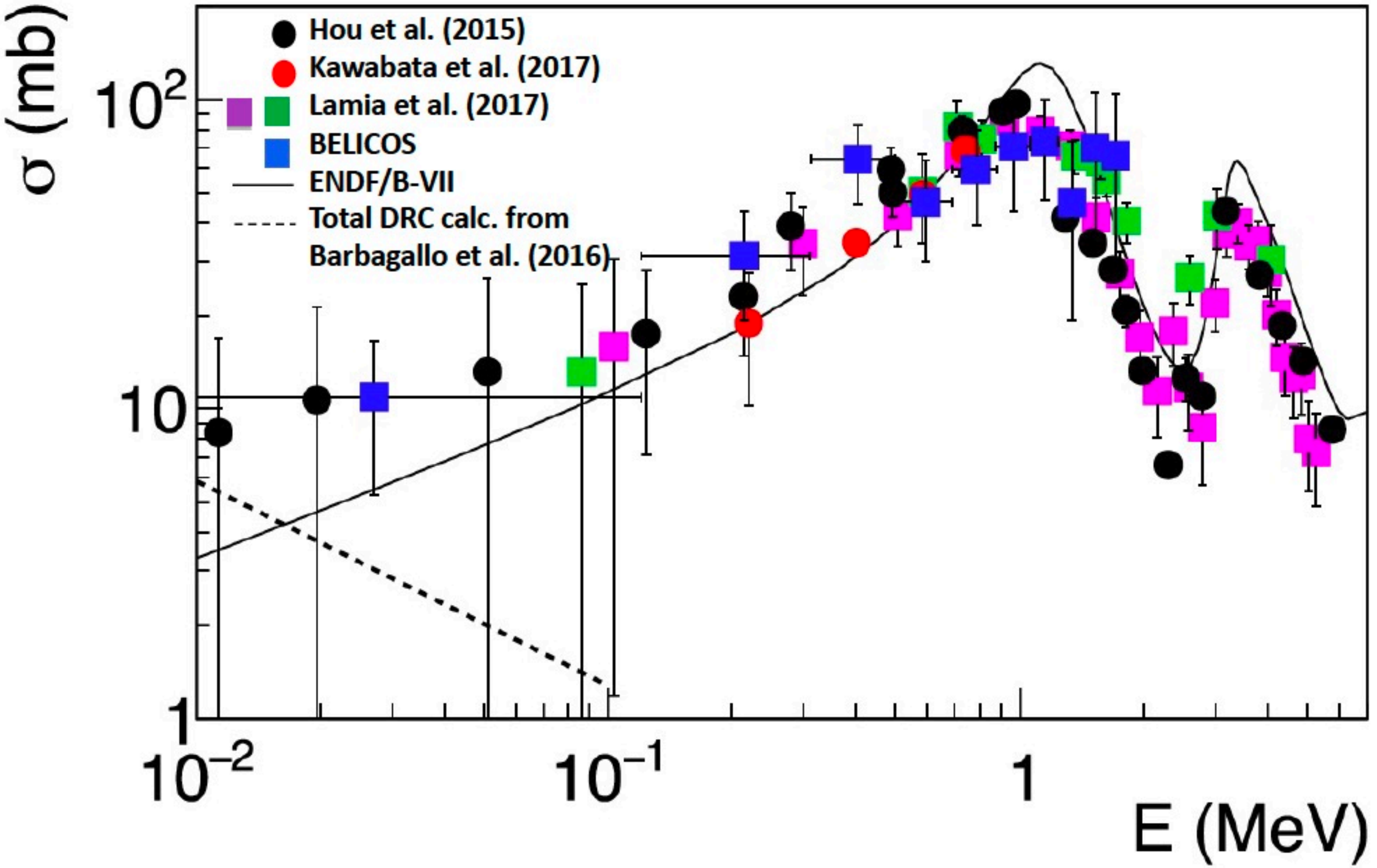
100 mbar isobuthane for IC

Setup symmetrical, respect to the beam line, in the reaction plane

Trigger: coincidence between two telescopes

Calibration with ^{7}Li beam on ^{12}C, ^{197}Au and CH_2

The $^{7}Be(n,\alpha)^{4}He$ THM cross section



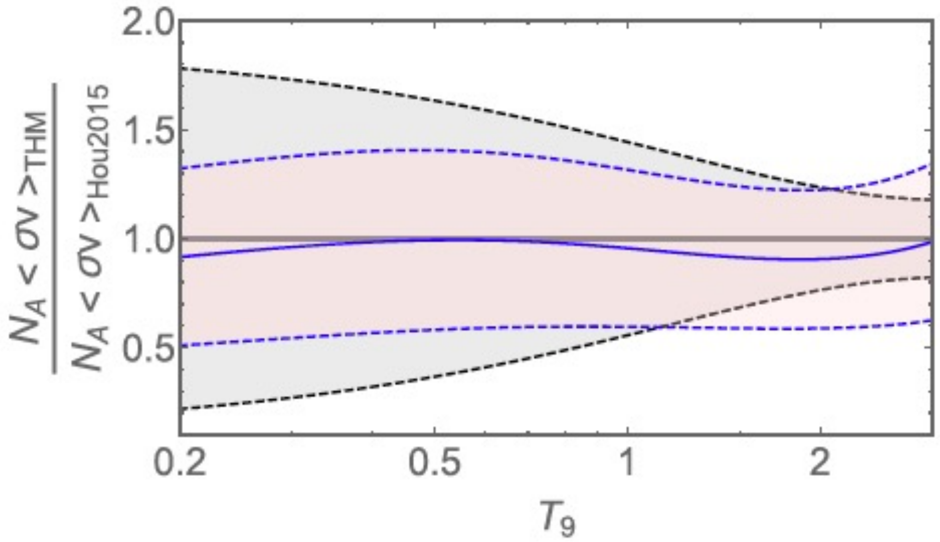
L. Lamia et al. The Astrophysical Journal, 879:23 (8pp), 2019

Impact of the THM $^7Be(n,\alpha)^4He$ reaction rate

Following the definition of the reaction rate

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{N_A}{kT_9^{\frac{3}{2}}} \int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE$$

THM RR have been compared with the one of Hou et al. 2015 one.



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The impact of such result has been evaluated through the BBN code of Kawano (1988) discussed in Pizzone 2014

Lithium Abundances Calculated via the BBN Code of Kawano (1988) with the Nuclear Inputs of Pizzone et al. (2014) (Labeled as Pizz2014)

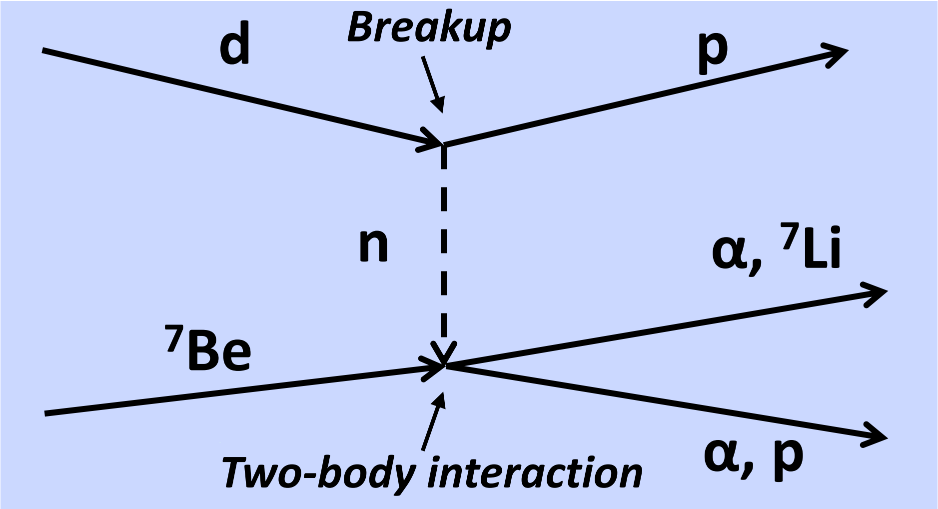
Reaction Rate	^{7}Li/H	^{7}Be/H	(^{7}Li/H+^{7}Be/H)
Pizz2014+Hou2015	2.840×10^{-11}	4.149×10^{-10}	4.433×10^{-10}
Pizz2014+Lam17	2.845×10^{-11}	4.156×10^{-10}	4.441×10^{-10}
Pizz2014+Present work	2.67×10^{-11}	3.99×10^{-10}	4.26×10^{-10}
Halo Stars Observ. as in Sbordone et al. (2010)			$(1.58^{+0.35}_{-0.28}) \times 10^{-10}$

Note. The first three rows display the primordial abundances using the $^7Be(n,\alpha)^4He$ reaction rates of Hou et al. (2015) (Hou2015), Lamia et al. (2017) (Lam17), and the present work. The last row refers to the ^{7}Li abundance for halo stars as reported in Sbordone et al. (2010).

The ^{7}Be –n interaction via THM @ CRIB

THM reactions

$^{7}Be(n,\alpha)^{4}He$	$^{2}H(^{7}Be, \alpha\ \alpha)H$
$^{7}Be(n,p)^{7}Li$	$^{2}H(^{7}Be, p\ ^{7}Li)H$



✓ **quasi-free breakup mechanism**

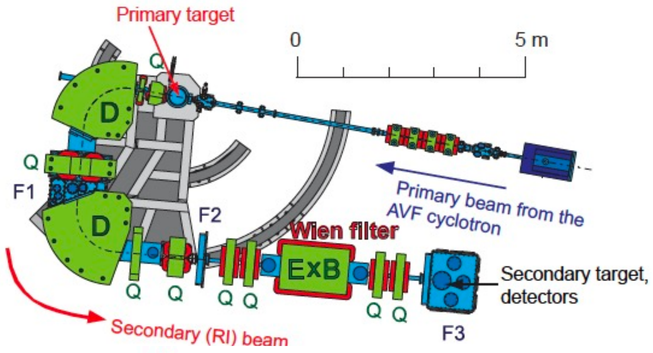
✓***d* as TH nucleus (p ⊕ n)**

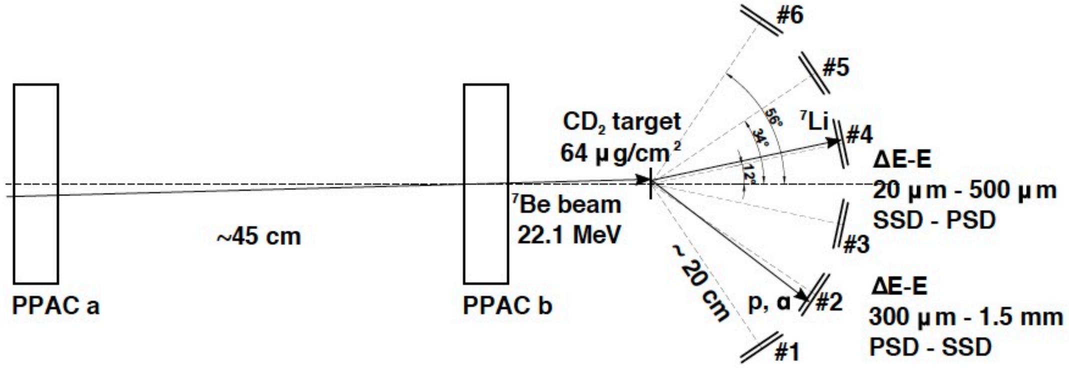
✓***⁷Be + n interaction***

✓***p is spectator***

✓***⁷Be @ 22.1 MeV by CRIB facilit***

✓***intensity 1 x 10⁶ pps***



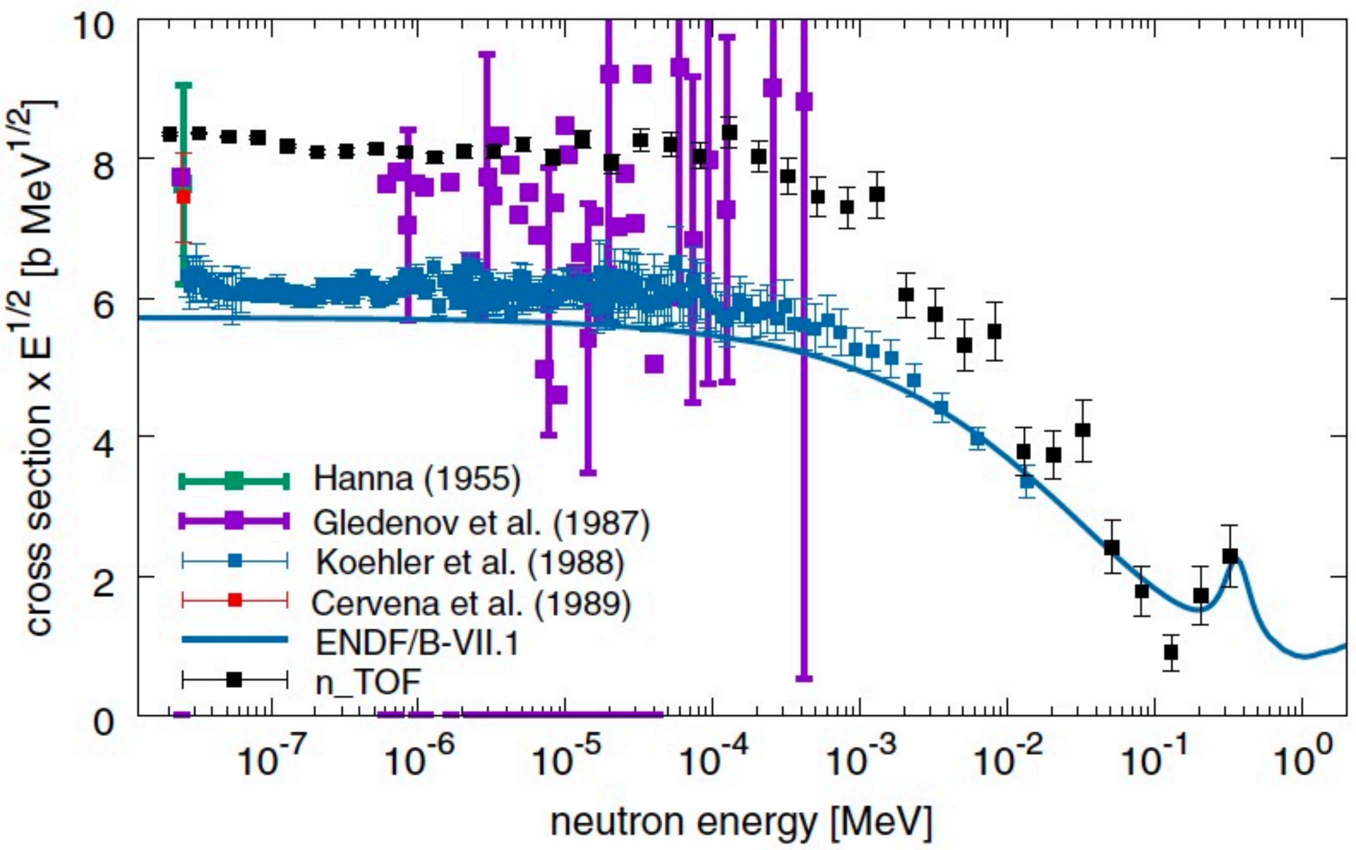


Improved with respect BELICOS:

- ✓ capability to detect the ^{7}Li
- ✓ PPACs for beam tracking
- ✓ thinner CD_2 target (64 μg/cm²)
- → better angular and energy resolutions

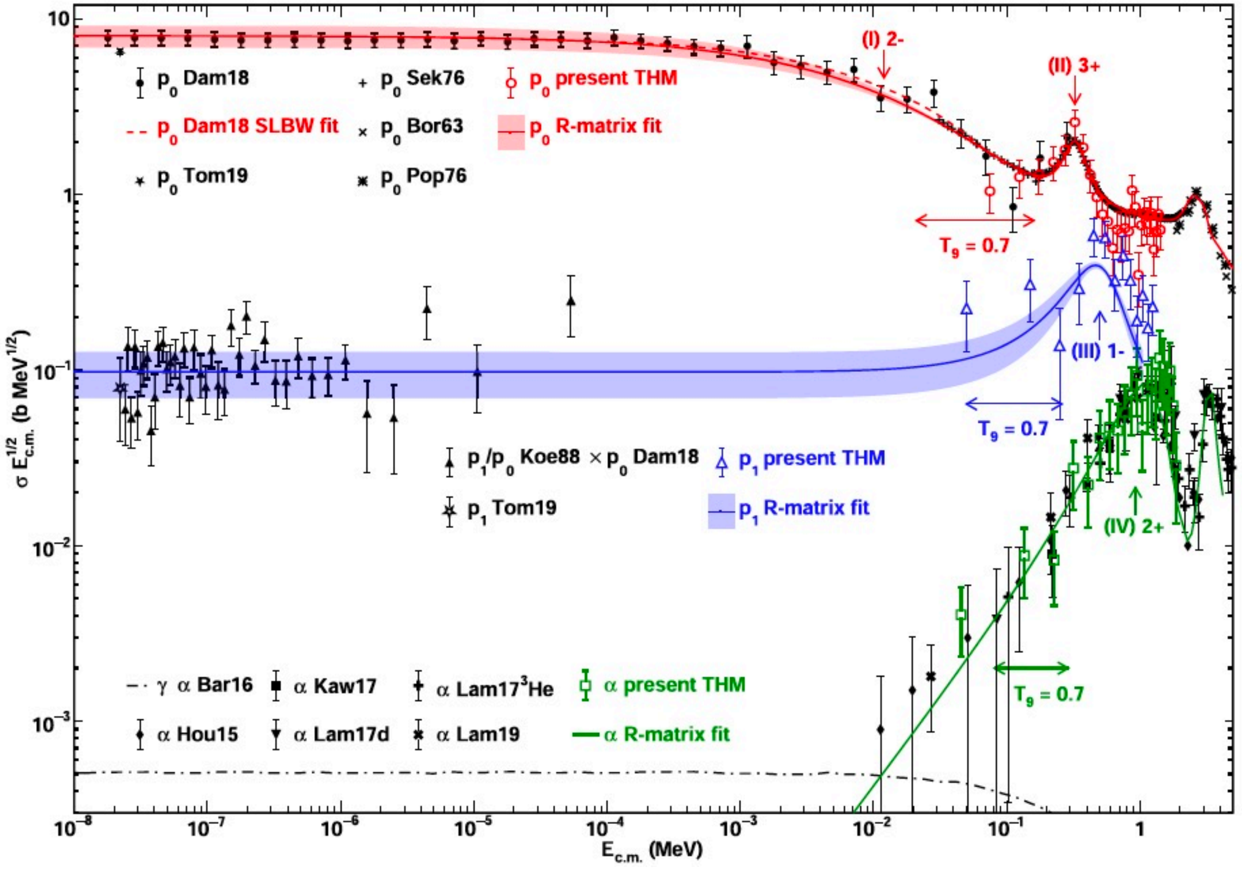
Typical E_{cm} resolutions: 50 keV for the (n, p) channel
180 keV for the (n, **α**) channel

$^7Be(n,p)^7Li$ cross section - direct measurement



L. Damone PRL 121, 042701 (2018)

^{7}Be(n,p)^{4}He and ^{7}Be(n,α)^{4}He THM cross sections



Hayakawa et al. The APJL, 915:L13 (14pp), 2021

^{7}Be(n,p_0) — p_0 present THM
- Gibbons1959
- Sekharan1976
- Koehler1988
● Damone2018

^{7}Be(n,p_1) — p_1 present THM
- Koehler1988

^{7}Be(n,α) — α present THM
× Hou2015
— Barbagallo2016 (Total DRC)
○ Kawabata2017
▲+ Lamia2017

- **Multichannel R-matrix fit** of all the measured channels considering THM cross sections and data set from literature

Low-lying Resonance Parameters Resulted from the *R*-matrix Fit

Level No.	J^π	E_x	$E_{c.m.}$	l_n	Γ_n	l_{p0}	Γ_{p0}	l_{p1}	Γ_{p1}	l_α	Γ_α	Γ	$\Gamma^{(Ref.)}$
I	2^-	18910[a]	10	0	$297\ ^{+23}_{-32}$	0	$651\ ^{+55}_{-73}$	2	∼0	⋯	⋯	$948\ ^{+59}_{-80}$	1634[b]
II	3^+	19230[b]	330	1	$89\ ^{+8}_{-9}$	1	$66\ ^{+4}_{-3}$	3	∼0	⋯	⋯	$155\ ^{+9}_{-10}$	165[b]
III	1^-	19400[a]	500	0	$263\ ^{+56}_{-46}$	0	∼0	0	$326\ ^{+75}_{-70}$	⋯	⋯	$589\ ^{+94}_{-84}$	645[a]
IV	2^+	(19885 ±20)	(985 ±20)	1	(89 ±3)	1	23[c]	1	143[c]	2	726[c]	(981)	880[a]

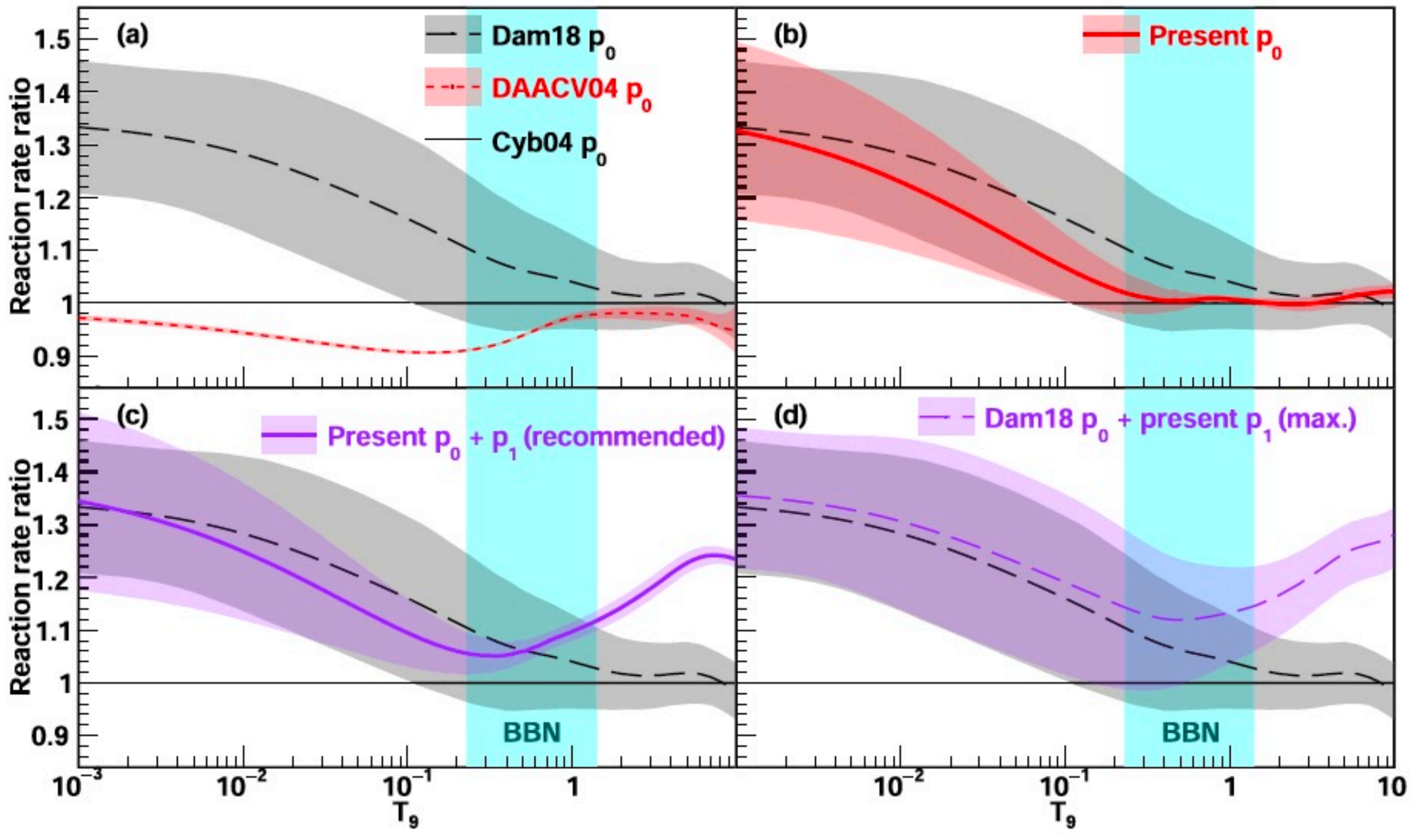
Notes. The brackets indicate provisional fit values. Energies are all in units of keV.
[a] From Tilley et al. (2004).
[b] From Adahchour & Descouvemont (2003).
[c] The proton and α widths of Level IV are fixed at a ratio $\Gamma_\alpha/\Gamma_p \sim 4.5$ (Tilley et al. 2004).

In the BBN energy range

↓

- A slightly smaller cross sections with better uncertainty evaluations with respect the result of Damone et al. (2018)
- The measurement of the contribution of the p1 channel for the first time

Impact of the THM $^7Be(n,p)^7Li$ reaction rate



Reaction Rate Source	BBN Code	$^7Li/H$ (10^{-10})
DAACV04 p_0 [c]	PRIMAT	$5.63^{+0.22}_{-0.24}$ [d]
Present p_0	PRIMAT	$5.37^{+0.22}_{-0.25}$
Present $p_0 + p_1$ (recommended)	PRIMAT	$5.18^{+0.22}_{-0.25}$
Dam18 p_0 [b] + present p_1 (max.)	PRIMAT	$4.97^{+0.47}_{-0.41}$
Observation	...	$1.58^{\pm0.3}$ [e]

Hayakawa et al. The APJL, 915:L13 (14pp), 2021

Ratio between reaction rates from different works and Cyburt 2004 rate for the (n,p_0) channel.

Fig. (a) Descouvemont et al. 2004 (DAACV04) rate and Damone et al. 2018 (Dam18) rate

Fig. (b) Present rate (for p0 channel) and Damone et al. 2018 (Dam18) rate. Present reaction rate is lover with respect Damone et al. 2018 (Dam18) with a strong reduction of the uncertainty in the BBN region.

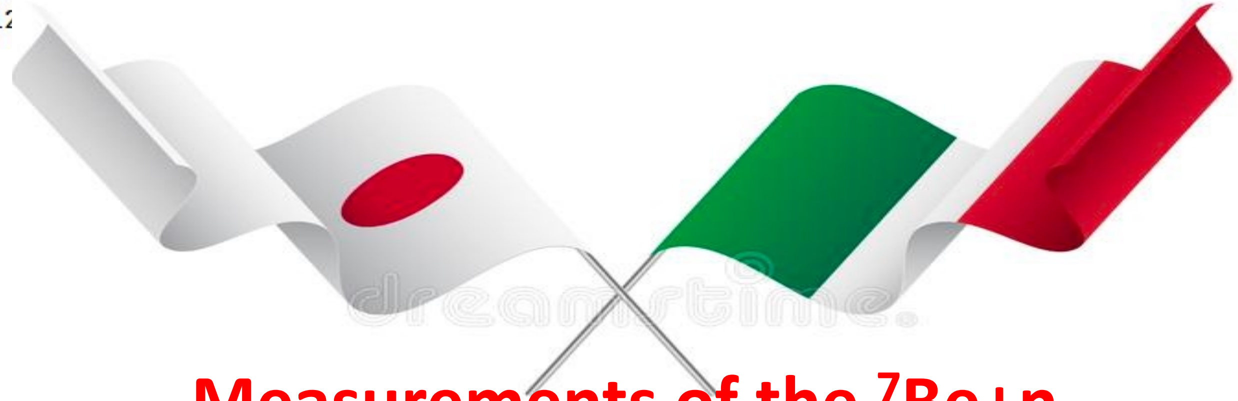
Fig.(c) Present recommended $p_0 + p_1$ rate in is comparable to Damone et al. 2018 in the BBN range, but with different temperature dependence due to the (n, p1) contribution.

Fig. (d) Sum of present p_1 rate and Damone et al. 2018 one. It represents a possible upper limit deducible from the adopted cross section data set.

The BeLiCos experiment @ INFN-LNL

Experimental study of the $^{7}Be(n,\alpha)^{4}He$ at astrophysical energies by means of the Trojan Horse Method applied to the $^{2}H(^{7}Be, \alpha^{4}He)p$ reaction

L. Lamia[1,2], M. Mazzocco[3,4], C. Spitaleri[1,2], M. La Cognata[2], R. G. Pizzone[2], X. Aslanouglu[5], Ch. Betsou[5], A. Boiano[6], C. Boiano[14], C. Broggini[4], A. Caciolli[4,3], S. Cherubini[1,2], G. D'Agata[1,2], R. Depalo[4,3], A. Di Pietro[2], P. Figuera[2], M. Fisichella[2], G.L. Guardo[1,2], S. Hayakawa[7], N. Iwasa[16], S. Kubono[8,15], M. La Commara[6,9], M. Lattuada[1,2], A. Pakou[5], C. Parascandolo[6], R. Menegazzo[4], D. Pierroutsakou[6], S. Romano[1,2], G. G. Rapisarda[1], K. Sakaguchi[7], M.L. Sergi[2], O. Sgouros[5], F. Soramel[3,4], V. Soukeras[5], E. Stiliaris[10], E. Strano[3,4], D. Torresi[1,2], A. Tumino[11], H. Yamaguchi[7], F.L. Villante[12]



Measurements of the $^{7}Be+n$ BBN reactions at CRIB by the Trojan Horse method

S. Hayakawa[1], K. Abe[1], O. Beliuskina[1], S. M. Cha[2], K. Y. Chae[2], S. Cherubini[3,4], P. Figuera[3,4], Z. Ge[5], M. Gulino[3,6], J. Hu[7], A. Inoue[8], N. Iwasa[9], D. Kahl[10], A. Kim[11], D. H. Kim[11], G. Kiss[5], S. Kubono[1,5,7], M. La Cognata[3], M. La Commara[12,13], L. Lamia[4], M. Lattuada[3,4], E. J. Lee[2], J. Y. Moon[14], S. Palmerini[15,16], C. Parascandolo[13], S. Y. Park[11], D. Pierroutsakou[13], R. G. Pizzone[3,4], G. G. Rapisarda[3], S. Romano[3,4], H. Shimizu[1], C. Spitaleri[3,4], X. D. Tang[7], O. Trippella[15,16], A. Tumino[3,6], P. Vi[5], H. Yamaguchi[1], L. Yang[1], and N. T. Zhang[7]

Some references

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- ✓ C. Spitaleri et al. Eur. Phys. J. A (2016) 52: 77
- ✓ A. Tumino et al. *Annu. Rev. Nucl. Part. Sci. 2021 71 1-33*

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- ✓ R.E. Tribble et al. NIM A285, 441 (1989)
- ✓ M. Mazzocco NIMB 317 (2013) 223–226

^{18}F(p,α)^{15}O (THM works)

- ✓ Cherubini et al. PRC 92, 015805 (2015)
- ✓ R.G. Pizzone et al. Eur. Phys. J. A 52 (2016) 24
- ✓ La Cognata et al. the APJ 846:65 2017

^{7}Be-n (THM works)

- ✓ L. Lamia et al. The Astrophysical Journal, 879:23 (8pp), 2019
- ✓ Hayakawa et al. The APJL, 915:L13 (14pp), 2021

Thanks for your attention

AsFiN people

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