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Trojan Horse Method for n-induced reaction investigations at astrophysical energies

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Indirect Method in Nuclear Astrophysics

Determination of astrophysically relevant cross section by selecting a precise reaction mechanism in a suitable chosen reaction and through the application of some theoretical consideration:

Coulomb dissociation

Asympotic Normalization Coefficient (ANC)

Trojan Horse Method (THM)

Usefull references about THM:

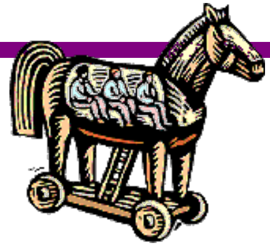
-G. Baur et al., Nucl. Phys. A 458, 188 (1986)

-R. Tribble et al., Rep. Prog. Phys. 77, 106901 (2014)

-C. Spitaleri et al., EpJA 55, 161 (2019)

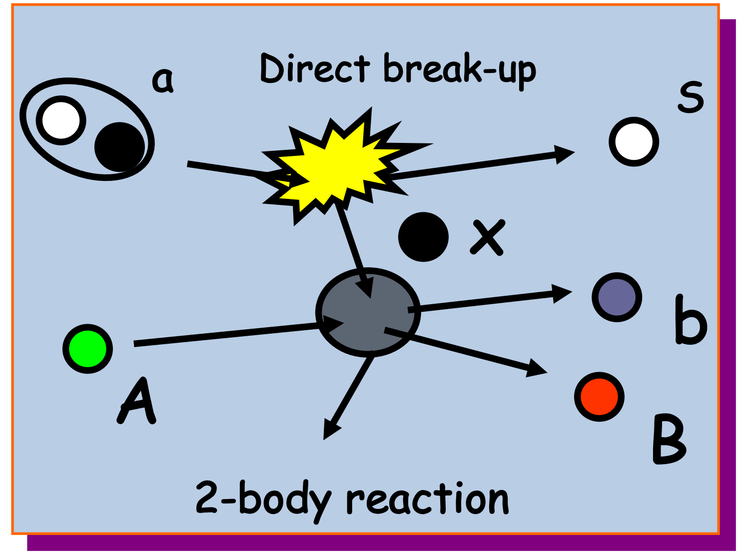
-A. Tumino et al., Ann. Rev. Nuc. Part. Science, 71, available from Sept.2021

…allows to deduce a charged-particle binary-reaction cross section inside the Gamow window by selecting the Quasi-Free (QF) contribuiton to an appropriate three-body reaction.



The Trojan Horse Method I

✓ The QF $A + a \rightarrow b + B + s$ reaction between the projectile *A* and the target *a* can be described by the polar-diagram:



✓ Upper pole describes the break-up process of nucleus *a* in its "x" and "s" constituents. The break-up is Quasi-Free if *s* maintains in the exit channel the same momentum distribution as in *a*;

✓ Lower pole describes the astrophysically relevant two-body reaction A(x,b)B;

✓ The nucleus *a* (the so-called "TH-nucleus") is chosen because of:

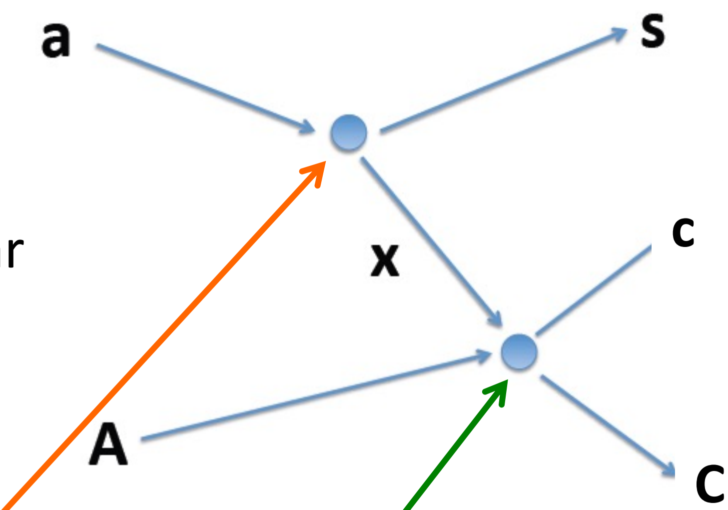
- its large amplitude in the $a=x \oplus s$ cluster configuration;
- its relatively low-binding energy;
- Its known *x-s* momentum distribution $|\Phi(\vec{p}_s)|^2$ in *a.*

✓ In this picture, "s" behaves as *spectator* while nucleus *"x"* is the *participant* of the astrophysical A(x,b)B reaction (Impulse Approximation approach).

The Trojan Horse Method II

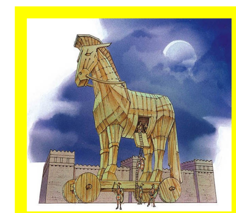
The A(a,cC)s is induced at energies of the order of 20-50 MeV, higher than the Coulomb barrier in the entrance A-a channel.

The A-x interaction occurs directly in the nuclear field, thus **Coulomb suppression effects are naturally removed.**



The **cross section** for the A(a,bB)s process can be derived in the simple PWIA approach as

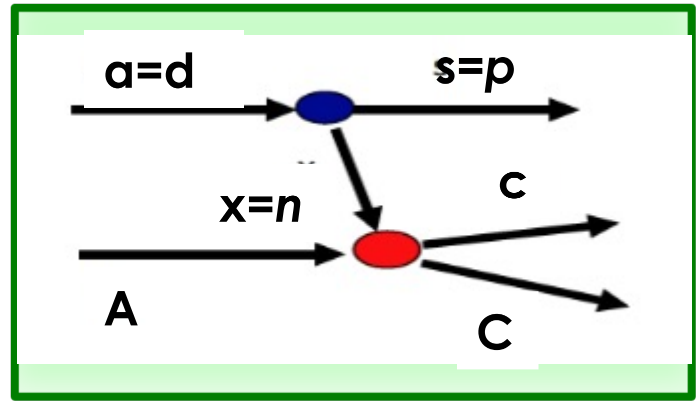
$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto KF \cdot |\Phi(\vec{p_s})|^2 \left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{A-x}^{N}$$



- $|\vec{\Phi}(p_S)|^2$ is a key quantity to be determined in each THM experiment!
- The A-x reaction is induced at energies $E_{c.m.}=E_{cC}-Q_{2body}$, where E_{bB} is the relative *c-C* energy and Q_{2body} the A(x,c)C Q-value. This allows to cover the energy region of interest for astrophysics by using only a mono-energetic beam!

THM on neutron induced reaction

✓ Deuterium as a virtual neutron source;

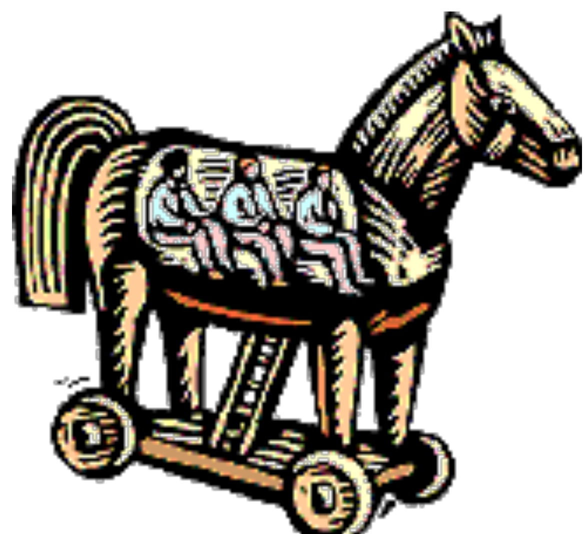


$^{6}Li(n,\alpha)^{3}H$
$^{10}B(n,\alpha)^{7}Li$
Validity test

$^{17}O(n,\alpha)^{14}C$
$^{14}N(n,p)^{14}C$
s-process

$^{3}He(n,p)^{3}H$ BBN

$^{7}Be(n,\alpha)^{4}He$
$^{7}Be(n,p)^{7}Li$
$^{18}F(n,\alpha)^{15}O$
radioactive beams application



The $^{14}N(n,p)^{14}C$ reaction

… astrophysical importance

s-processes: ^{14}N is very abundant since it is the dominant product of hydrogen burning in the CNO cycle, step prior to s process. Hence, due to its high cross section, the $^{14}N(n,p)^{14}C$ reaction acts as a strong **neutron poison** in the chain of reactions for the production of heavier elements.

Origin of fluorine: the He burning shell in AGBs is the primary site for fluorine synthesis, via the reaction chain

$$^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$$

→ The protons captured by ^{18}O are mostly those produced in the $^{14}N(n,p)^{14}C$ reaction

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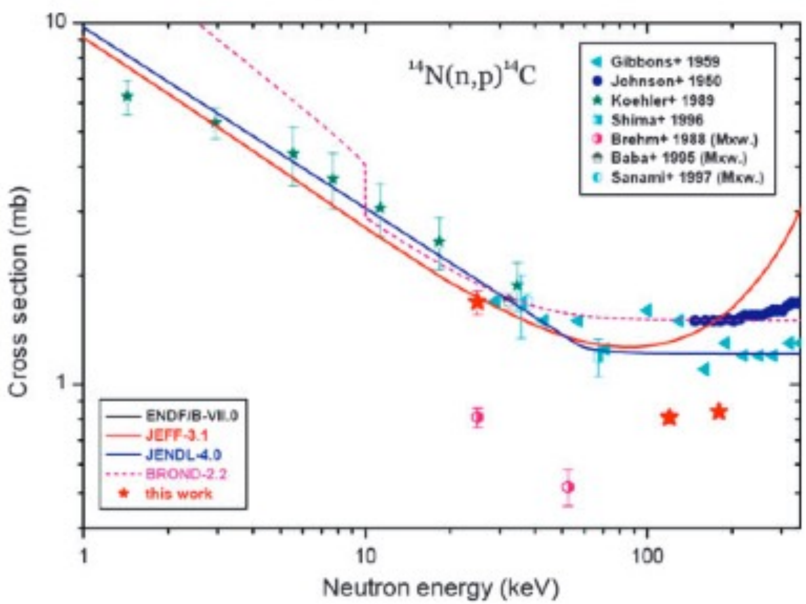

… state of the art

Wallner et al., Astronomical Society of Australia, (2012), 29, 115

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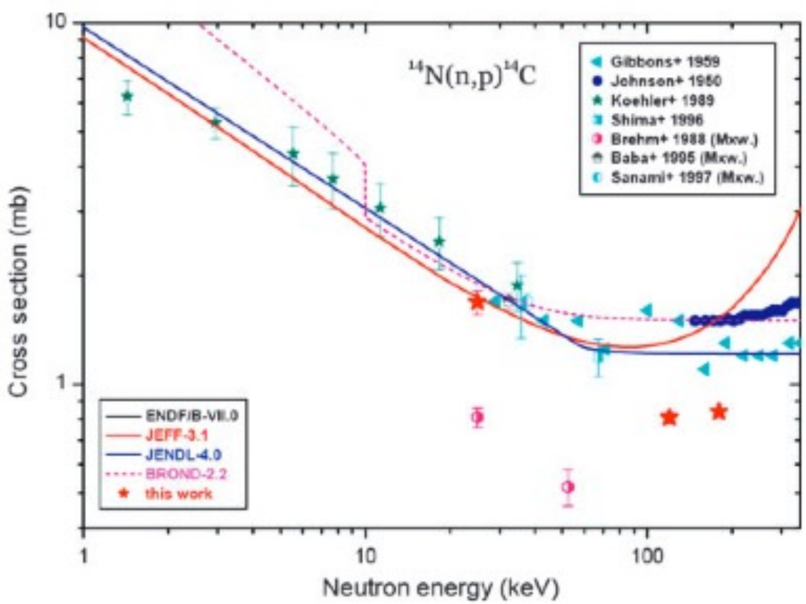
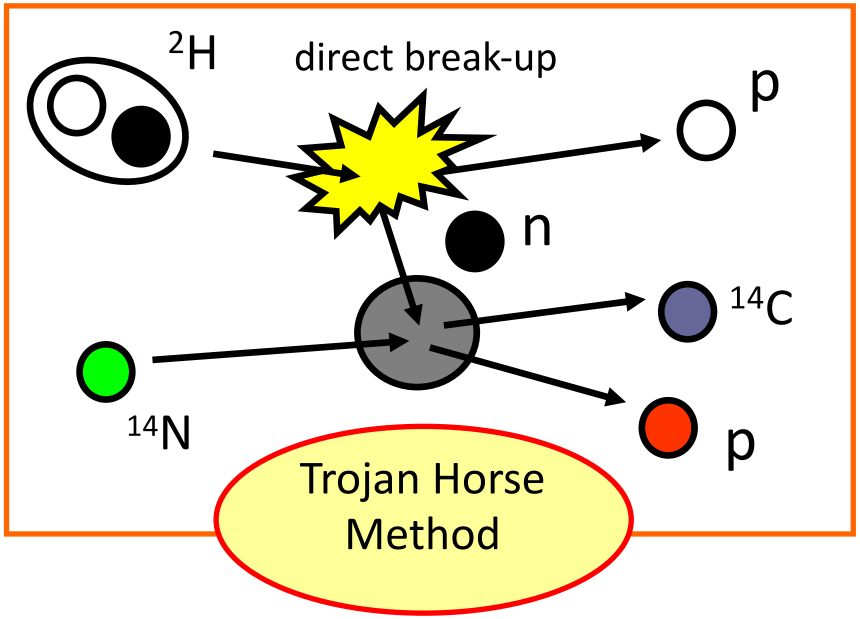


Wallner et al., Astronomical Society of Australia, (2012), 29, 115

… state of the art

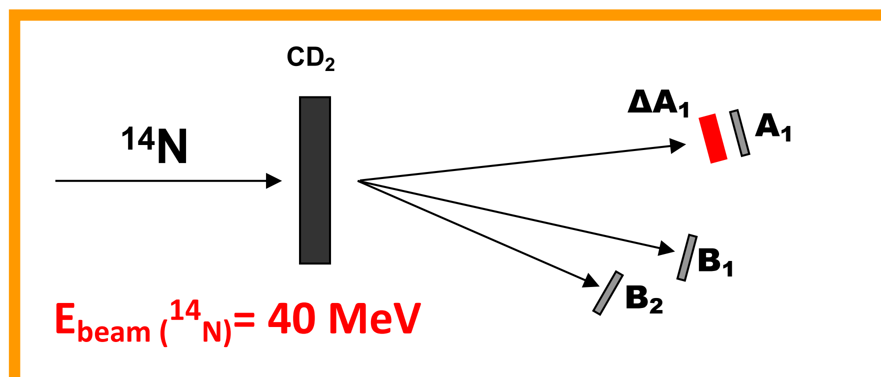
Further measurements needed!

$^{14}N(n,p)^{14}C$ studied by $^{2}H(^{14}N,p^{14}C)^{1}H$ via the THM



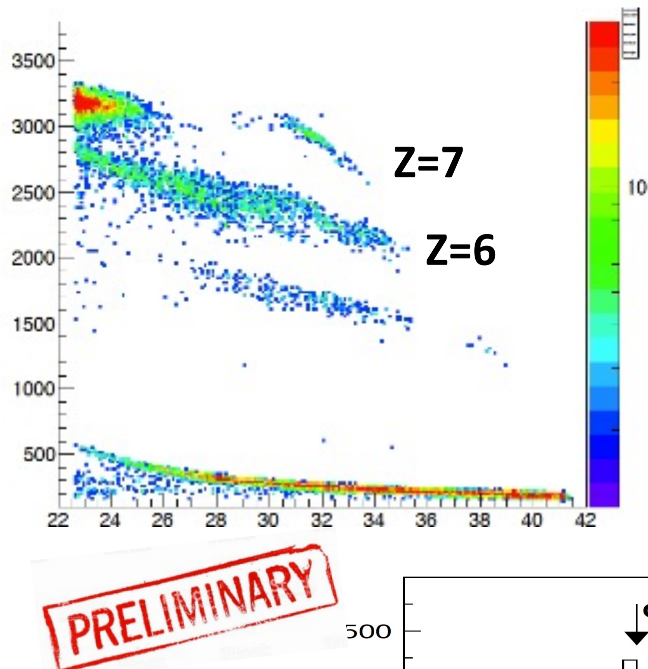
1) The experiment was performed @LNS-INFN (Catania)
2) The two body reaction **$^{14}N(n,p)^{14}C$ (Q-value=0.626 MeV)** was studied by applying the THM to the reaction **$^{2}H(^{14}N, p\ ^{14}C)p$ (Q-value=-1.599 MeV)** by properly selecting the corresponding quasi-free contribution (QF) to the total reaction yield;
3) Deuteron "d" was used as **TH-nucleus**
4) Use of large area 5x5 cm^2 DSSSD

Detectors	Thickness [μm]	θ [deg]	r [cm]	Δθ [deg]
A_1 (STRIP)	500	5.0 ± 0.1	80	±1.8
ΔA_1(STRIP)	20	5.0 ± 0.1	80	±1.8
B_1(STRIP)	1000	25.0 ± 0.1	25	±5.7
B_2(PSD)	500	40.0 ± 0.1	25	±5.7

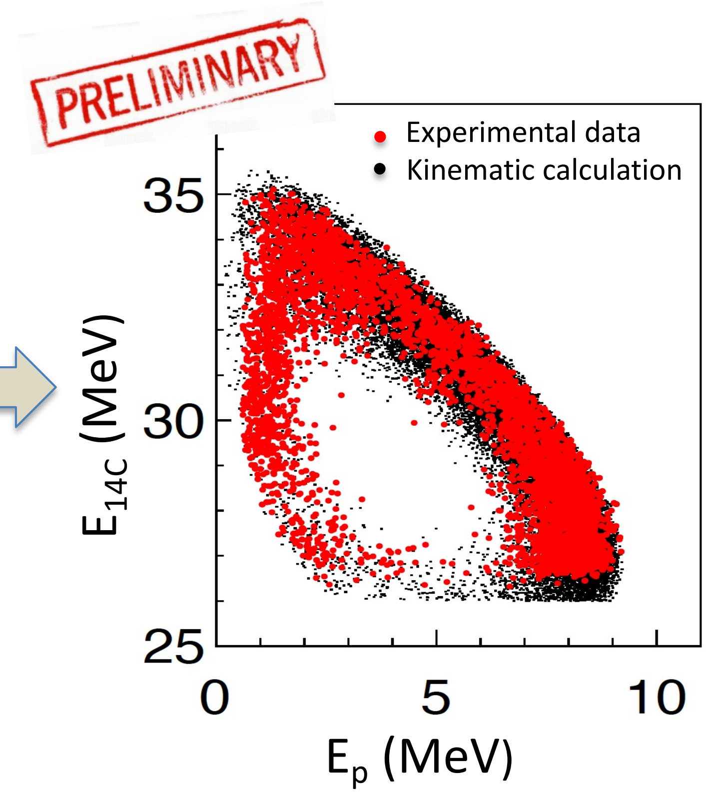


$^{14}N(n,p)^{14}C$ studied by $^{2}H(^{14}N,p^{14}C)^{1}H$ via the THM

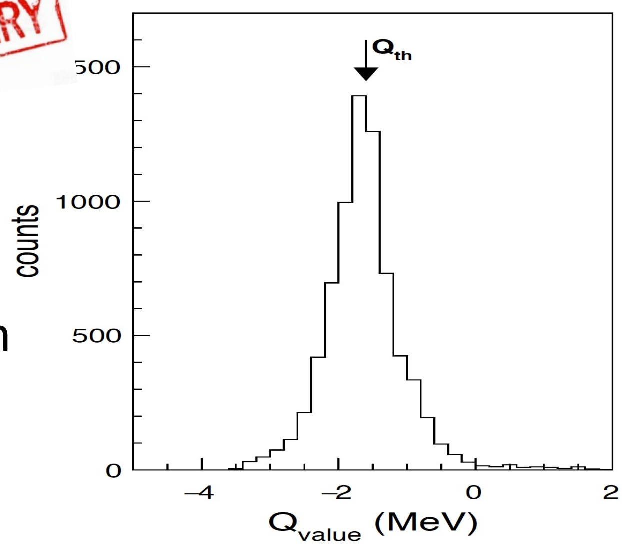
Reaction channel selection….



For the selected events (Z=6), the obtained experimental kinematical locus (red points) ….



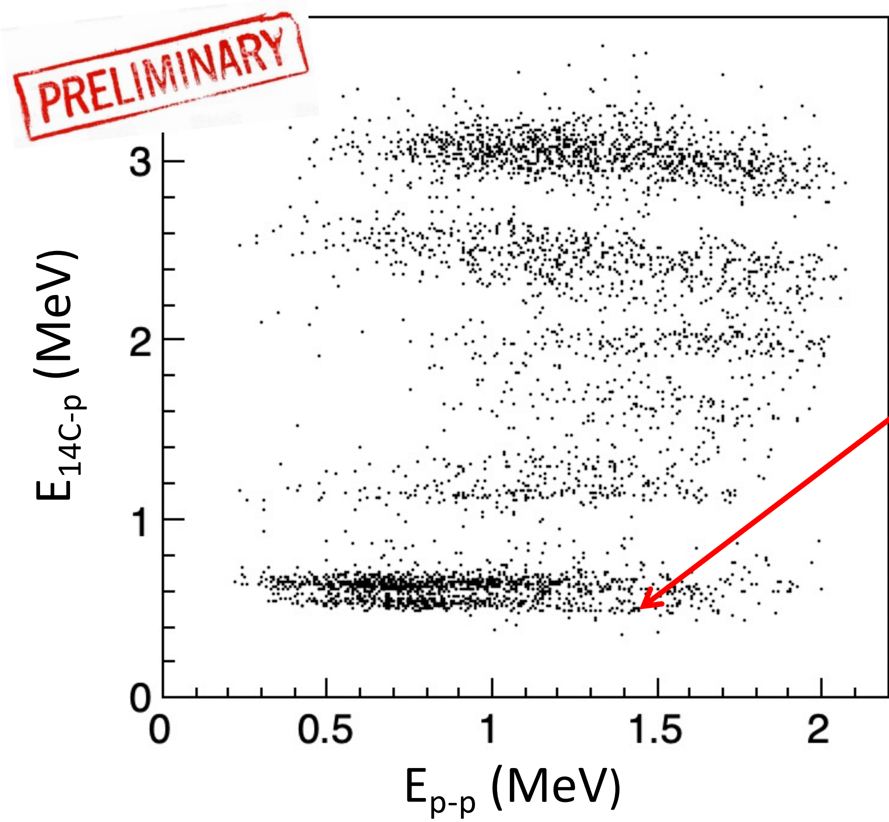
and the experimental Q_{value} spectrum



- **Good agreement with the theoretical value $Q_{theor.}$=-1.599 MeV**
- **correct selection of the reaction channel;**
- **good calibration procedure**
- **No other competing channels in the exit channel.**

Study of the relative energy two dimensional plot

By using both the angles and energies of the ^{14}C and proton in the exit channel, it has been possible to reconstruct their relative energy E_{12}. Additionally, the kinematical properties of the UNDETECTED proton were reconstructed by using energy-momentum conservation laws.

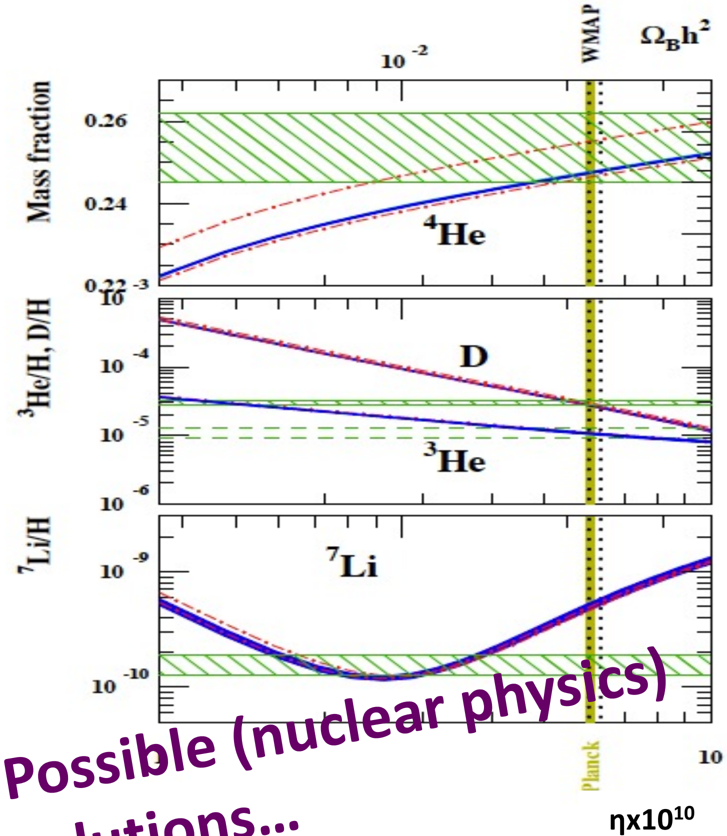


subthreshold levels

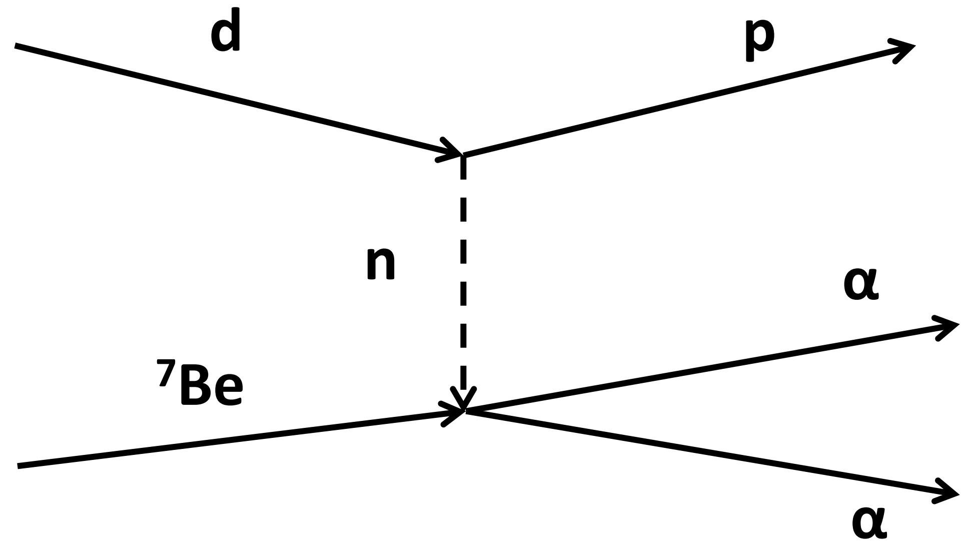
E_{14C-p} (MeV)	E_{15N^*} (MeV) E_x (MeV ± keV)	$J^\pi;T$
	9.9250 ± 0.2	$\frac{3}{2}^-$
	10.0660 ± 0.2 [c]	$\frac{3}{2}^+$
0.411 MeV	10.4497 ± 0.3	$\frac{5}{2}^-$
0.495 MeV	10.5333 ± 0.5	$\frac{5}{2}^+$
	10.6932 ± 0.3	$\frac{9}{2}^+$
0.553 MeV	10.7019 ± 0.3	$\frac{3}{2}^-$
0.655 MeV	10.804 ± 2	$\frac{3}{2}^+$
1.028 MeV	11.235 ± 5 [b]	$\geq \frac{3}{2}$
1.086 MeV	11.2928 ± 0.7	$\frac{1}{2}^-$
1.231 MeV	11.4376 ± 0.7	$\frac{1}{2}^+$
1.408 MeV	11.615 ± 4	$\frac{1}{2}^+; T = \frac{3}{2}$
1.556 MeV	11.763 ± 3	$\frac{3}{2}^+$
	11.876 ± 3	$\frac{3}{2}^-$
.	11.942 ± 6	$\frac{9}{2}^-$
	11.965 ± 3	$\frac{1}{2}^-$
.	12.095 ± 3	$\frac{5}{2}^+$
	12.145 ± 3	$\frac{3}{2}^-$
.	12.327 ± 4	$\frac{5}{2}^{(+)}$
	12.493 ± 4	$\frac{5}{2}^+; \frac{1}{2}$
.	12.522 ± 8	$\frac{5}{2}^+; \frac{3}{2}$
	12.551 ± 10	$\frac{9}{2}^+$
.	12.920 ± 4	$\frac{3}{2}^-$
	12.940 ± 10	$\frac{5}{2}^+$
.	13.004 ± 10	$\frac{11}{2}^-$
	13.149 ± 10	
.	13.174 ± 7	$(\frac{9}{2})$
3.155 MeV	13.362 ± 8	$\frac{3}{2}^-$
	13.390 ± 10	$\frac{3}{2}^+$

The clear horizontal loci in E_{14C-p} represent an evidence for the formation of the ^{15}N excited states.

RIB+n: THM investigation of the $^{7}Be(n,\alpha)^{4}He$ reaction (BELICOS)



Possible (nuclear physics) solutions…



Nuclear Physics Inputs: Cross section measurements at BBN energies (≤100 keV) for ^{7}Li formation/destruction

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

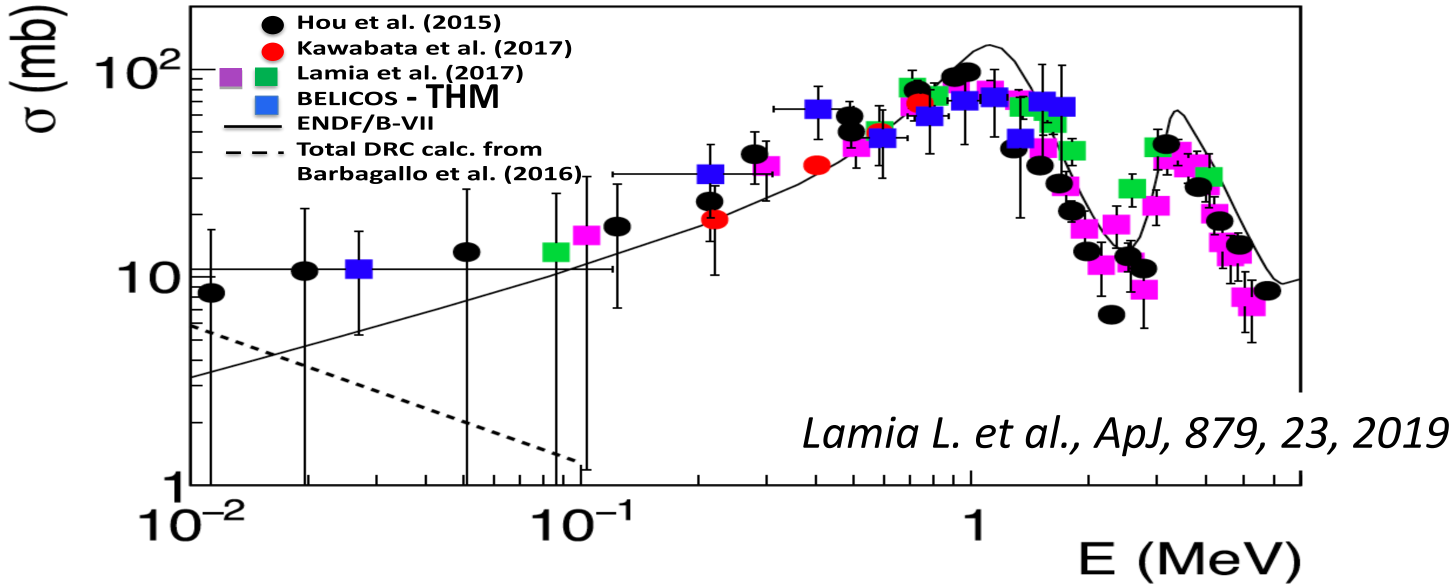
and for the ones involving ^{7}Be

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

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

1) The two body reaction **$^{7}Be(n,\alpha)\alpha$ (Q-value=18.99 MeV)** was studied by applying the THM to the reaction **$^{2}H(^{7}Be, \alpha\, ^{4}He)p$ (Q-value=16.765 MeV)** by using a **20 MeV ^{7}Be beam**;
2) Deuteron "d" was used as **TH-nucleus**
3) Use of large area 6x6 cm^2 IC & DSSSD
4) **Performed at INFN-LNL in collaboration with CRIB-RIKEN (S. Hayakawa)**

The $^{7}Be(n,\alpha)^{4}He$ cross section data at BBN energies



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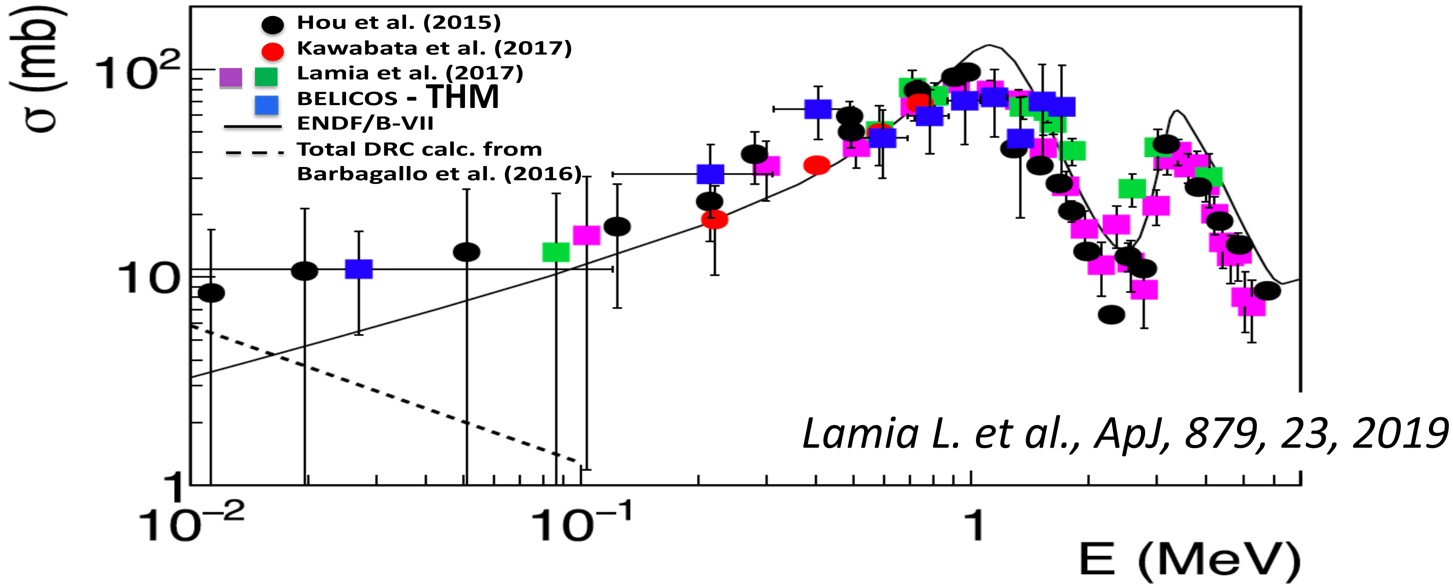

Impact of the THM $^7Be(n,\alpha)^4He$ result

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	$^7Li/H$	$^7Be/H$	$(^7Li/H+^7Be/H)$
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 ^7Li abundance for halo stars as reported in Sbordone et al. (2010).

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

THE ASTROPHYSICAL JOURNAL LETTERS, 915:L13 (14pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac061f

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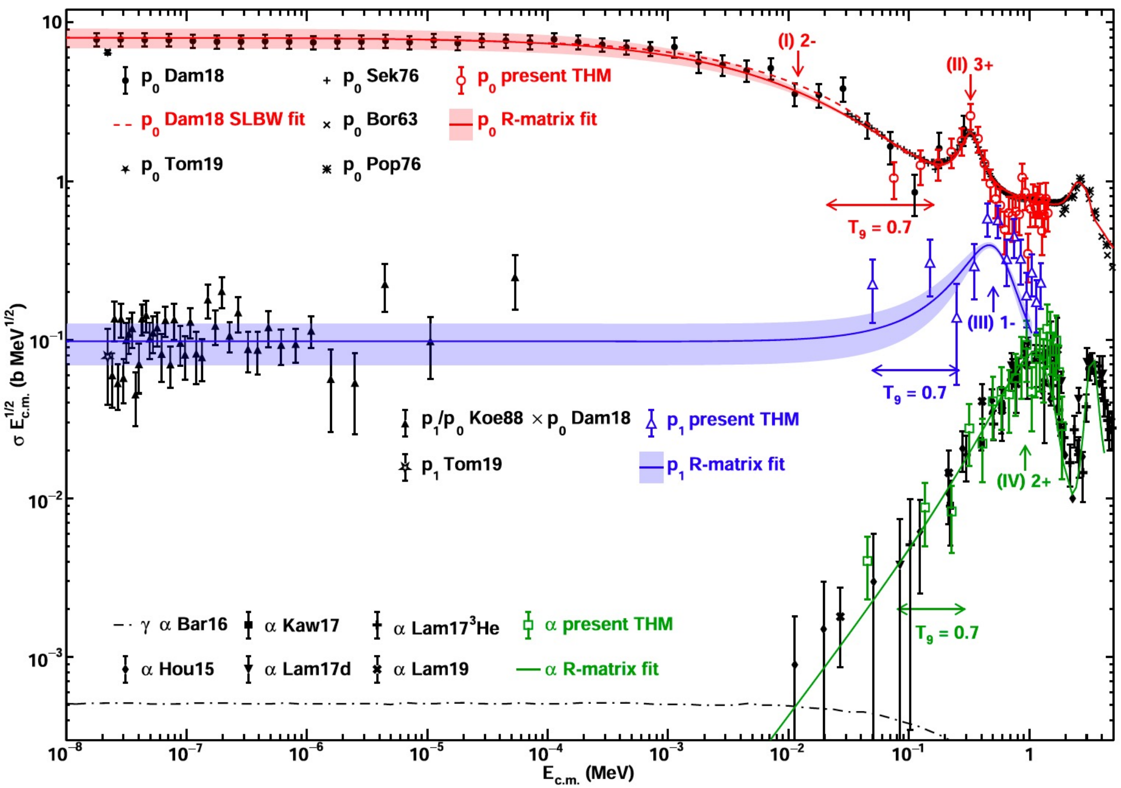
Constraining the Primordial Lithium Abundance: New Cross Section Measurement of the ^{7}Be + n Reactions Updates the Total ^{7}Be Destruction Rate

S. Hayakawa[1], M. La Cognata[2], L. Lamia[2,3,4], H. Yamaguchi[1,5], D. Kahl[6,19], K. Abe[1], H. Shimizu[1], L. Yang[1,20], O. Beliuskina[1,21], S. M. Cha[7,22], K. Y. Chae[7], S. Cherubini[2,3], P. Figuera[2], Z. Ge[8,21], M. Gulino[2,9], J. Hu[10], A. Inoue[11], N. Iwasa[12], A. Kim[13], D. Kim[13,22], G. Kiss[8,23], S. Kubono[1,8,10], M. La Commara[14,15], M. Lattuada[2,3], E. J. Lee[7], J. Y. Moon[16], S. Palmerini[17,18], C. Parascandolo[15], S. Y. Park[13,24], V. H. Phong[8,25], D. Pierroutsakou[15], R. G. Pizzone[2], G. G. Rapisarda[2], S. Romano[2,3,4], C. Spitaleri[2,3], X. D. Tang[10], O. Trippella[17,18], A. Tumino[2,9], and N. T. Zhang[10]



courtesy of Seiya Hayakawa

Thanks for your attention

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