The 10th international conference
on Direct Reactions with Exotic Beams (DREB2018)

A POSSIBLE NUCLEAR SOLUTION TO THE ^{18}F DEFICIENCY IN NOVAE

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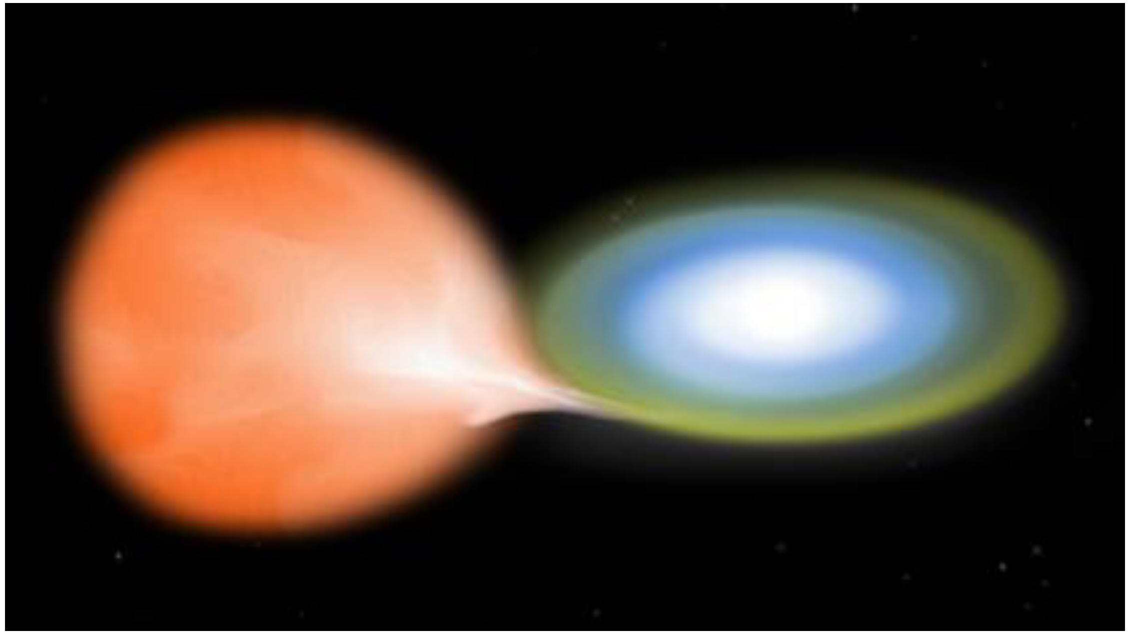
^{18}F in Astrophysics: Classical Novae



Classical novae are stellar explosions that occur in close binary systems.

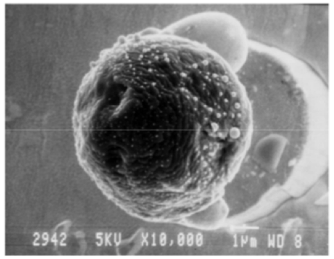
Hydrogen-rich matter is transferred via Roche lobe overflow from a low-mass main-sequence star to the surface of a compact white dwarf where it forms an accretion disk surrounding the white dwarf.

Why are classical novae important?

- Nucleosynthesis (e.g. lithium? ^{13}C to ^{19}F. More important: ^{22}Na, ^{26}Al)
- Formation of presolar grains

How can we study them?

- Light curves
- Ejected material
- Emission of γ–rays (from ^{22}Na decay and ^{18}F e^+-e^- annihilation)



However… no observations so far! Only upper limits

^{18}F in Astrophysics: Production and Destruction

Synthesis of ^{18}F ($T_{1/2}$=110 minutes)
$^{16}O(p,\gamma)^{17}F(\beta^+)^{17}O(p,\gamma)^{18}F$

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

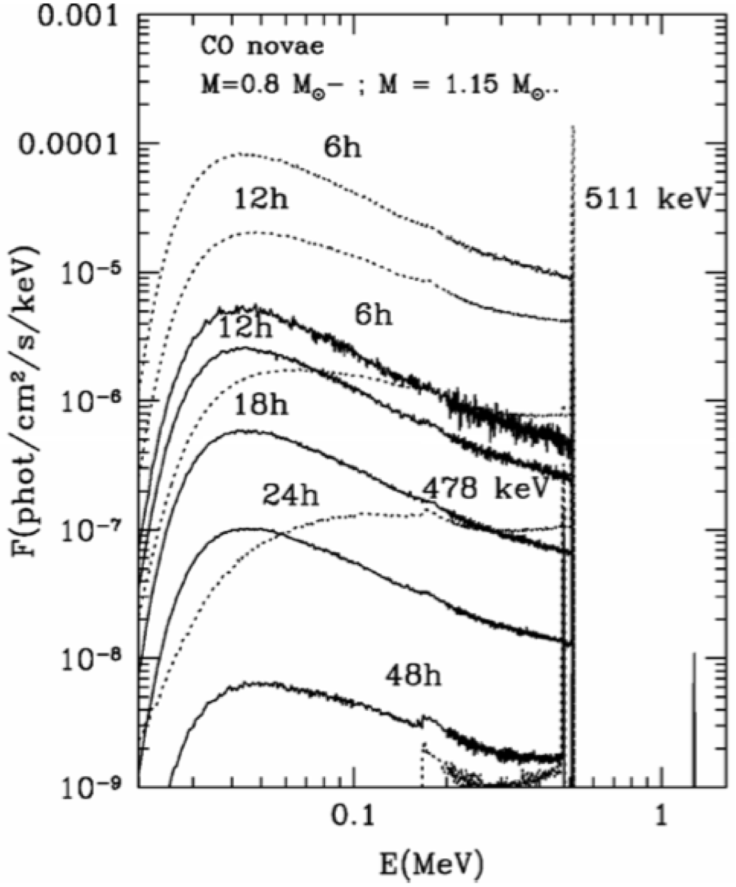
~~$^{18}F(p,\gamma)^{19}Ne$~~

1000 smaller than the p,α reaction

^{18}F has a quite long lifetime, so it decays when the envelope becomes transparent

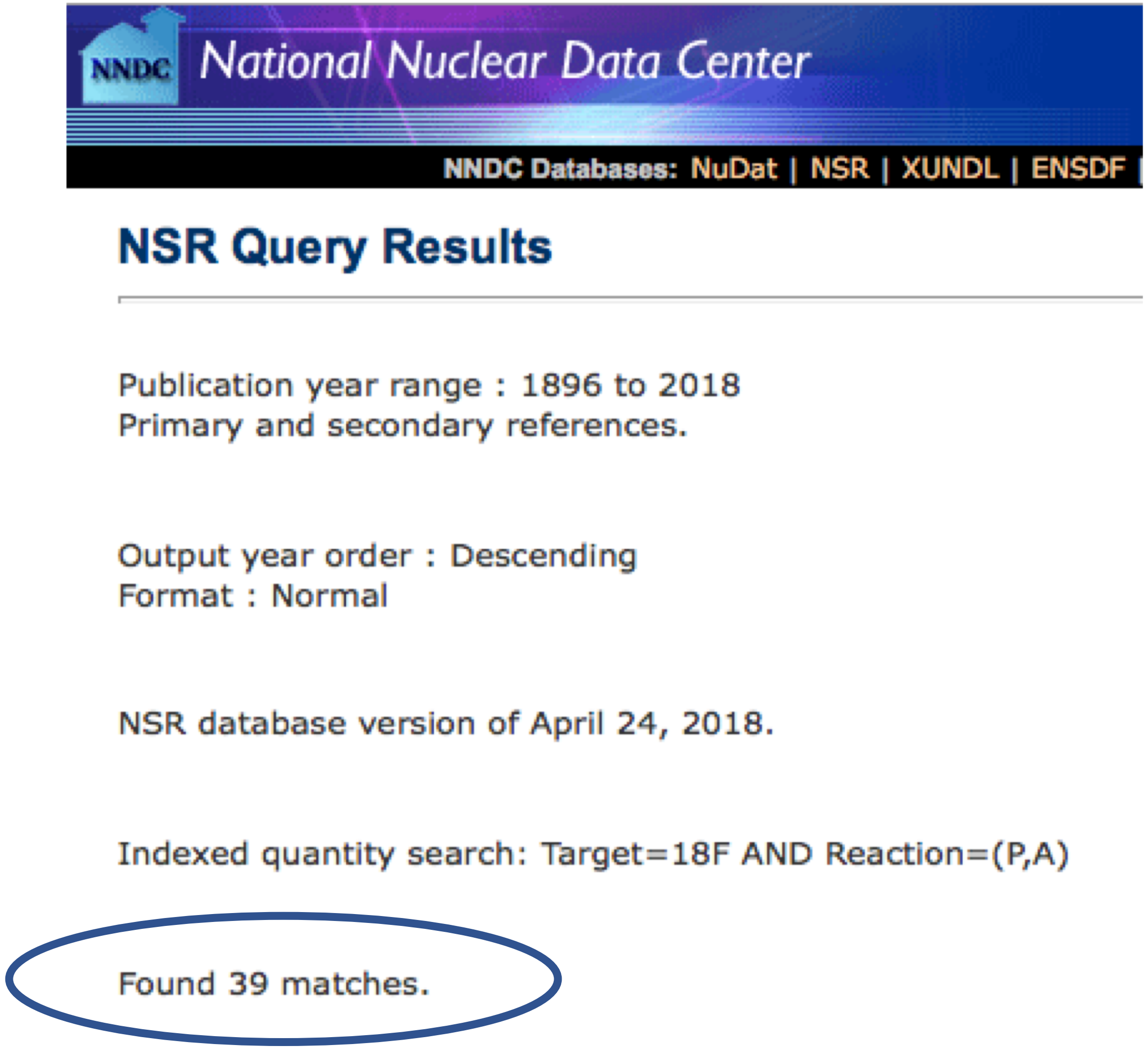
Useful probe of novae "interior"

γ -rays would provide hints on the thermal history of the explosion or the main nuclear reaction path (**if observed!**)



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

Many investigations have been performed, the first one in 1995



Direct measurements

- Using ^{18}F RIBs (~10^6 pps)

Indirect measurements

- Spectroscopic studies to constrain ^{19}Ne resonance parameters (e.g. d,p reactions, p,p scattering)

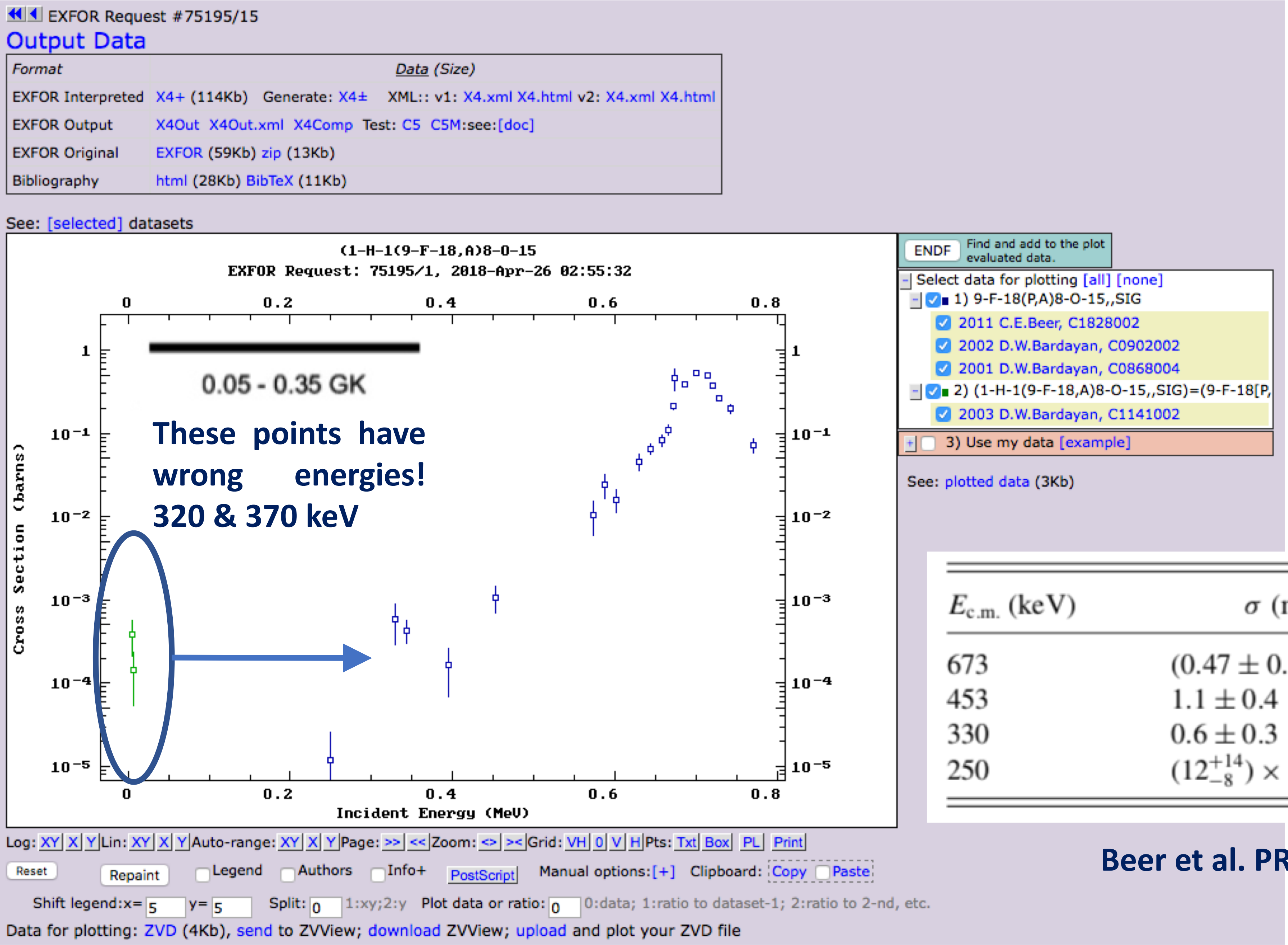
Extrapolations

- Using R-matrix

Theoretical calculations

- Microscopic cluster model

Status of the Art from EXFOR (Direct Measurements)

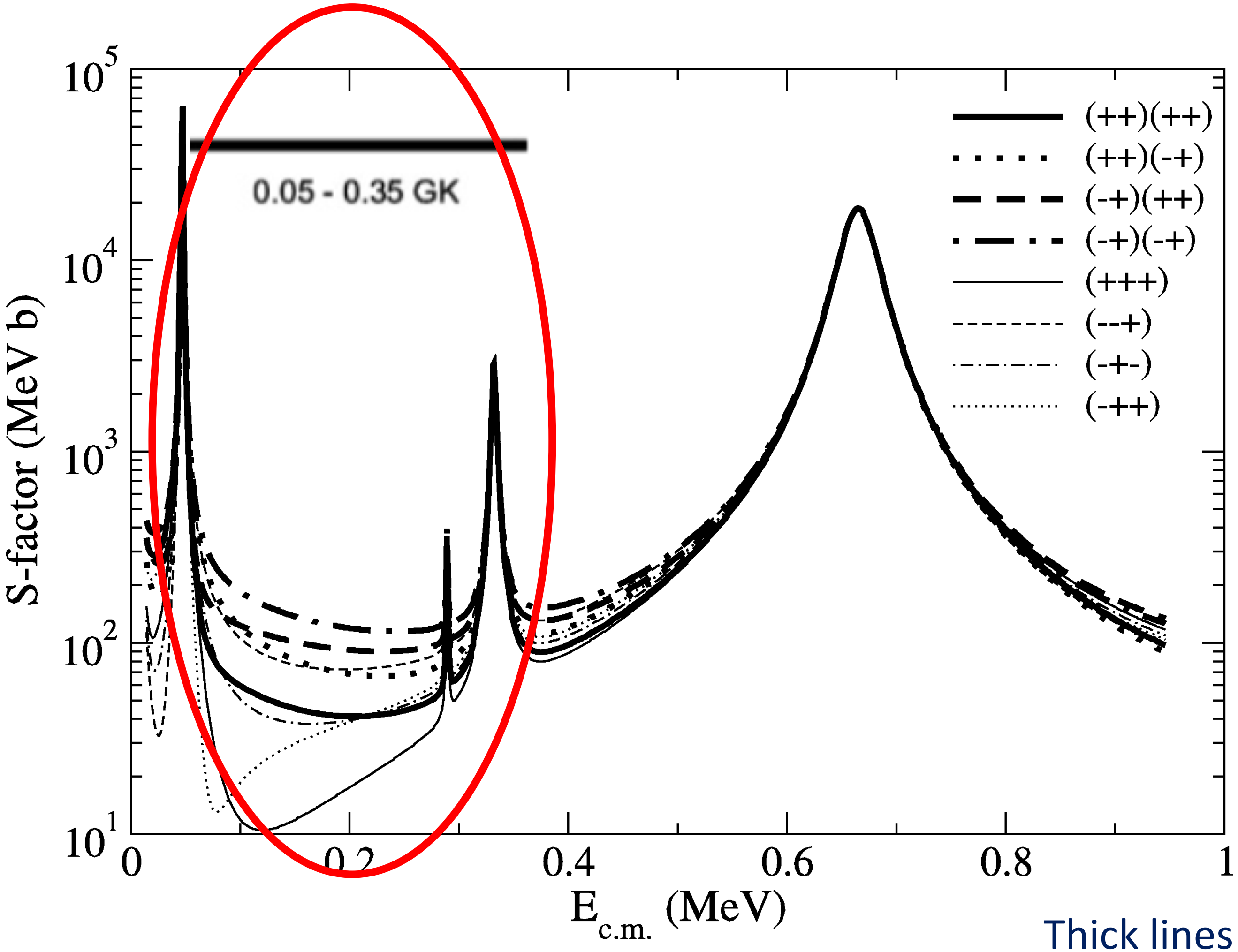


peak temperatures reached in novae: around 0.05–0.35 GK

$E_{c.m.}$ (keV)	σ (mb)	S factor (MeV barn)
673	$(0.47 \pm 0.14) \times 10^3$	$(1.3 \pm 0.4) \times 10^4$
453	1.1 ± 0.4	$(2.0 \pm 0.8) \times 10^2$
330	0.6 ± 0.3	$(8 \pm 4) \times 10^2$
250	$(12^{+14}_{-8}) \times 10^{-3}$	(110^{+120}_{-70})

Beer et al. PRC 83 (2011) 042801

Comprehensive R-Matrix Calculation



E_{res} (keV)	E_x (MeV)	$2J^{\pi}$	Γ_p (keV) or ANC ($\mathrm{fm}^{1/2}$)	Γ_α (keV)
−124(3)	6.286(3)	1^+	83.5	11.6[a]
7(3)	6.417(3)	3^-	1.6×10^{-41}	<0.5[a]
29(3)	6.439(3)	1^-	$<3.8 \times 10^{-19}$[b]	220
47(3)	6.457(3)	3^+[a]	$<2.1 \times 10^{-13}$	1.3[a]
289(3)	6.699(3)	5^+[a]	$<2.4 \times 10^{-5}$[a]	1.2[a]
332(2)	6.742(2)	3^-	2.22×10^{-3}	5.2[a]
664.7(16)	7.0747(17)	3^+	15.2	23.8
1461(19)		1^+	55	347

a

Adopted from mirror level.

b

Based on assumed reduced proton width.

Thick lines show the present values considering interference effects between 1/2+ and 3/2+ resonances.

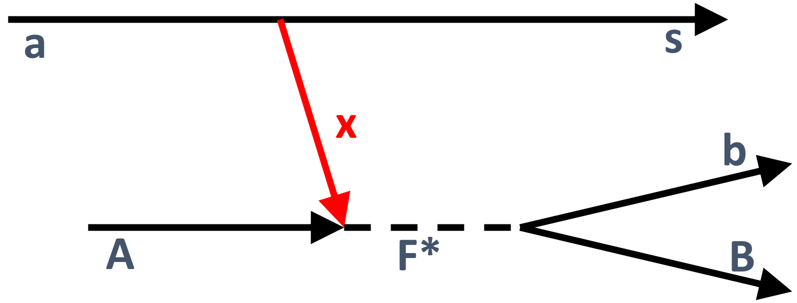
Most recent R-matrix calculation

Thin curves show the now excluded S-factors with a 3/2+ subthreshold resonance and interference between 3 resonances.

Bardayan et al. PLB 751 (2015) 311

THM: Basic Ideas

Is it possible to carry out the measurement of the cross section at astrophysical energies?



The Trojan Horse Method was introduced to investigate reactions at vanishing energies, inside the Gamow window (see Tribble et al. Rep. Prog. Phys. 77 (2014) 106901 for a recent review)

From

A+a(x⊕s) → b+B+s @ 50 MeV

A + x → b + B @ 0-1 MeV

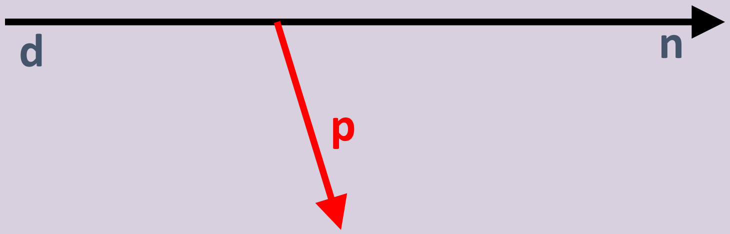
by selecting the QF contribution

Though E_A >> V_{Coul} it is possible to measure at the Gamow peak since:

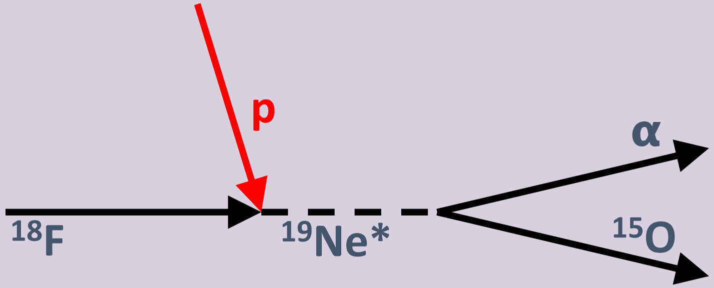
$$E_{c.m.}=E_{A-x}-Q_{x-s}$$

Ingredients:

Direct breakup
of deuteron, dropping a proton inside fluorine nuclear field



Quasifree reaction, Induced by a virtual proton (HOES cross section)



THM for Resonant Reactions

In the latest years, large efforts were made to give a quantitative justification of THM, to estimate the uncertainties and improve the description of the 2→3 cross section

$$\frac{d^3\sigma}{dE_{c.m.}d\Omega_{c.m.}d\Omega_n} \approx \mathrm{KF}\left|\phi(p_n)\right|^2 \frac{d\sigma^{HOES}}{d\Omega_{c.m.}}$$

$$\begin{aligned}
M^{\mathrm{PWA(prior)}}(P,\boldsymbol{k}_{aA}) &= (2\pi)^2\sqrt{\frac{1}{\mu_{bB}k_{bB}}}\varphi_a(\boldsymbol{p}_{sx}) \\
&\times \sum_{J_F M_F j' l l' m_{j'} m_l m_{l'} M_n} i^{l+l'}\langle j m_j l m_l | J_F M_F\rangle\langle j' m_{j'} l' m_{l'} | J_F M_F\rangle \\
&\times \langle J_x M_x J_A M_A | j' m_{j'}\rangle\langle J_s M_s J_x M_x | J_a M_a\rangle\, \mathrm{e}^{-\mathrm{i}\delta^{hs}_{bBl}} Y_{l m_l}(-\hat{\boldsymbol{k}}_{bB}) \\
&\times \sum_{\nu,\tau=1}^{N} [\Gamma_{\nu bBjlJ_F}(E_{bB})]^{1/2}[\boldsymbol{A}^{-1}]_{\nu\tau} Y^{*}_{l' m_{l'}}(\hat{\boldsymbol{p}}_{xA}) \\
&\times \sqrt{\frac{R_{xA}}{\mu_{xA}}}[\Gamma_{\nu xAl'j'J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA},R_{xA})(j_{l'}(p_{xA}R_{xA}) \\
&\times [(B_{xAl'}(k_{xA},R_{xA})-1)-D_{xAl'}(p_{xA},R_{xA})] \\
&+ 2Z_x Z_A e^2 \mu_{xA}\int_{R_{xA}}^{\infty} \mathrm{d}r_{xA}\frac{O_{l'}(k_{xA},r_{xA})}{O_{l'}(k_{xA},R_{xA})} j_{l'}(p_{xA}r_{xA})).
\end{aligned}$$

The THM simple formula can be deduced from the full one in the case of resonant reactions

Same R-matrix term as in OES cross section but for the appearence of the inverse penetration factor, making it possible to observe suppressed resonances at low energies

(Rep. Prog. Phys. 77 (2014) 106901)

With a single beam energy, the excitation function over a broad energy range can be deduced –> very useful for the application to RIBS

THM for Resonant Reactions

Very powerful approach: see our recent Letter on Nature:

Nature volume 557, pages687–690 (2018) Published: 23 May 2018

LETTER

https://doi.org/10.1038/s41586-018-0149-4

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]

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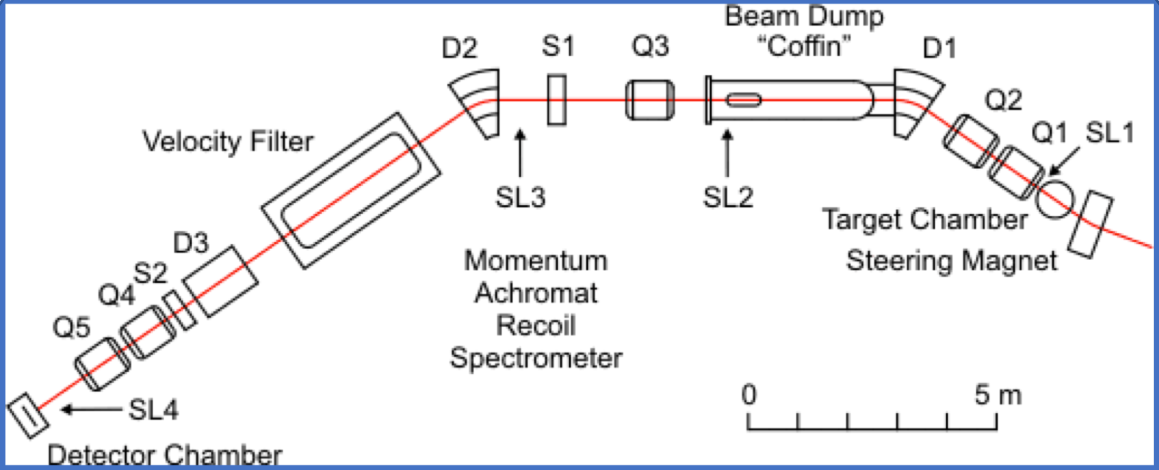
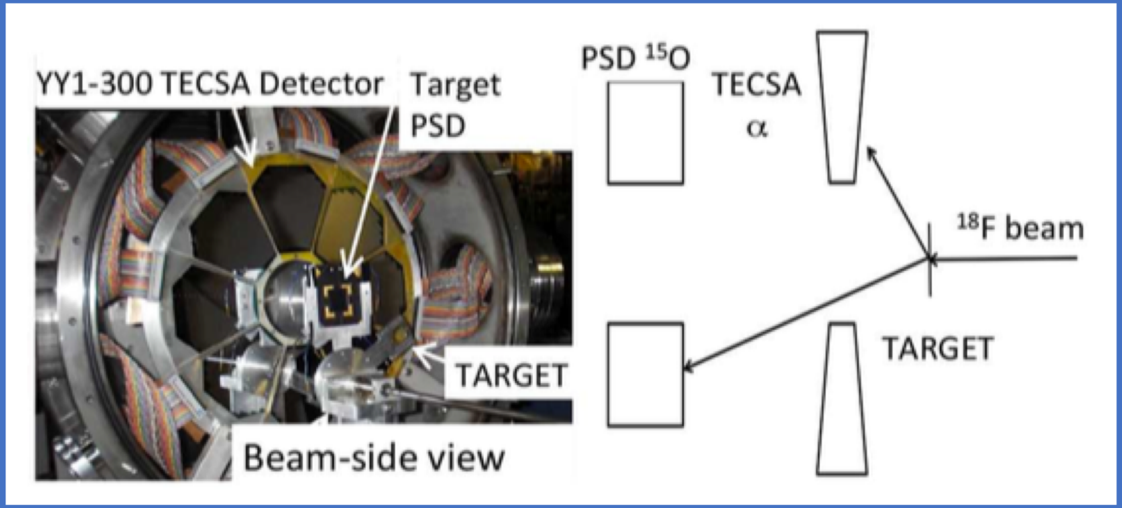
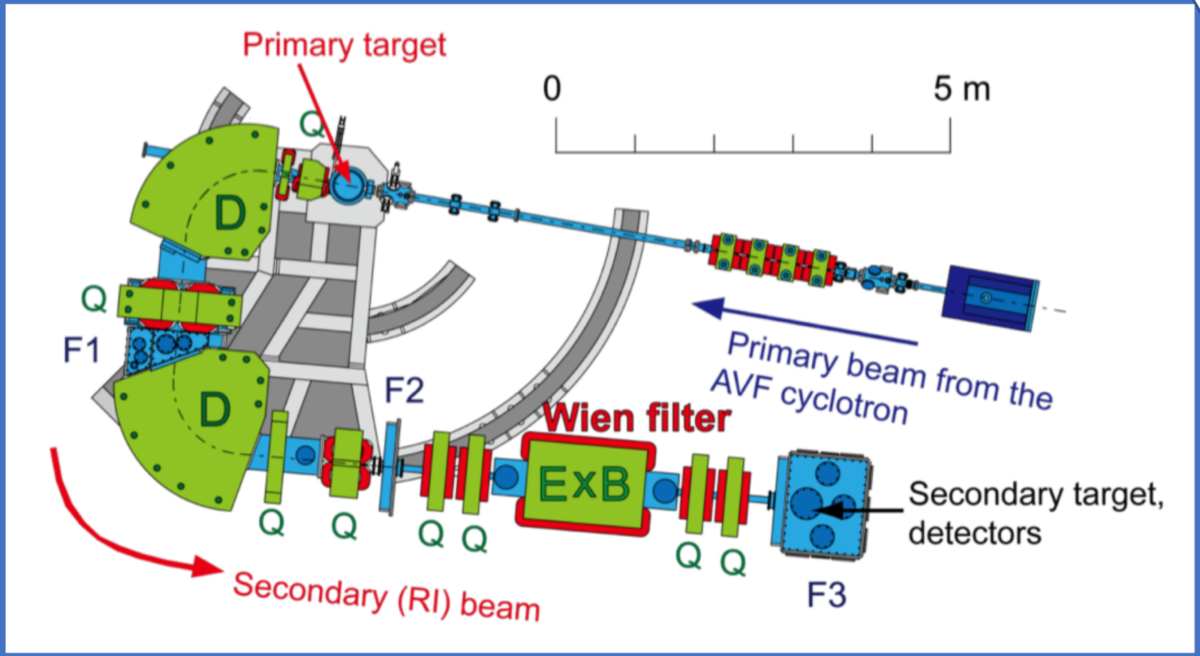
$^{18}F(p,\alpha)^{15}O$ Measurement using THM



MARS Texas A&M (USA)



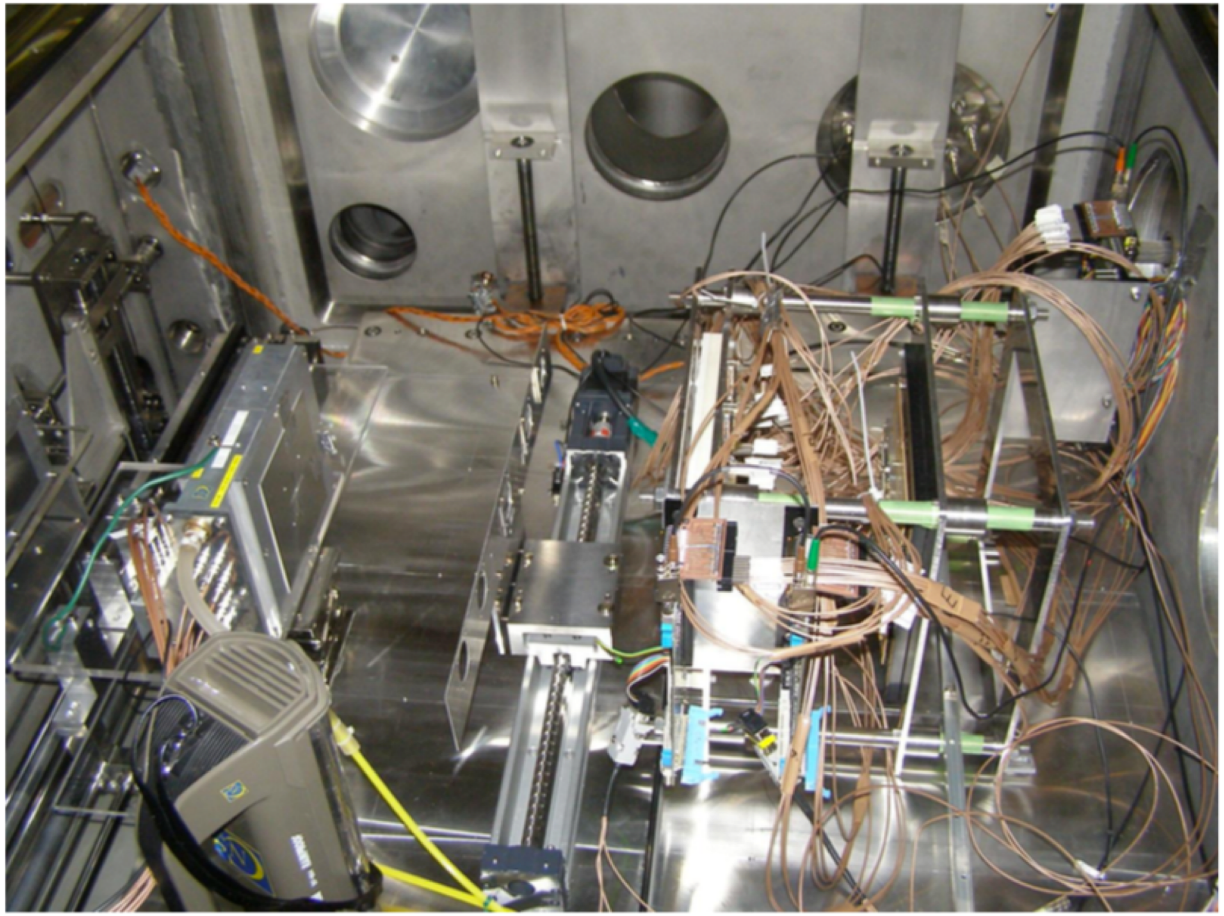
Pizzone et al. EPJ A 52, 24 (2016)



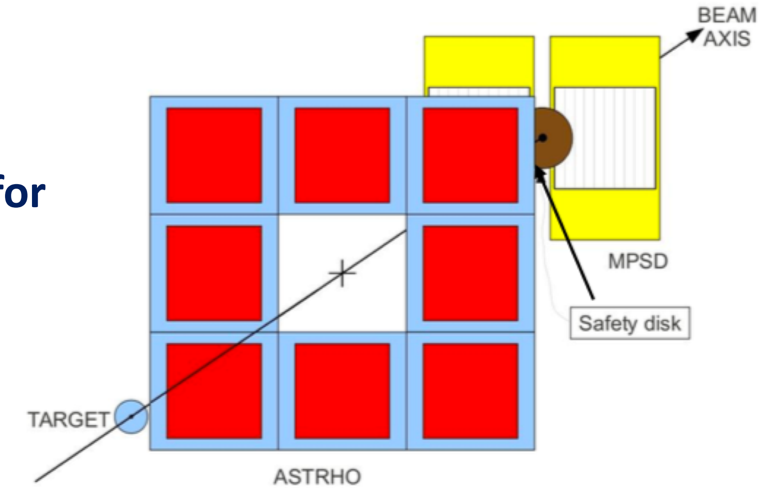
CRIB CNS/RIKEN (Japan)

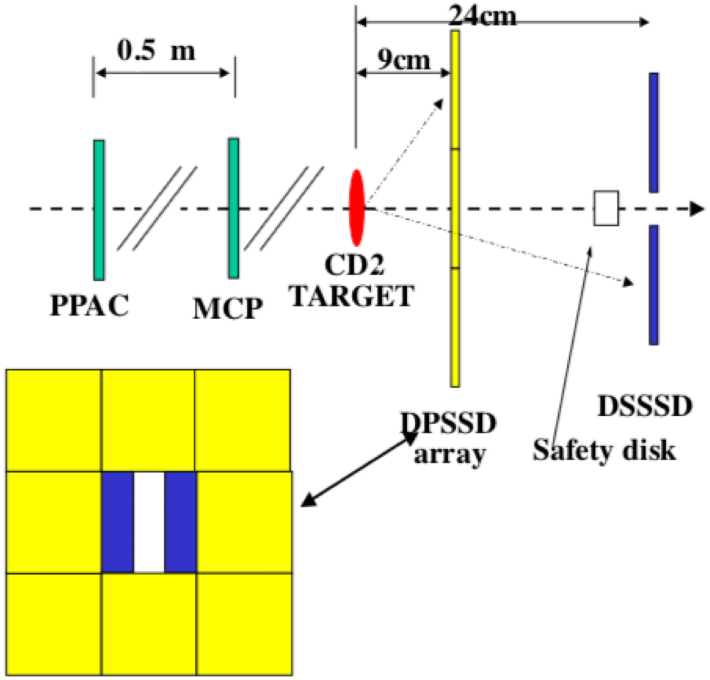
- ❑ 3 10^5 pps obtained
- ❑ Beam purity > 98%
- ❑ Normalization and definition of the beam particle by particle (PPACs)

Experimental Setup @CRIB

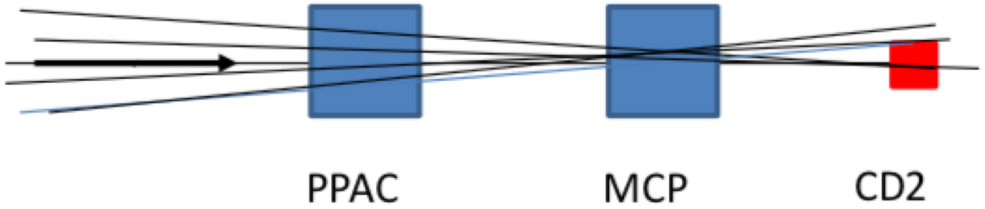


The use of charge-partition PSD allowed for a reduction of the number of electronic channels



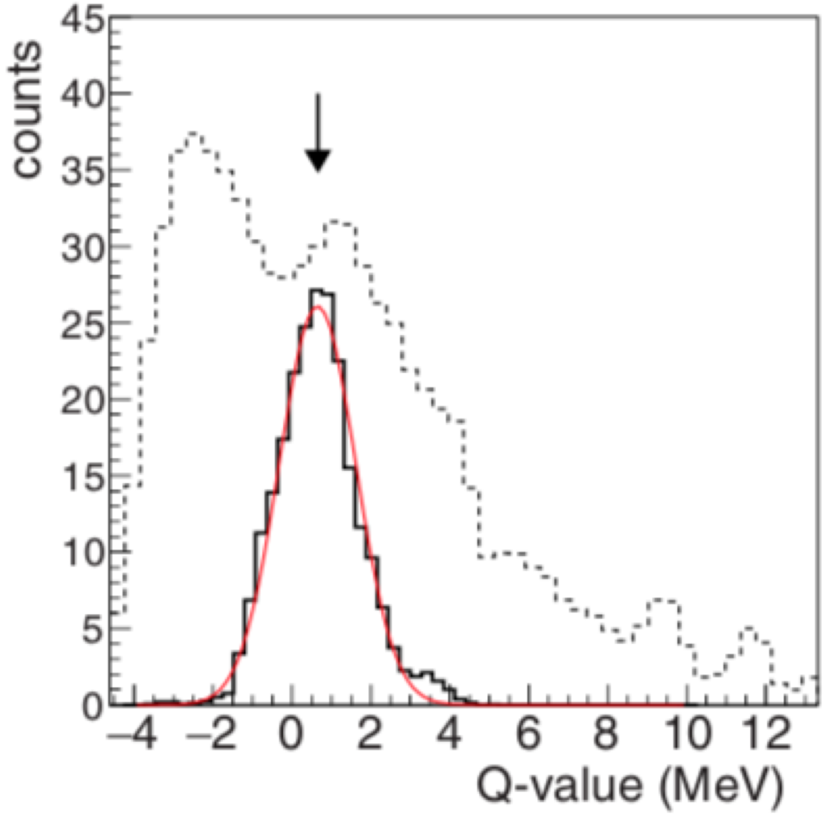


Thanks to ray tracking, better resolution wrt MARS

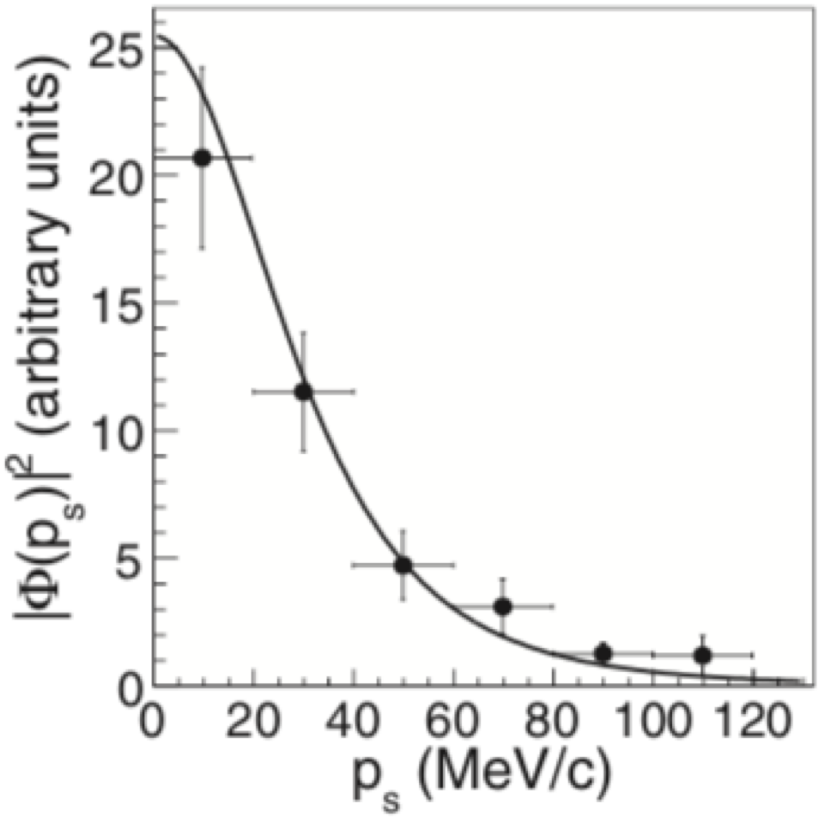


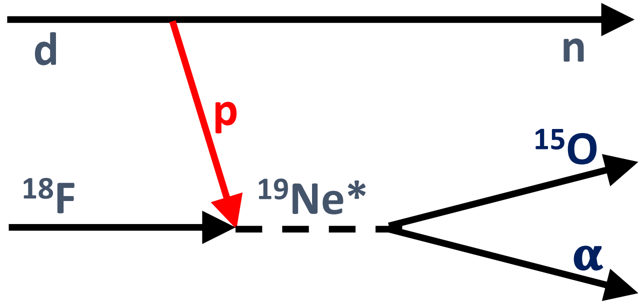
S. Cherubini et al. PRC 92, 015805 (2015)

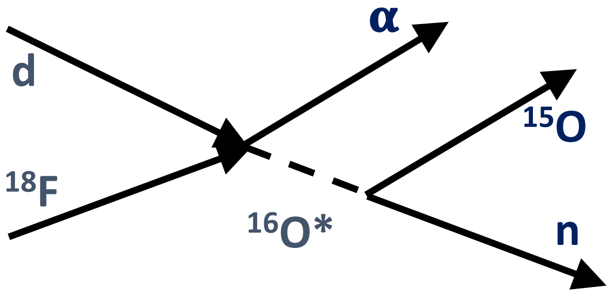
Few Details about the Data Analysis



S. Cherubini et al. PRC 92, 015805 (2015)







Selection of the reaction channel

Detector coincidences, ToF, reaction kinematics (2 vs. 3 body reactions) were used to single out the $^{2}H(^{18}F,\alpha^{15}O)n$ from others

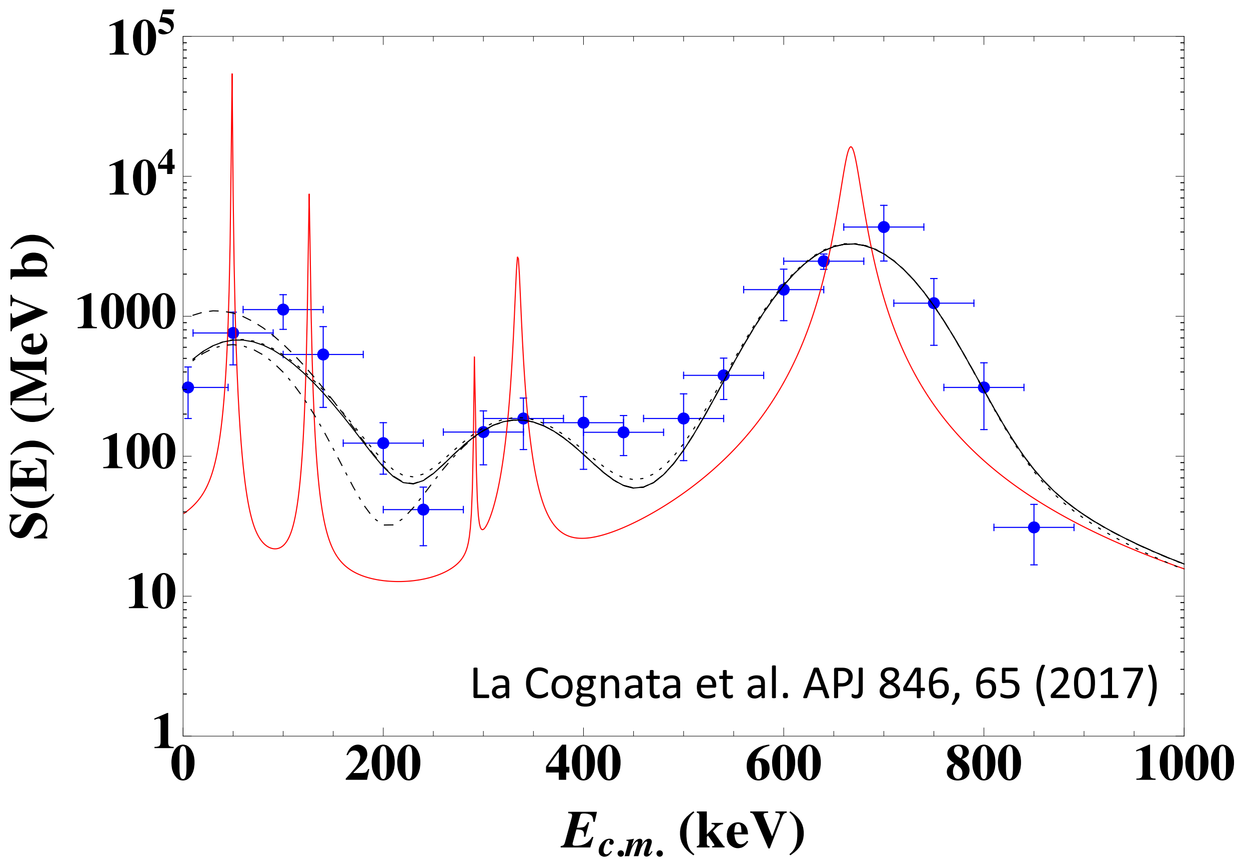
Selection of the reaction mechanism

The same channel can be populated through different reaction mechanisms

In particular: sequential (two-step) reactions

The momentum distribution tells us if THM equations apply

Pinpointing the Contributing Resonances



For the first time, the whole Gamow window for novae nucleosynthesis could be covered

However, energy resolution was 53 keV (sigma)
→ Need to disentangle resonance contribution

R-matrix analysis of the THM astrophysical factor (blue points)

Solid black line: the smoothed R-matrix calculation, accounting for a 53keV energy spread (best fit)

Red line: corresponding deconvoluted astrophysical factor

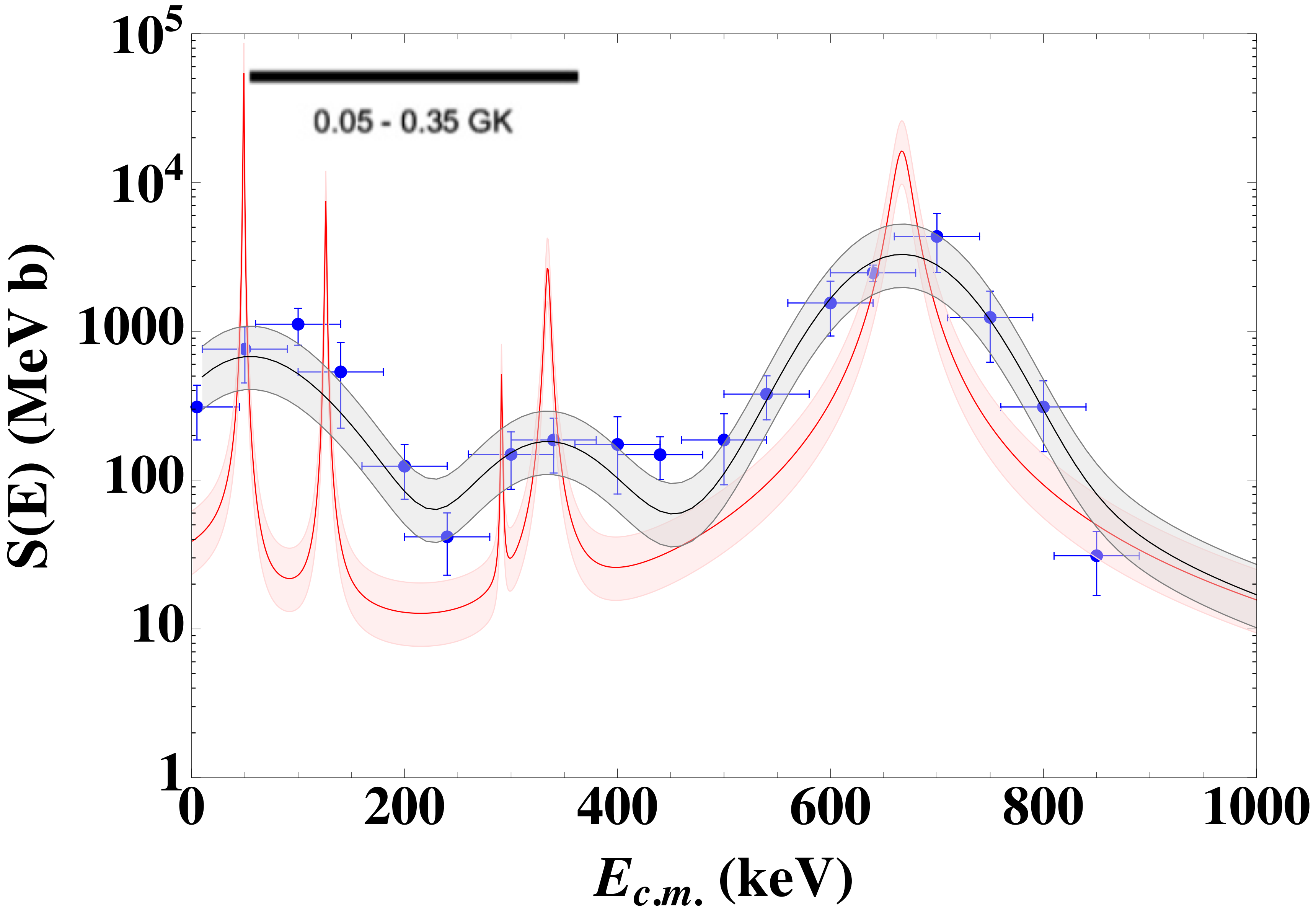
Dashed black line: smoothed R-matrix calculation including the 6417 keV level

Dotted–dashed line: the smoothed R-matrix calculation, where the 6537 keV is excluded

Dotted line: smoothed R-matrix calculation where the interference signs were changed to (++)(−+)

→ No sensitivity to interference, differences accounted for in the final total error

Recommended Astrophysical Factor and Error Propagation



For the first time, the whole Gamow window was experimentally investigated

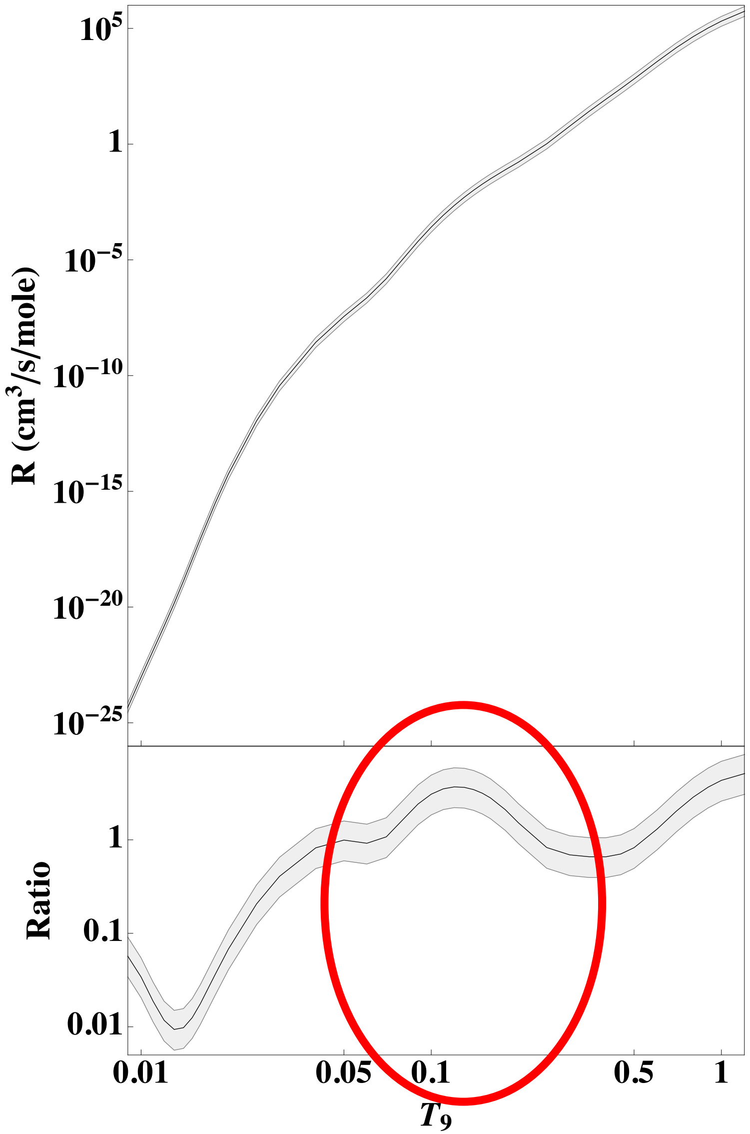
We use R-matrix to deconvolute the S-factor

Total error: ~40%

Dominant contribution is still statistical error

Normalization to the 665 keV peak is also introducing some uncertainty

Reaction Rate



Upper panel: $^{18}F(p, \alpha)^{15}O$ reaction rate calculated using the deconvoluted THM S-factor (red line).

Lower panel: ratio of the THM reaction rate to the one reported in the JINA REACLIB database (https://groups.nscl.msu.edu/jina/reaclib/db/f18(p,a)o15/il10/).

In both plots, the uncertainties of the reaction rate are represented as a shadowed band.

In the temperature region of interest for astrophysics, $0.05 < T9 < 0.35$ ($T9 = T/10^9$ K), an increase in the reaction rate ratio is observed, compatible with the results by Bardayan et al. (2015)

Reaction rate calculation based on experimental data

→ Evaluation of astrophysical consequences using the SHIVA code
(J. Josè, Stellar Explosions: Hydrodynamics and Nucleosynthesis, 2016)

Astrophysical Impact: chemical composition of the ejected matter

	Model A	Model B	Model C	Model D	Model D′	Model E
WD	CO	CO	ONe	ONe	ONe	ONe
M_{wd} ($M_\odot$)	1	1.15	1.15	1.25	1.25	1.35
Reference	This Work	This Work	This Work	This Work	Iliadis et al. (2010)	This Work
^{12}C	4.52E–2	4.76E–2	2.28E–2	2.61E–2	2.61E–2	2.21E–2
^{13}C	1.10E–1	7.87E–2	2.15E–2	2.54E–2	2.55E–2	1.56E–2
^{14}N	1.18E–1	1.33E–1	3.36E–2	4.15E–2	4.15E–2	5.47E–2
^{15}N	9.63E–3	3.66E–2	3.57E–2	5.66E–2	5.66E–2	1.07E–1
^{16}O	2.40E–1	2.23E–1	1.09E–1	6.12E–2	6.11E–2	5.97E–3
^{17}O	4.74E–3	1.15E–2	2.90E–2	3.67E–2	3.68E–2	4.05E–2
^{18}O[a]	3.09E–7	5.67E–7	1.49E–6	2.09E–6	4.59E–6	8.81E–6
^{18}F[a]	7.14E–7	1.29E–6	3.48E–6	4.82E–6	1.03E–5	1.98E–5
^{19}F	2.03E–8	1.86E–8	3.62E–8	1.19E–7	1.40E–7	1.42E–6

No change in the dynamical properties of the explosion is found (e.g., peak temperature attained, amount of mass ejected)

D & D’ are equal but the reaction rate used for the ^{18}F(p,α)^{15}O reaction

Model D shows a factor of 2 lower ^{18}F than model D’ → which reduces previous estimates of the detectability distance of the 511 keV annihilation line by γ-ray satellites by a factor ~ √2

18O and 19F abundances in the ejecta are also smaller in model D wrt D’

Summary

The $^{18}F(p,\alpha)^{15}O$ reaction is one of the most important astrophysical reactions, since it influences ^{18}F yield, used to probe novae nucleosynthesis

- Many studies have been attempted over the past 20 years, reaching the upper tail of the Gamow window

The Trojan Horse Method has been successfully used for reactions involving stable nuclei

- Since S/N → 0 even more dramatically with RIBs, its application turned out to be very successful

First time measurement of the $^{18}F(p,\alpha)^{15}O$ reaction at astrophysical energies

- Possibility to establish the contribution of resonances inside the Gamow window

Evaluation of the astrophysical implications (thanks to J. Josè)

- Lower ^{18}F yield may help to explain the lack of observation of the 511 keV gamma line

Thanks for you attention

Collaboration & Papers

PHYSICAL REVIEW C **92**, 015805 (2015)

First application of the Trojan horse method with a radioactive ion beam: Study of the $^{18}F(p,\alpha)^{15}O$ reaction at astrophysical energies

S. Cherubini,[1,2,*] M. Gulino,[1,3] C. Spitaleri,[1,2] G. G. Rapisarda,[1,2] M. La Cognata,[1] L. Lamia,[2] R. G. Pizzone,[1] S. Romano,[1,2] S. Kubono,[4,5] H. Yamaguchi,[5] S. Hayakawa,[1,5] Y. Wakabayashi,[5] N. Iwasa,[6] S. Kato,[7] T. Komatsubara,[8] T. Teranishi,[9] A. Coc,[10] N. de Séréville,[11] F. Hammache,[11] G. Kiss,[12] S. Bishop,[4,13] and D. N. Binh[5,14]

Eur. Phys. J. A (2016) **52**: 24
DOI 10.1140/epja/i2016-16024-3

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Trojan Horse measurement of the $^{18}F(p,\alpha)^{15}O$ astrophysical S(E)-factor

R.G. Pizzone[1,2,a], B.T. Roeder[1], M. McCleskey[1], L. Trache[1,3], R.E. Tribble[1,4], C. Spitaleri[2,5], C.A. Bertulani[6], S. Cherubini[2,4], M. Gulino[2,7], I. Indelicato[2,5], M. La Cognata[2], L. Lamia[5], G.G. Rapisarda[2,5], and R. Spartá[2,5]

THE ASTROPHYSICAL JOURNAL, 846:65 (6pp), 2017 September 1
https://doi.org/10.3847/1538-4357/aa845f

CrossMark

A Trojan Horse Approach to the Production of ^{18}F in Novae

M. La Cognata[1], R. G. Pizzone[1], J. José[2,3], M. Hernanz[3,4], S. Cherubini[1,5], M. Gulino[1,6], G. G. Rapisarda[1,5], and C. Spitaleri[1,5]