IV International Conference on Nuclear Structure and Dynamics - NSD2019

May 13-17, 2019 Centro Culturale Don Orione Artigianelli, Venice (Italy)

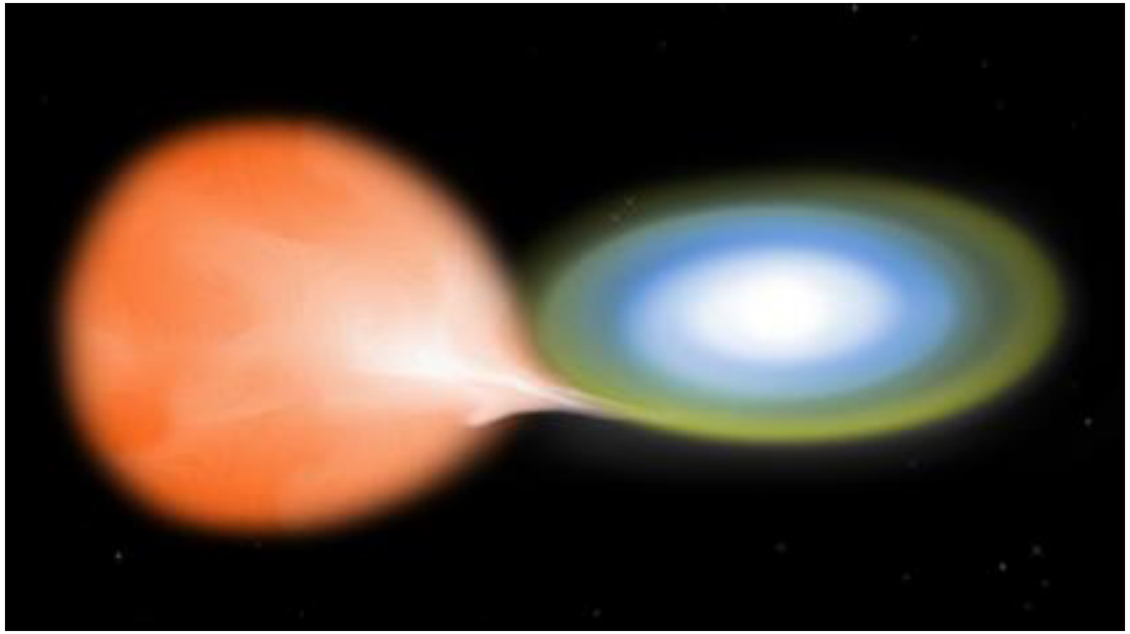
A POSSIBLE NUCLEAR SOLUTION TO THE ^{18}F DEFICIENCY IN NOVAE

Marco La Cognata

INFN

Istituto Nazionale di Fisica Nucleare

^{18}F in Astrophysics: Classical Novae

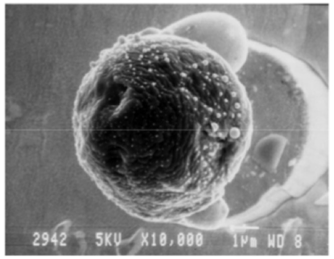


Classical novae are stellar explosions that occur in close binary systems.

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

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

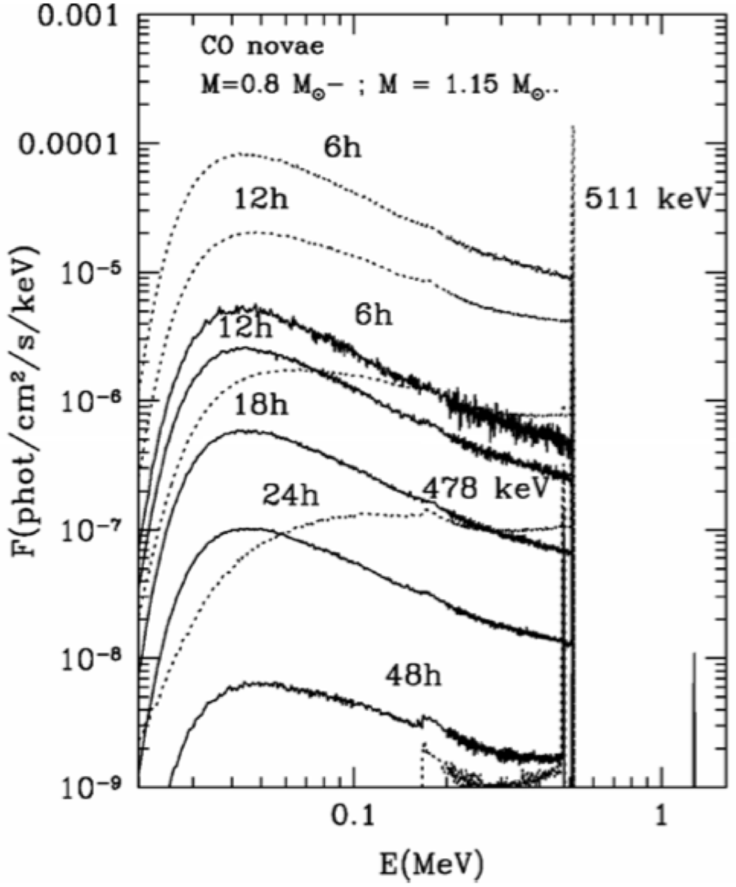
~~$^{18}F(p,\gamma)^{19}Ne$~~

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

National Nuclear Data Center

NNDC Databases: NuDat | NSR | XUNDL | ENSDF

NSR Query Results

Publication year range : 1896 to 2018
Primary and secondary references.

Output year order : Descending
Format : Normal

NSR database version of April 24, 2018.

Indexed quantity search: Target=18F AND Reaction=(P,A)

Found 39 matches.

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

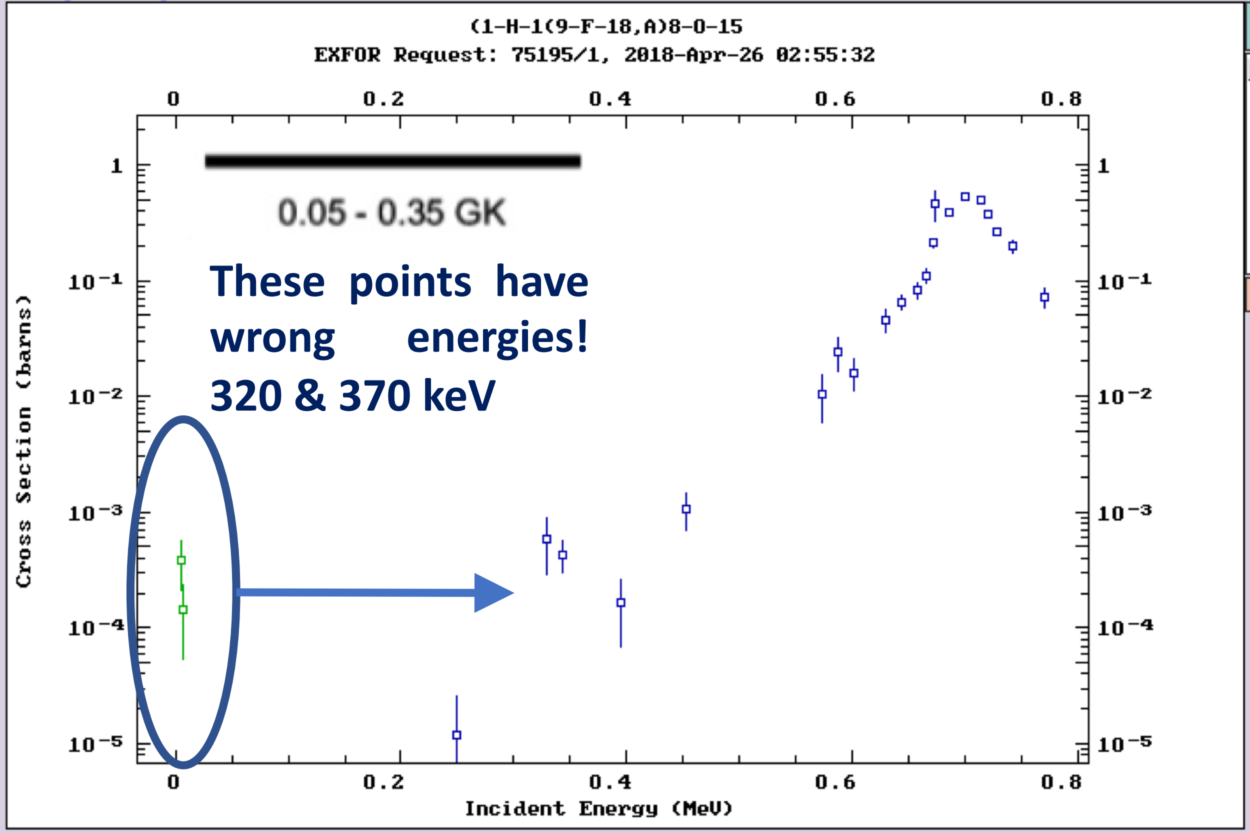
Status of the Art from EXFOR (Direct Measurements)

EXFOR Request #75195/15

Output Data

Format	Data (Size)
EXFOR Interpreted	X4+ (114Kb) Generate: X4± XML:: v1: X4.xml X4.html v2: X4.xml X4.html
EXFOR Output	X4Out X4Out.xml X4Comp Test: C5 C5M:see:[doc]
EXFOR Original	EXFOR (59Kb) zip (13Kb)
Bibliography	html (28Kb) BibTeX (11Kb)

See: [selected] datasets



ENDF Find and add to the plot evaluated data.

Select data for plotting [all] [none]
- 1) 9-F-18(P,A)8-O-15,,SIG
  - 2011 C.E.Beer, C1828002
  - 2002 D.W.Bardayan, C0902002
  - 2001 D.W.Bardayan, C0868004
- 2) (1-H-1(9-F-18,A)8-O-15,,SIG)=(9-F-18[P,
  - 2003 D.W.Bardayan, C1141002
- 3) Use my data [example]

See: plotted data (3Kb)

Log: XY X Y Lin: XY X Y Auto-range: XY X Y Page: >> << Zoom: <> >< Grid: VH 0 V H Pts: Txt Box PL Print

Reset Repaint Legend Authors Info+ PostScript Manual options: [+] Clipboard: Copy Paste

Shift legend: x= 5 y= 5 Split: 0 1:xy;2:y Plot data or ratio: 0 0:data; 1:ratio to dataset-1; 2:ratio to 2-nd, etc.

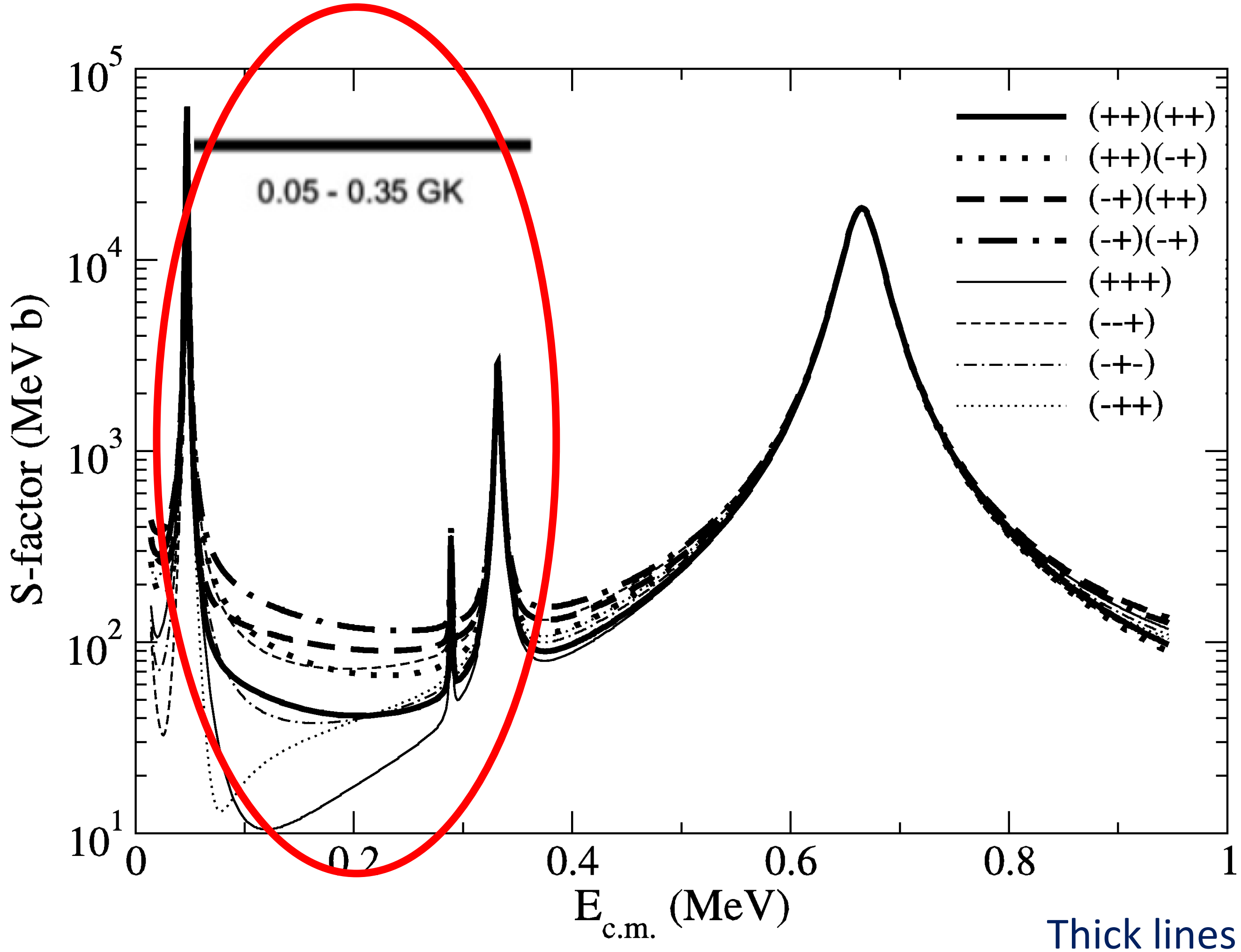
Data for plotting: ZVD (4Kb), send to ZVView; download ZVView; upload and plot your ZVD file

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 ($fm^{1/2}$)	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.

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

R-matrix calculation in

Bardayan et al. PLB 751 (2015) 311

Latest (indirect) measurement 1

Eur. Phys. J. A (2019) **55**: 4
DOI 10.1140/epja/i2019-12682-9

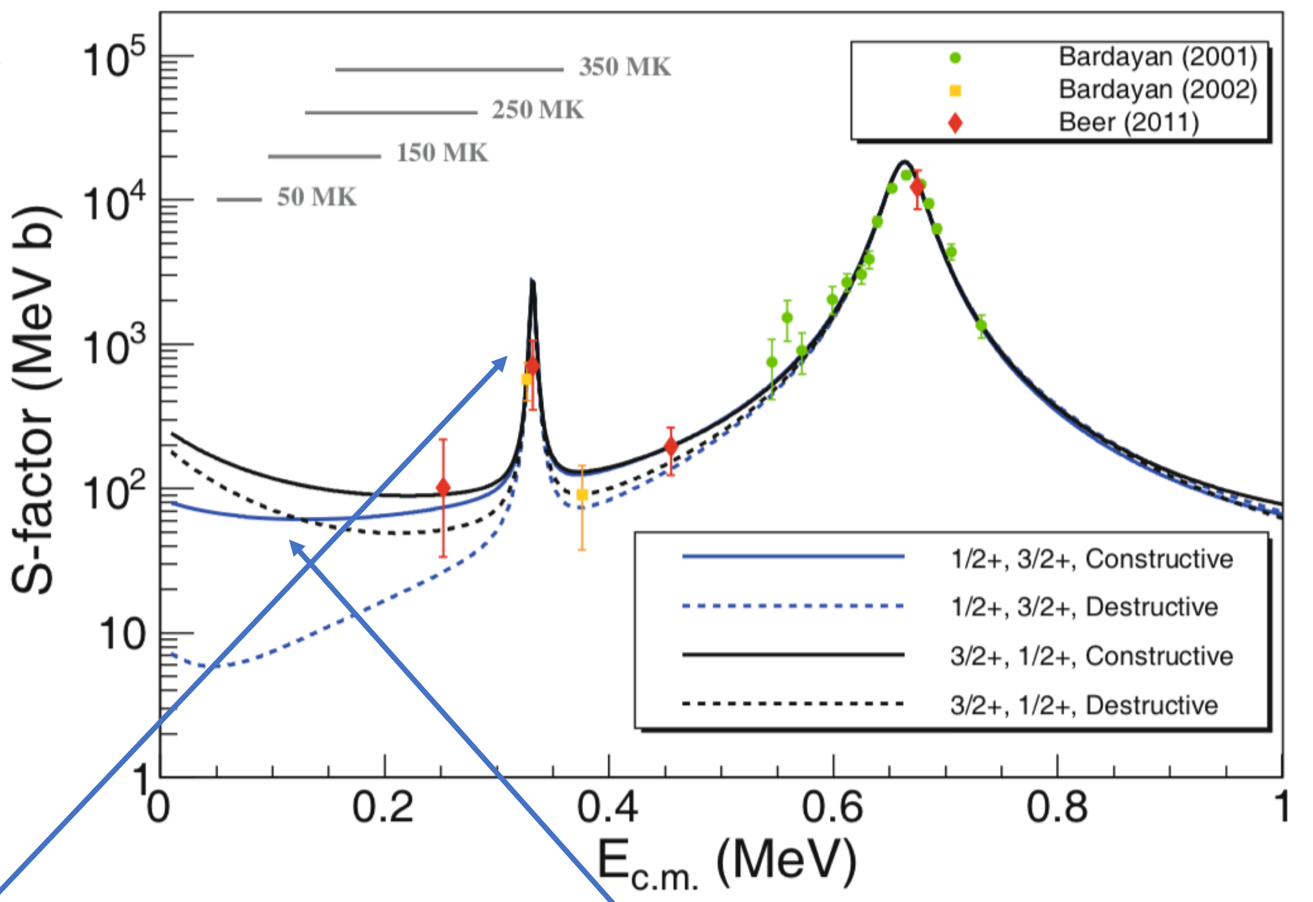
THE EUROPEAN PHYSICAL JOURNAL A

Letter

s-wave resonances for the $^{18}F(p,\alpha)^{15}O$ reaction in novae

D. Kahl[1,a], P.J. Woods[1], Y. Fujita[2,3], H. Fujita[2,3], K. Abe[4], T. Adachi[2], D. Frekers[5], T. Ito[4], N. Kikukawa[4], M. Nagashima[4], P. Puppe[5], D. Sera[4], T. Shima[2], Y. Shimbara[4], A. Tamii[2], and J.H. Thies[5]

[1] School of Physics & Astronomy, University of Edinburgh, Edinburgh EH9 3FD, UK
[2] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[3] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[4] Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata 950-2181, Japan
[5] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany



Study of the $^{19}F(^{3}He,t)^{19}Ne$ reaction at intermediate energies and forward angles.

→ simple, model-independent, mechanism to identify states near the proton threshold energy in 19Ne corresponding to ΔL = 0 transitions.

→ ΔL = 0 state at 6.13MeV which could significantly affect the 18F(p,α) astrophysical S-factor at nova burning temperatures.

Drawbacks: discrepancy with existing direct data (energy resolution???)

incomplete information on the S-factor

Latest (indirect) measurement 2

PHYSICAL REVIEW LETTERS **122**, 052701 (2019)

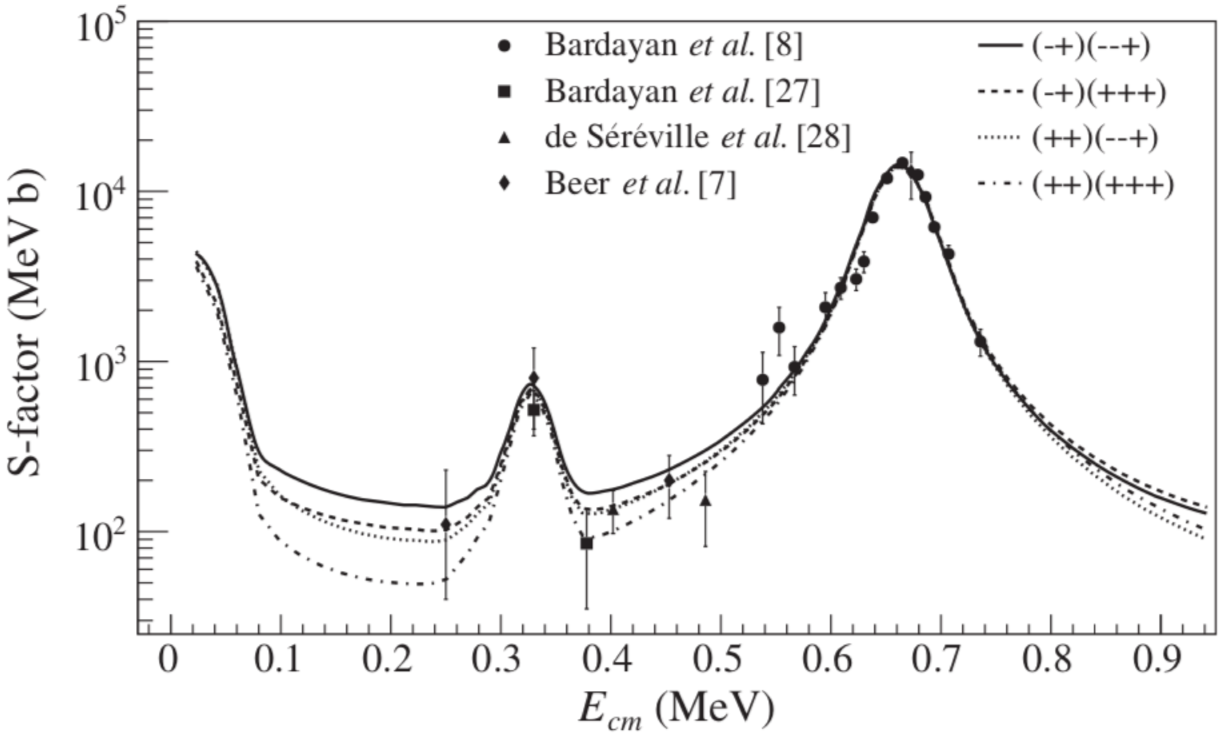
Key ^{19}Ne States Identified Affecting γ-Ray Emission from ^{18}F in Novae

M. R. Hall,[1,*] D. W. Bardayan,[1] T. Baugher,[2] A. Lepailleur,[2] S. D. Pain,[3] A. Ratkiewicz,[2] S. Ahn,[4] J. M. Allen,[1] J. T. Anderson,[5] A. D. Ayangeakaa,[5] J. C. Blackmon,[6] S. Burcher,[7] M. P. Carpenter,[5] S. M. Cha,[8] K. Y. Chae,[8] K. A. Chipps,[3] J. A. Cizewski,[2] M. Febbraro,[3] O. Hall,[1,9] J. Hu,[1] C. L. Jiang,[5] K. L. Jones,[7] E. J. Lee,[8] P. D. O'Malley, S. Ota,[10] B. C. Rasco,[6] D. Santiago-Gonzalez,[6] D. Seweryniak,[5] H. Sims,[2,9] K. Smith,[7] W. P. Tan,[1] P. Thompson,[3,7] C. Thornsberry,[7] R. L. Varner,[3] D. Walter,[2] G. L. Wilson,[6,11] and S. Zhu[5]

First measurement of the ^{19}F(3He,tγ)^{19}Ne reaction, in which the placement of two long-sought 3/2+ levels is suggested via triton-γ-γ coincidences.

Based on mirror symmetry, there should be two near-threshold 3/2+ states in ^{19}Ne, corresponding to the 6497- and 6527-keV states in ^{19}F

The cross section exhibits interference between these states and the broad 3/2+ resonance at E_{cm}=665 keV. This interference is a dominant source of uncertainty in the reaction rate!



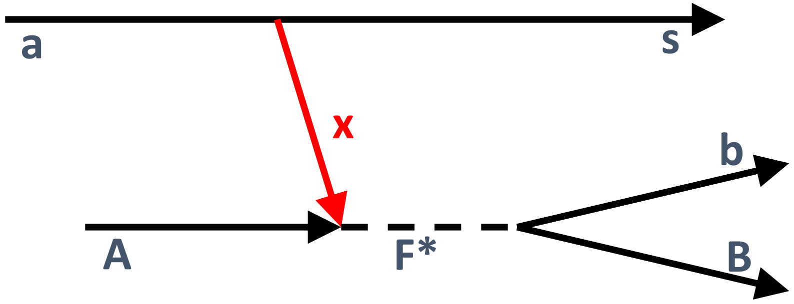
E_x (keV)	E_r (keV)	J^π	Γ_p (keV)	Γ_α (keV)
6286(3) [a]	−124	$1/2^+$	83.5 [c]	11.6
6416(4) [b]	6	$3/2^-$	4.7×10^{-50}	0.5
6423(3)	13	$3/2^+$	$\leq 3.9 \times 10^{-29}$	1.2
6439(3) [a]	29	$1/2^-$	$\leq 3.8 \times 10^{-19}$	220
6441(3)	31	$3/2^+$	$\leq 8.4 \times 10^{-18}$	1.3
6459(5) [b]	49	$5/2^-$	8.4×10^{-14}	5.5
6699(3) [a]	289	$5/2^+$	2.4×10^{-5}	1.2
6742(2) [a]	332	$3/2^-$	2.22×10^{-3}	5.2
7075(2) [a]	665	$3/2^+$	15.2	23.8
7871(19) [a]	1461	$1/2^+$	55	347

6416 from Laird et al./spectroscopic factor

Only upper limits!

THM: Basic Ideas

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



From

A+a(x⊕s) → b+B+s @ 50 MeV

A + x → b + B @ 0-1 MeV

by selecting the QF contribution

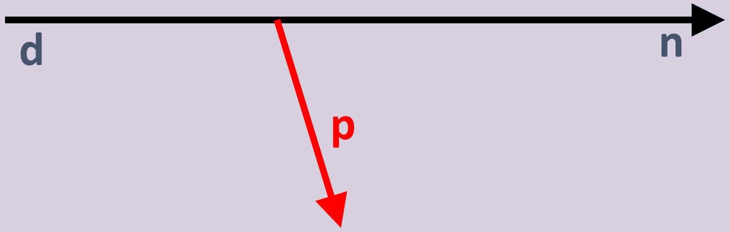
Though E_A >> V_{Coul} it is possible to measure at the Gamow peak since:

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

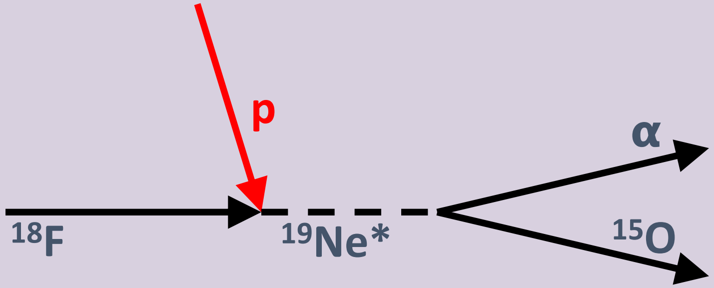
The Trojan Horse Method was introduced to investigate reactions at vanishing energies, inside the Gamow window (see Tribble et al. Rep. Prog. Phys. 77 (2014) 106901 for a recent review)

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]

[1]Facoltá di Ingegneria e Architettura, Universitá degli Studi di Enna "Kore", Enna, Italy. [2]INFN, Laboratori Nazionali del Sud, Catania, Italy. [3]Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Catania, Italy. [4]Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, Bucharest-Magurele, Romania. [5]Center for Nuclear Studies, The University of Tokyo, Tokyo, Japan. *e-mail: tumino@lns.infn.it

NATURE | www.nature.com/nature

THM for Resonant Reactions

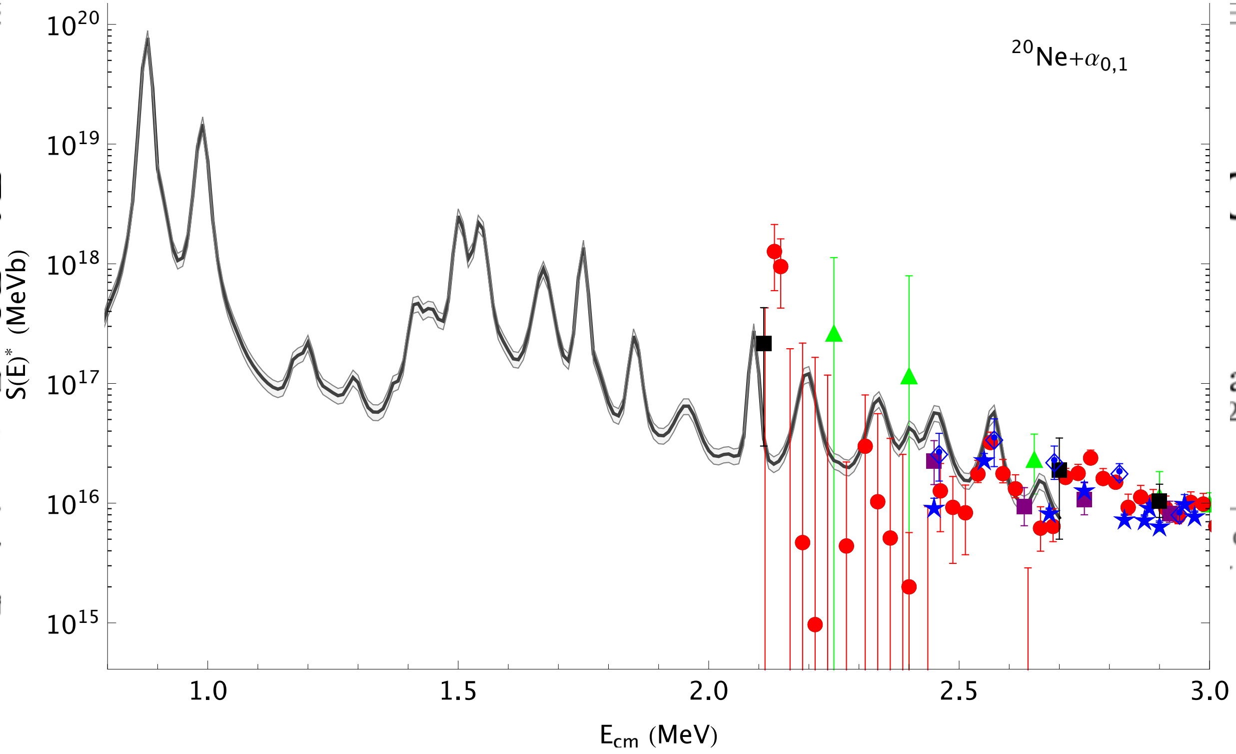
Very powerful approach: see our recent Letter on Nature:

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

LET

Great independent PRELIMINARY confirmation from direct measurement by the STELLA collaboration

41586-018-0149-4



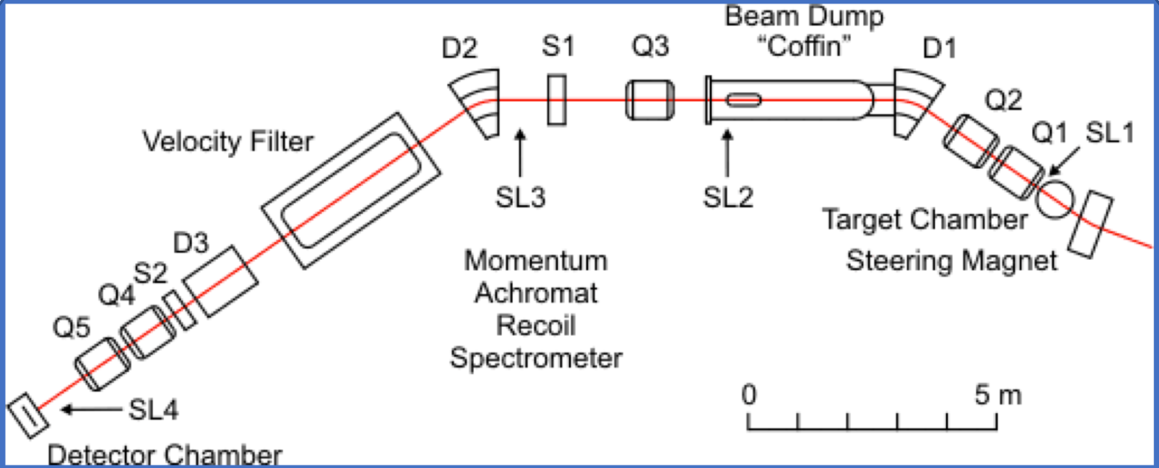
An increa... ...om resonance...

A. Tumino[1,2]*, C. Spitale... ...awa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4] ... [2], R. Spartá[2] & L. Trache[4]

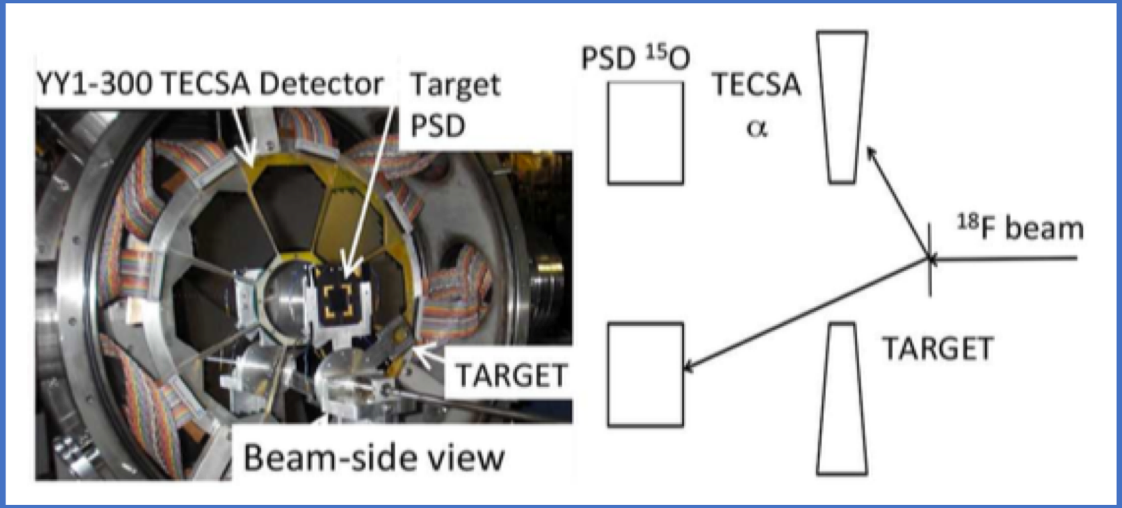
[1]Facoltá di Ingegneria e Architettura, U... ...di Fisica e Astronomia, Università degli Studi di Catania, Catania, Italy. [4]Horia ... Nuclear Studies, The University of Tokyo, Tokyo, Japan. *e-mail: tumino@lns.inf...

NATURE | www.nature.com/nature

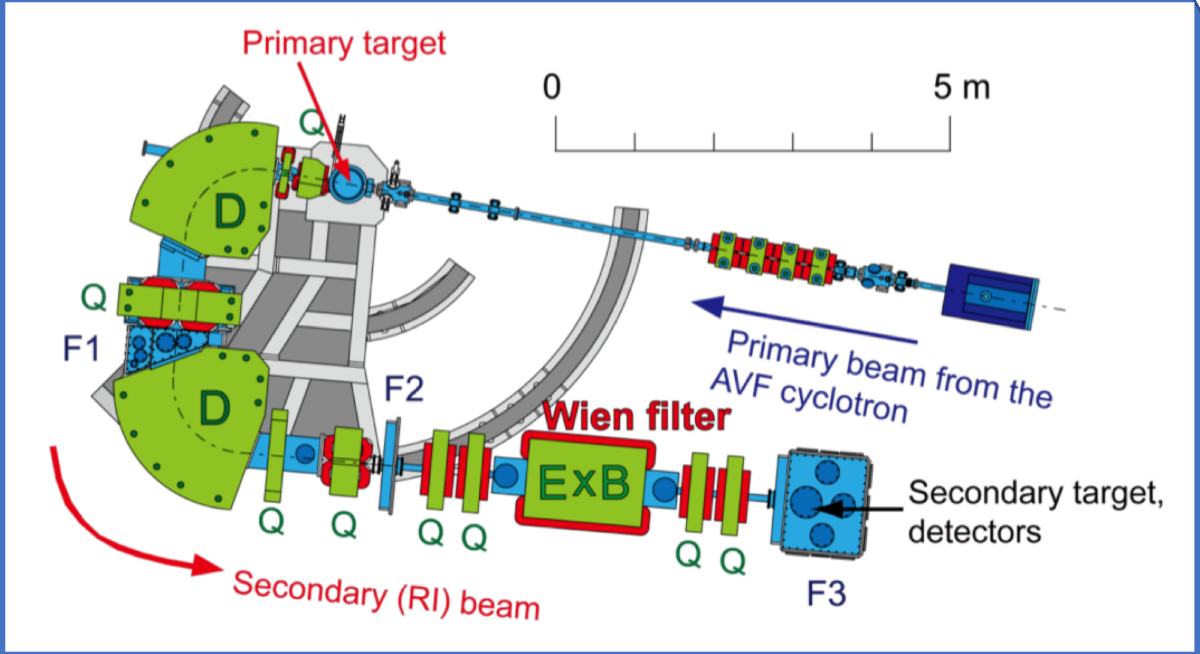
$^{18}F(p,\alpha)^{15}O$ Measurement using THM



MARS Texas A&M (USA)



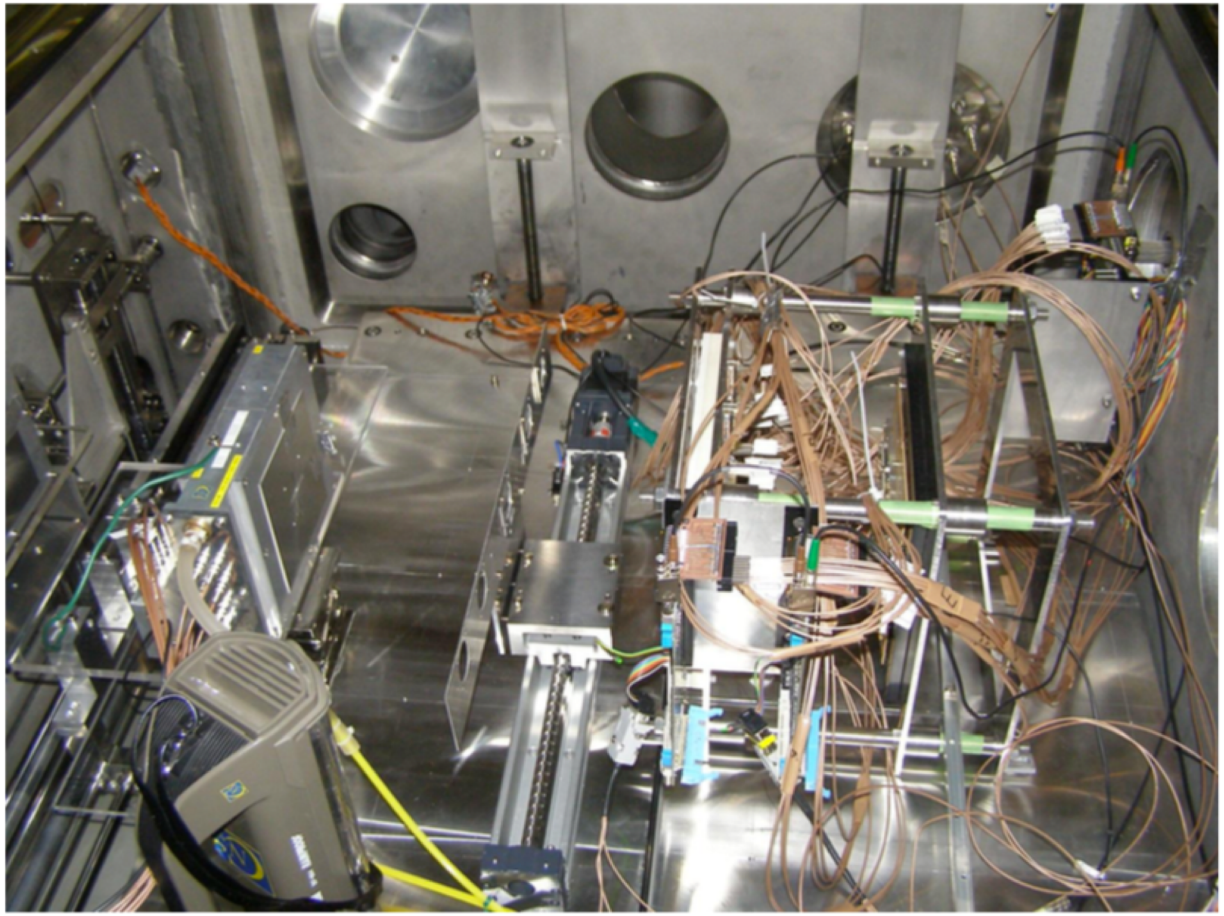
Pizzone et al. EPJ A 52, 24 (2016)



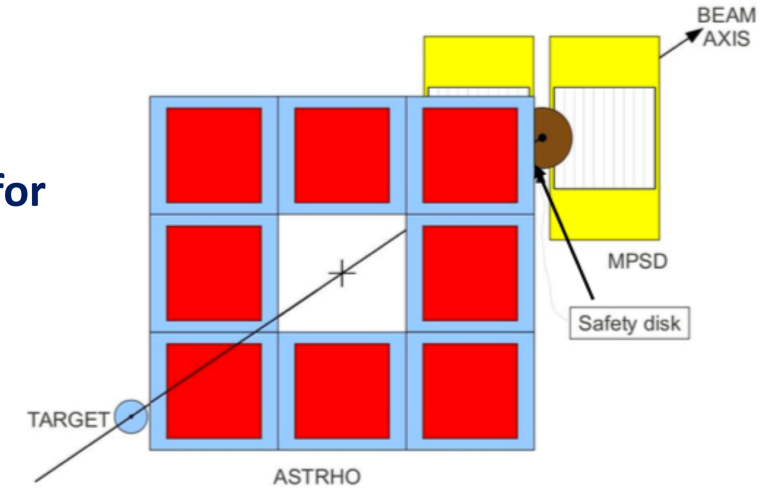
CRIB CNS/RIKEN (Japan)

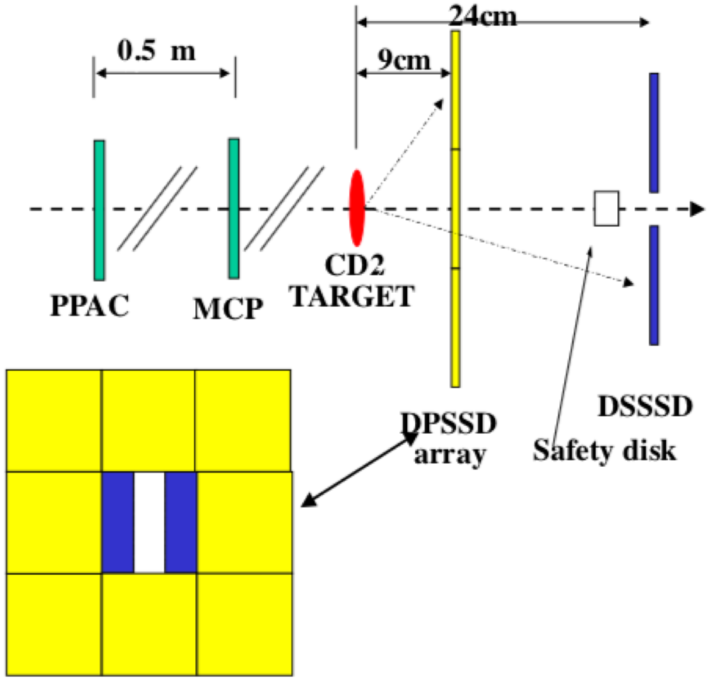
- ❑ $3\ 10^5$ pps obtained
- ❑ Beam purity > 98%
- ❑ Normalization and definition of the beam particle by particle (PPACs)

Experimental Setup @CRIB

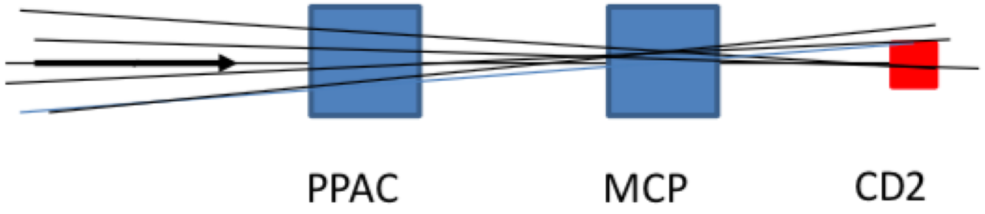


The use of charge-partition PSD allowed for a reduction of the number of electronic channels



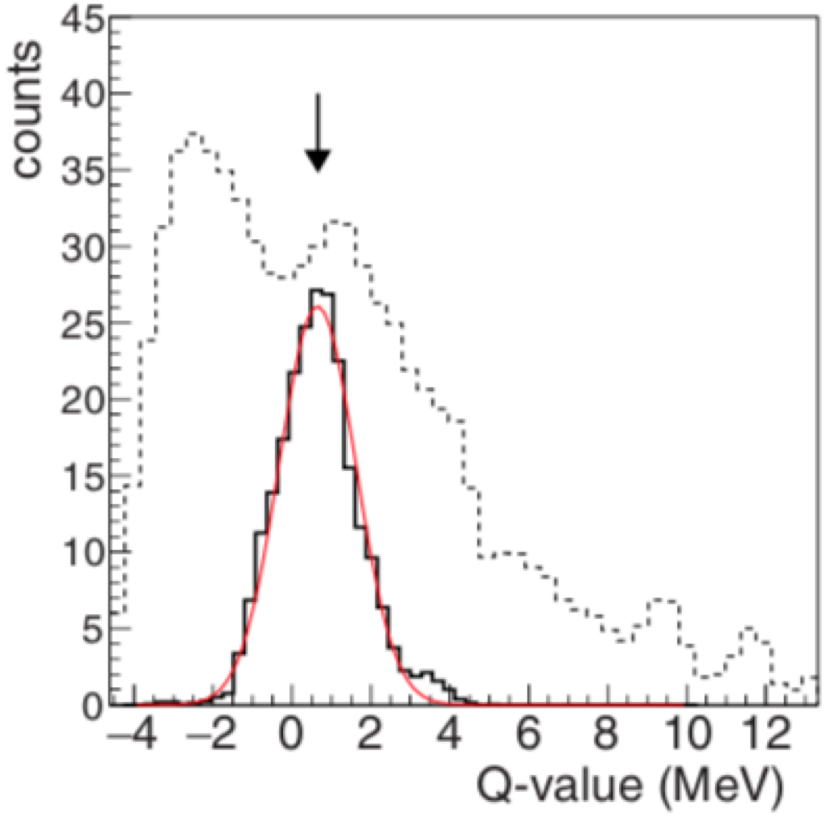


Thanks to ray tracking, better resolution wrt MARS

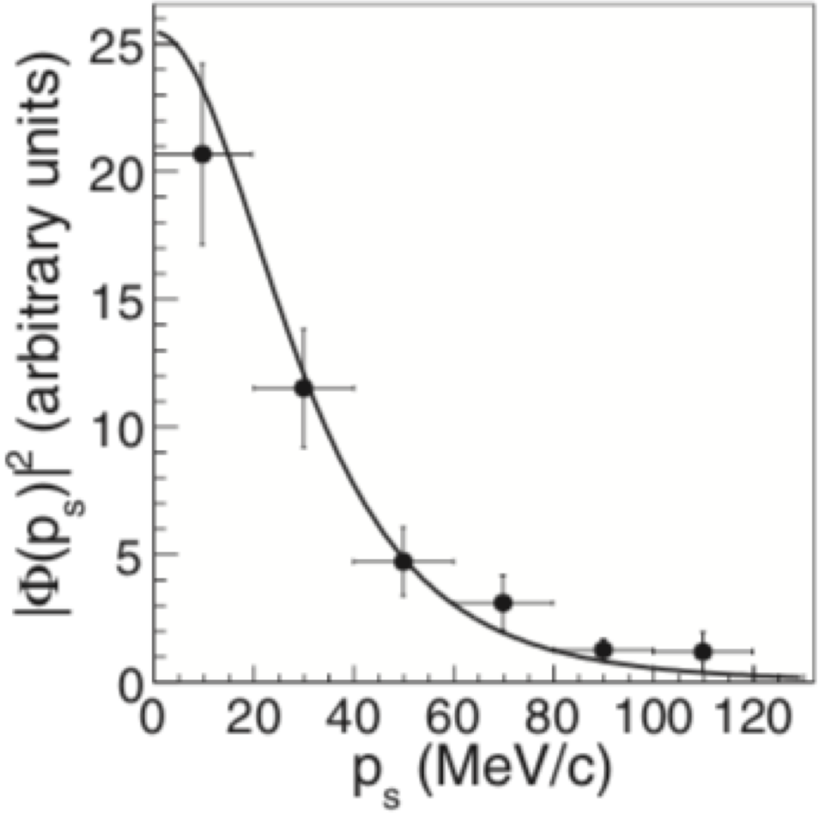


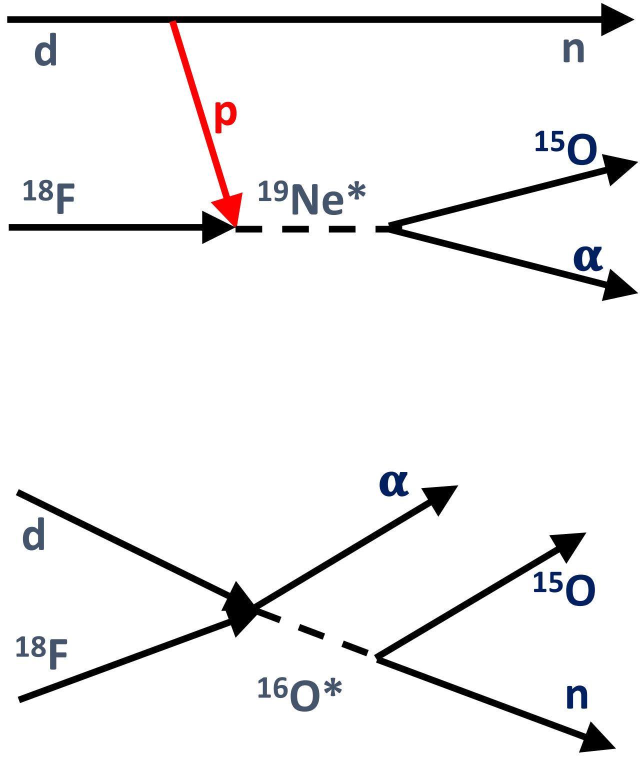
S. Cherubini et al. PRC 92, 015805 (2015)

Few Details about the Data Analysis



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





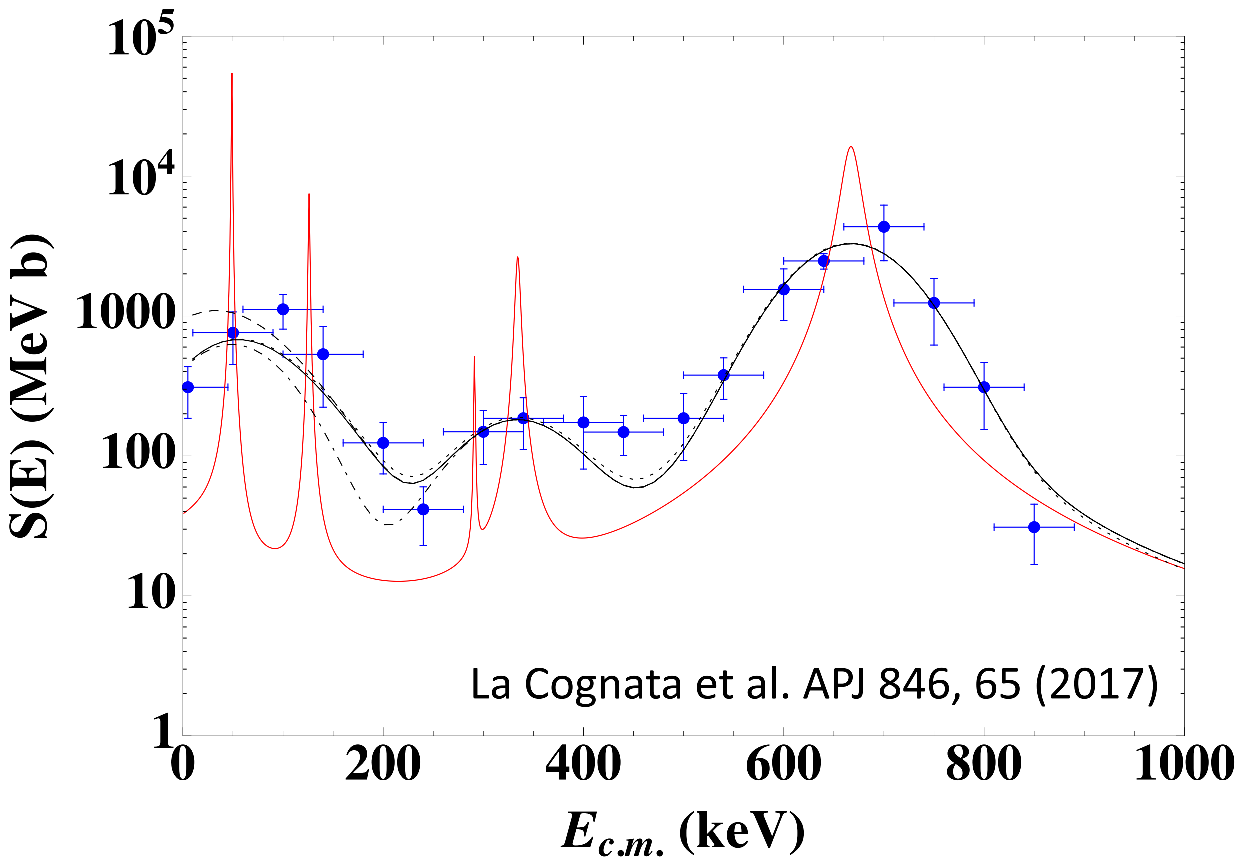
Selection of the reaction channel

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



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

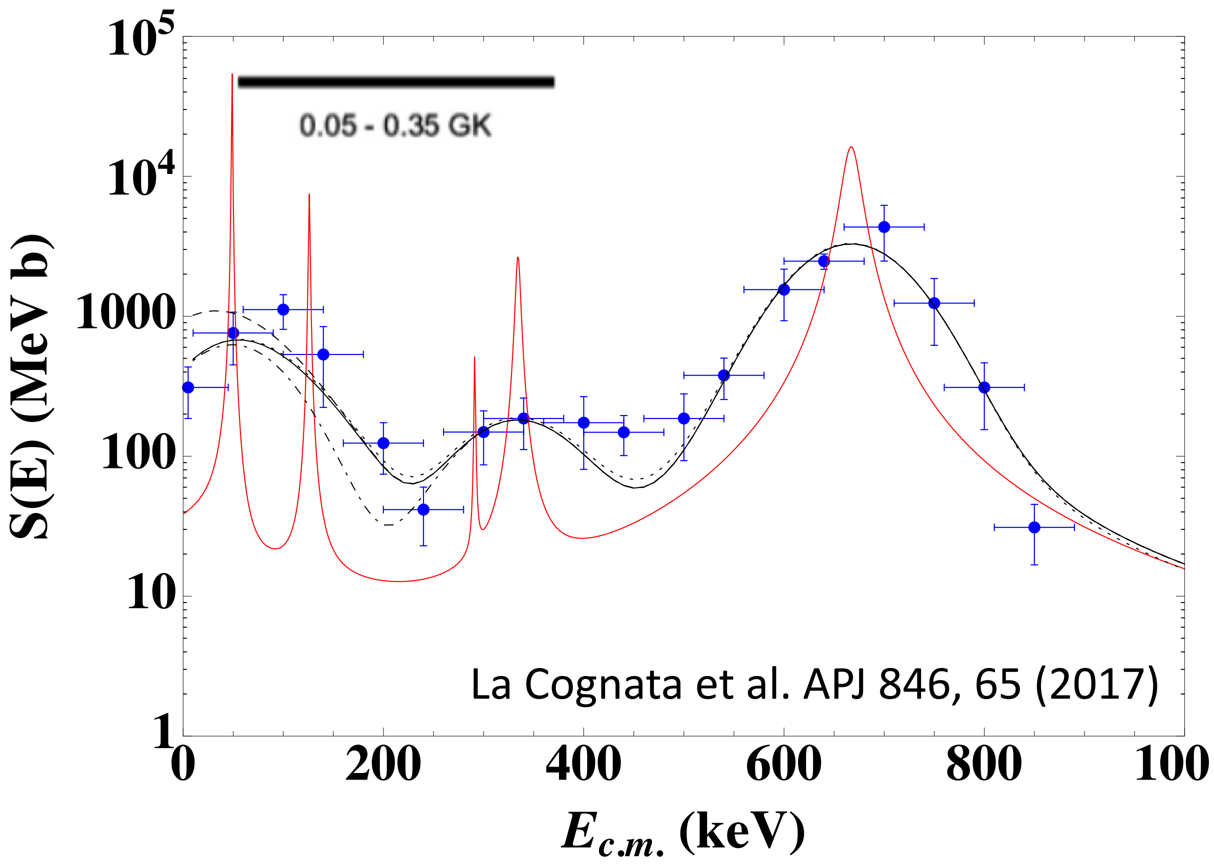
Dotted line: smoothed R-matrix calculation where the interference signs were changed to (++)(−+)

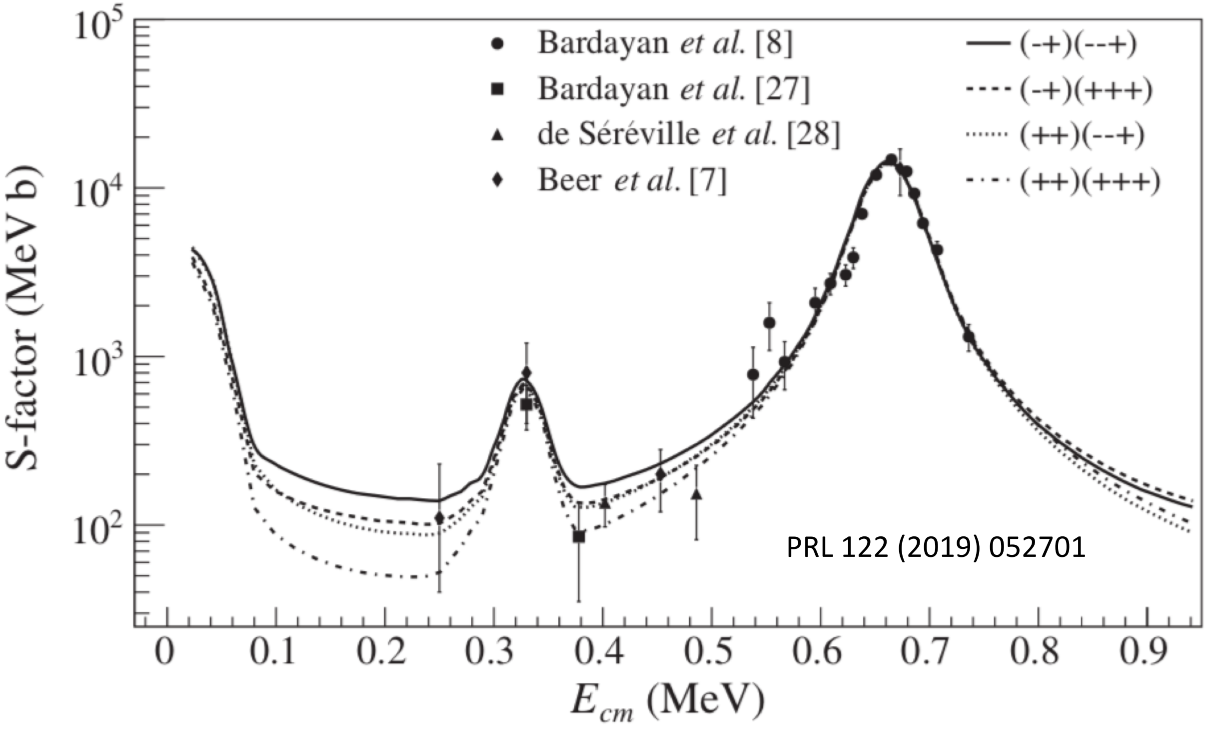
→ No sensitivity to interference, differences accounted for in the final total error

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

Pinpointing the Contributing Resonances





calculation, where the 6537 keV is excluded

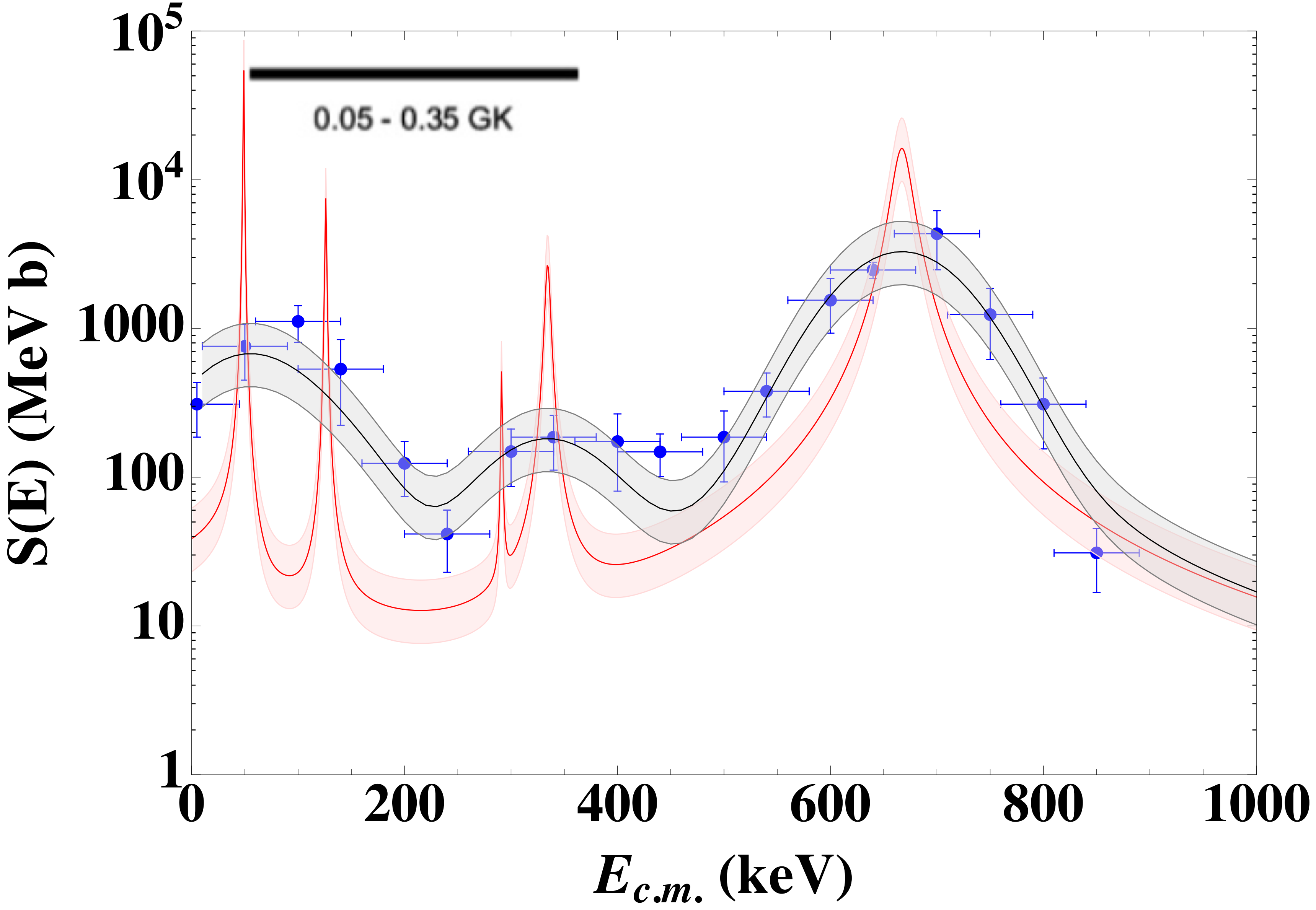
For the first time, the whole Gamow window for novae nucleosynthesis could be covered

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

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**

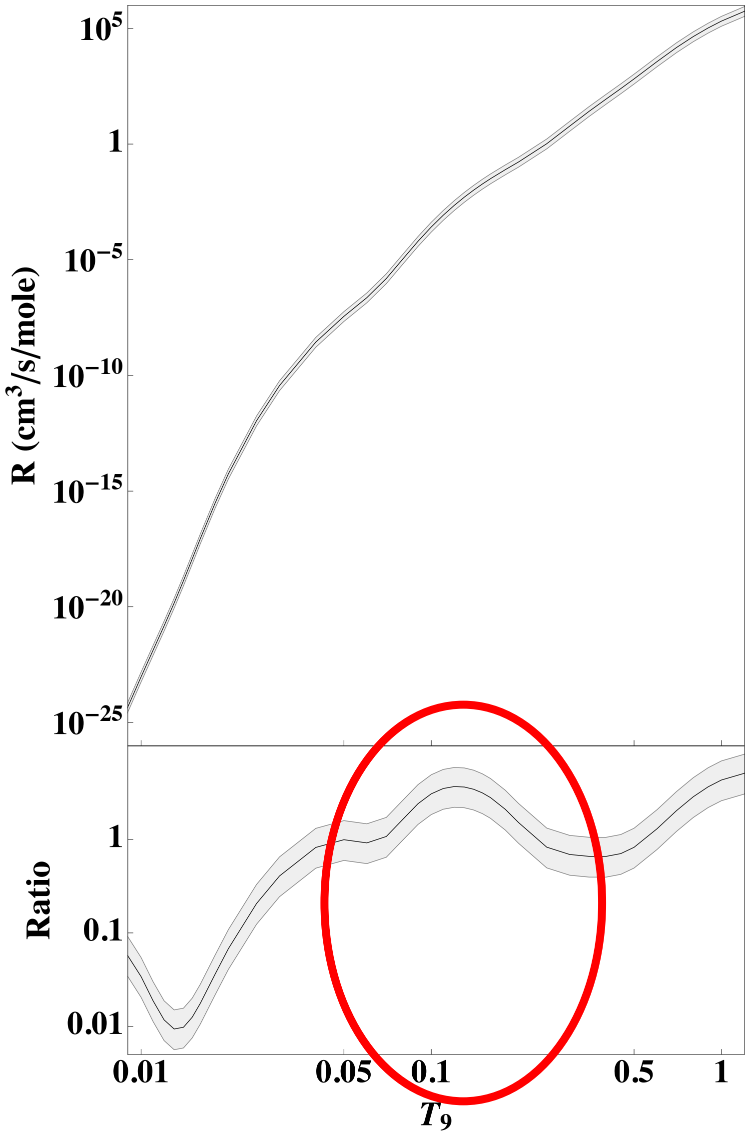
We use R-matrix to deconvolute the S-factor

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 $\rightarrow$ 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

The analysis of a new experiment with better statistics and energy resolution is ongoing

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

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]