# Study of two missing states of $^{19}$Ne affecting the classical novae

2023. 09. 22. NIC conference

Center for Exotic Nuclear Studies (CENS)
Dahee Kim

# $^{19}$Ne: $^{18}$F(p,α)$^{15}$O reaction in rp-process

**s-process in AGB stars**
- Harvesting of targets for n-capture on branch points

**p-process in supernovae**
- Direct reaction rates

**rp-process in X-ray burst/Novae/Supernovae**
- Direct reaction rates (SECAR)
- Indirect reaction rate studies
- Masses and p-drip line

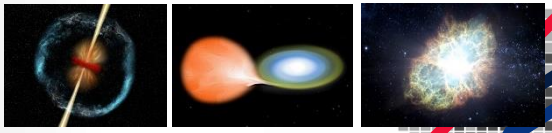
**r-process**
- Beta decay properties
- Masses
- Indirect neutron capture rate studies
- Fission barriers

**Supernova cores**
- Electron capture rates with charge exchange reactions

Unexplored region

Number of Proton (P)

Number of Neutron (N)



**Important reactions**

- $^{15}$O(α,γ)$^{19}$Ne
- $^{18}$F(p,α)$^{15}$O
- $^{25}$Mg(p,γ)$^{26}$Al **Triple α process**

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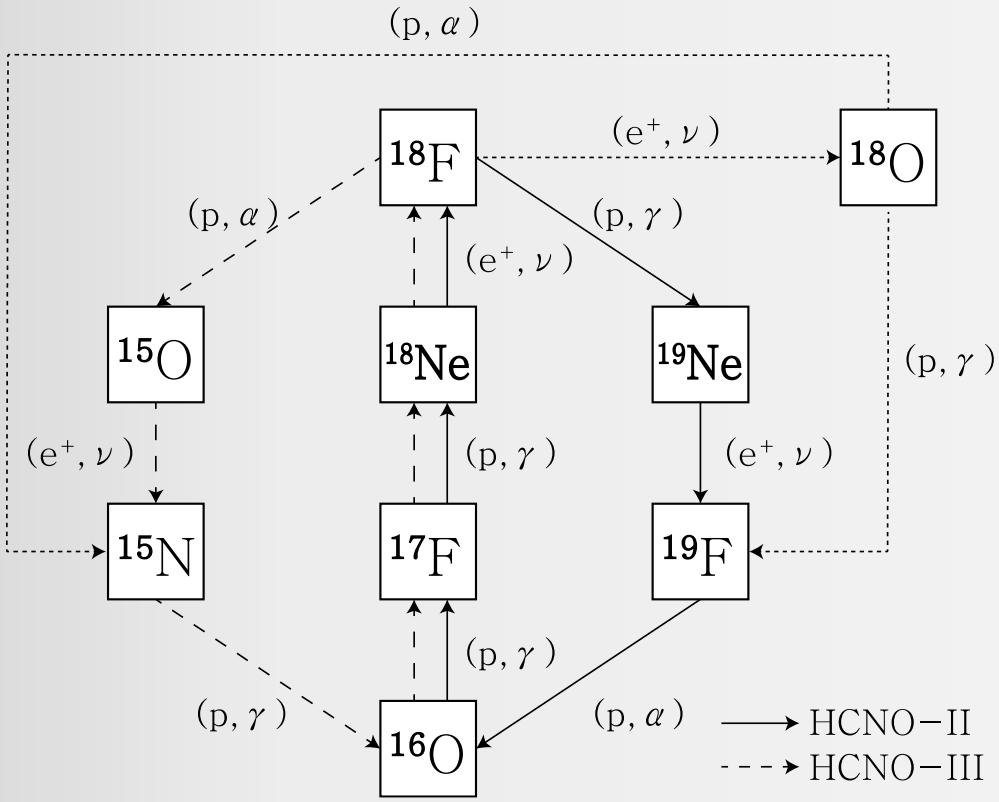
# $^{19}$Ne: Nucleosynthesis of $^{18}$F in classical nova




## Production of $^{18}$F in classical nova

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

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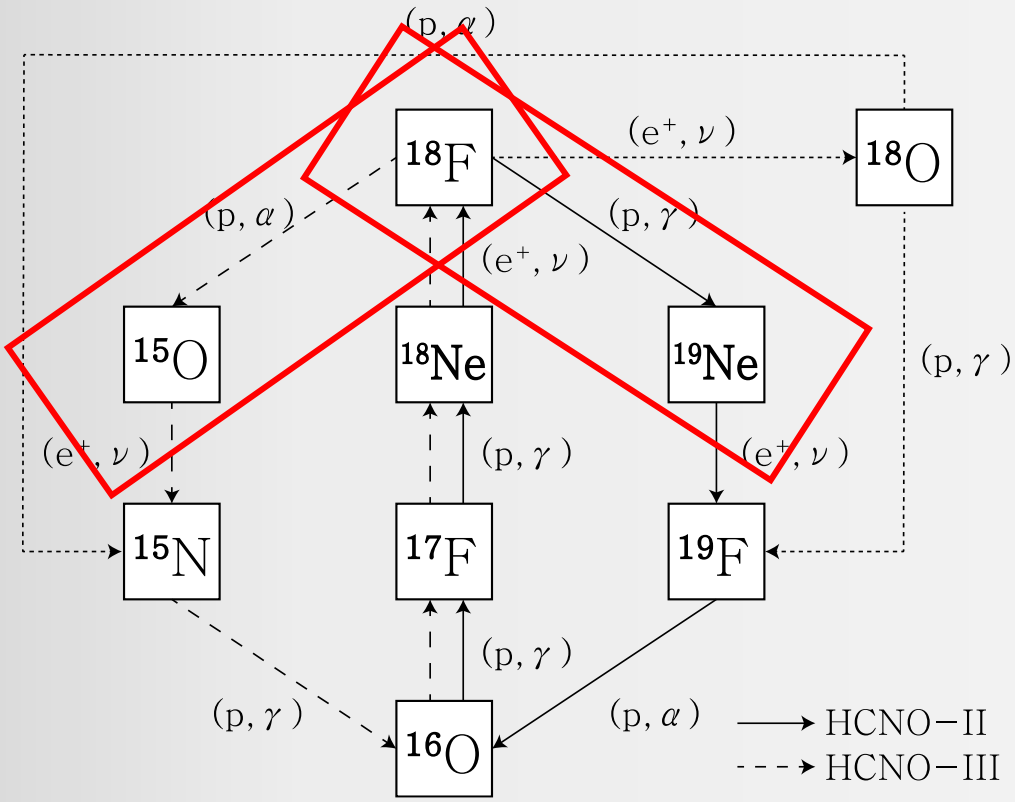


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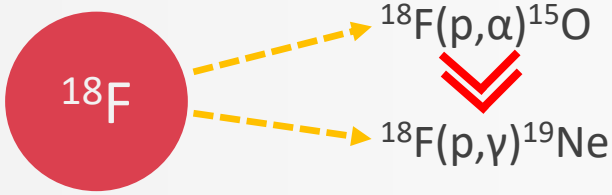
## Destructive reactions of $^{18}$F



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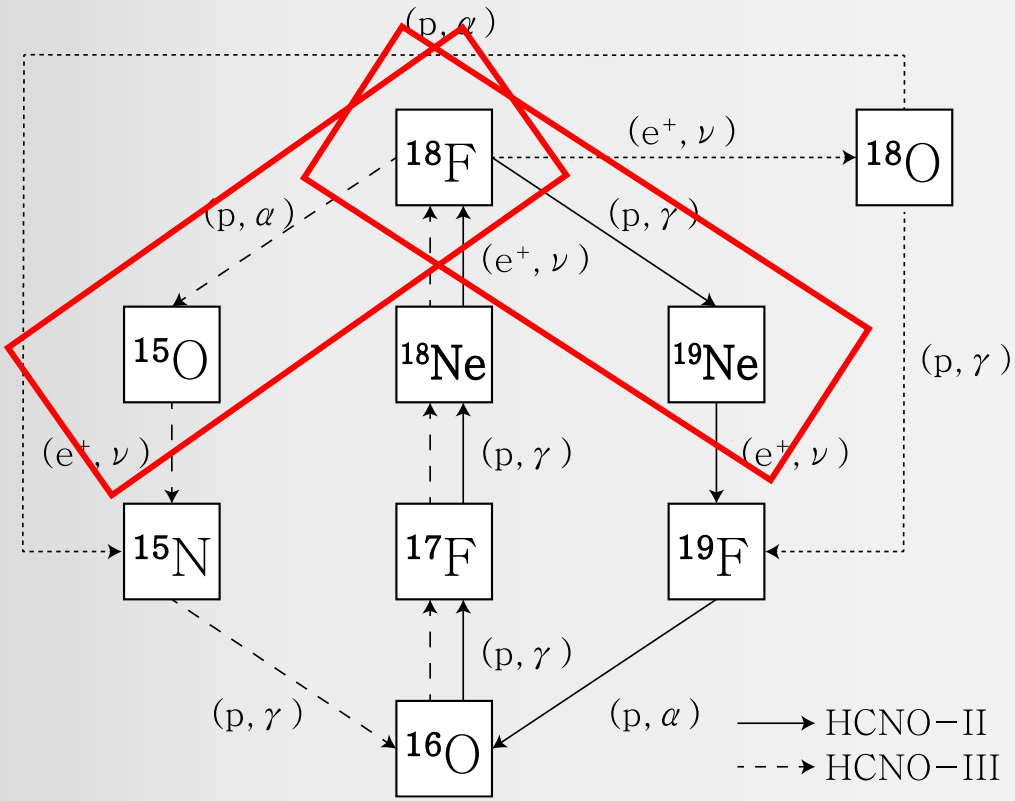


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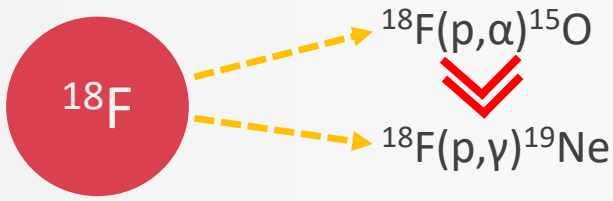



## Reaction rate calculation

$$< \sigma v > = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 (\omega\gamma)_R exp\left(-\frac{E}{kT}\right),$$

$$(\omega\gamma)_R = \frac{2J+1}{(2J_a+1)(2J_b+1)} \frac{\Gamma_a \Gamma_b}{\Gamma}.$$

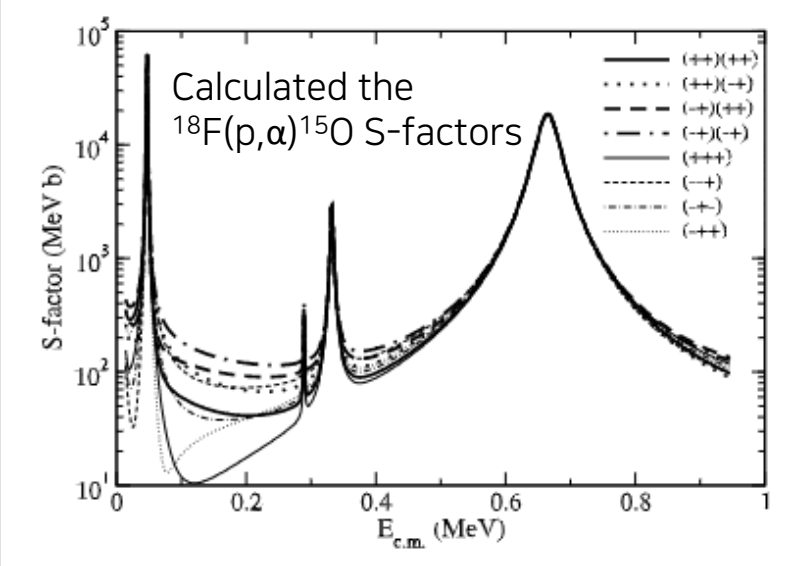
**Study $^{19}$Ne level structure is a key role for the $^{18}$F(p,α)$^{15}$O reaction which determines the abundance of $^{18}$F in classical nova!**

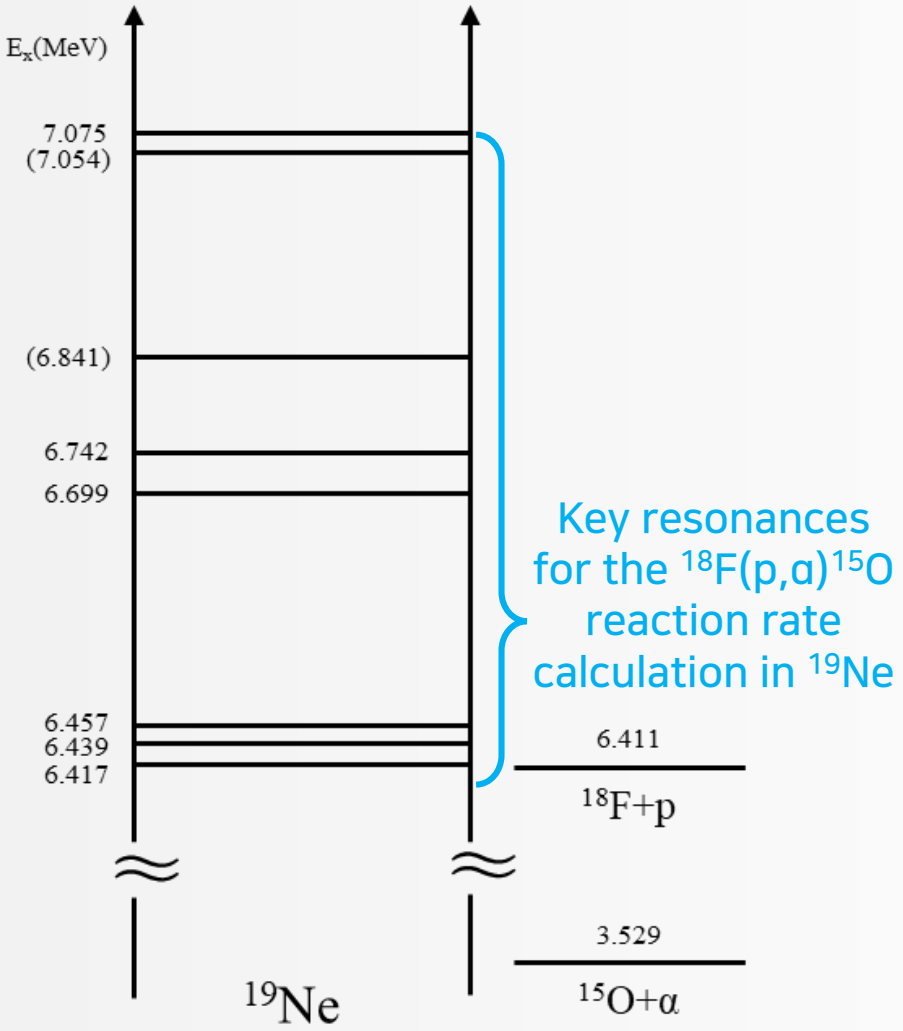
# Motivation: Missing states in $^{19}$Ne

Known resonances in $^{19}$Ne for the $^{18}$F(p,α)$^{15}$O reaction

| $E_x$ (MeV) | $\Gamma_\alpha$ (keV) | $\Gamma_p$ (keV) or ANC($fm^{1/2}$) | $J^\pi$ |
|---|---|---|---|
| 6.286(3) | 11.6 | 83.5 | 3/2- |
| 6.417(3) | <0.5 | 1.6E-41 | 3/2- |
| 6.439(3) | 220 | 3.8E-19 | 1/2- |
| 6.457(3) | 1.3 | 2.1E-13 | 3/2+ |
| 6.699(3) | 1.2 | 2.4E-05 | 5/2+ |
| 6.742(2) | 5.2 | 2.2E-03 | 3/2- |
| 7.075(17) | 23.8 | 15.2 | 3/2+ |

D. Bardayan et al., PLB 751, 311 (2015)



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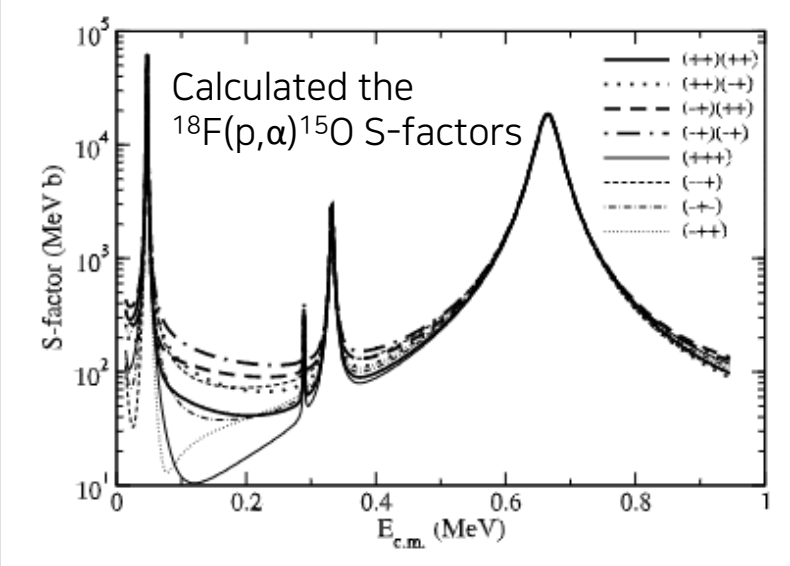


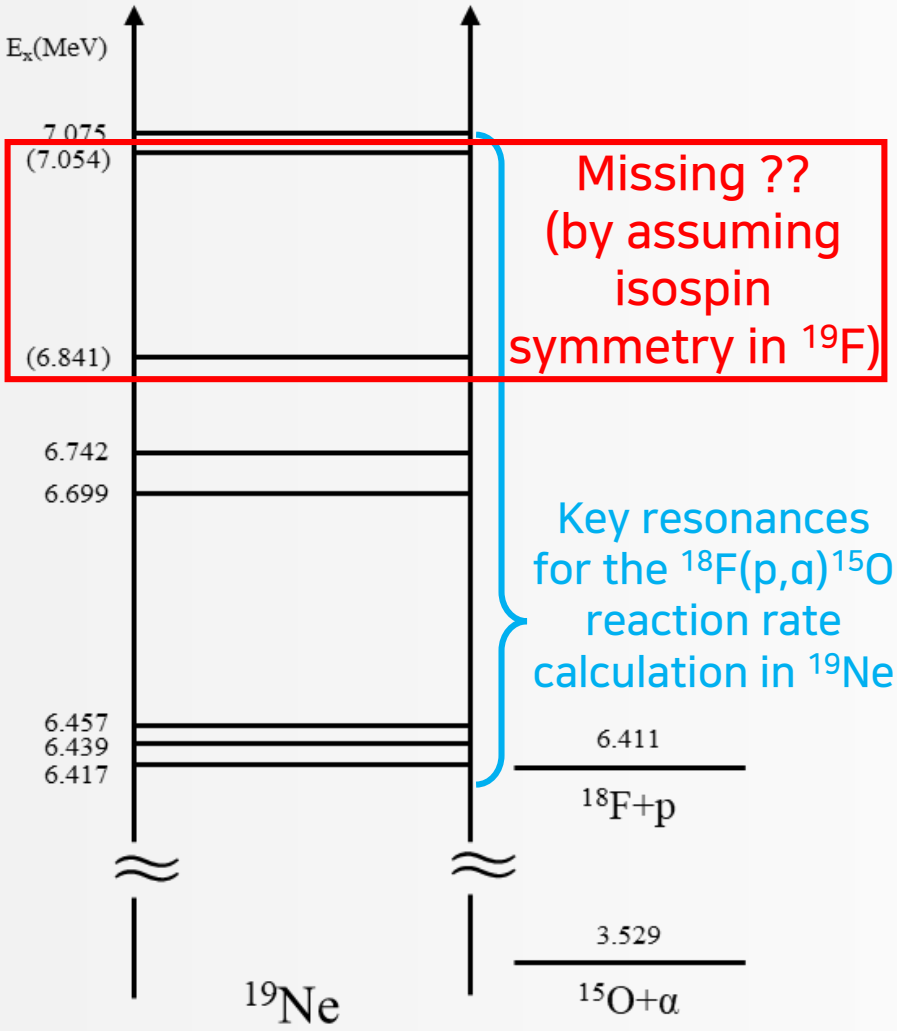

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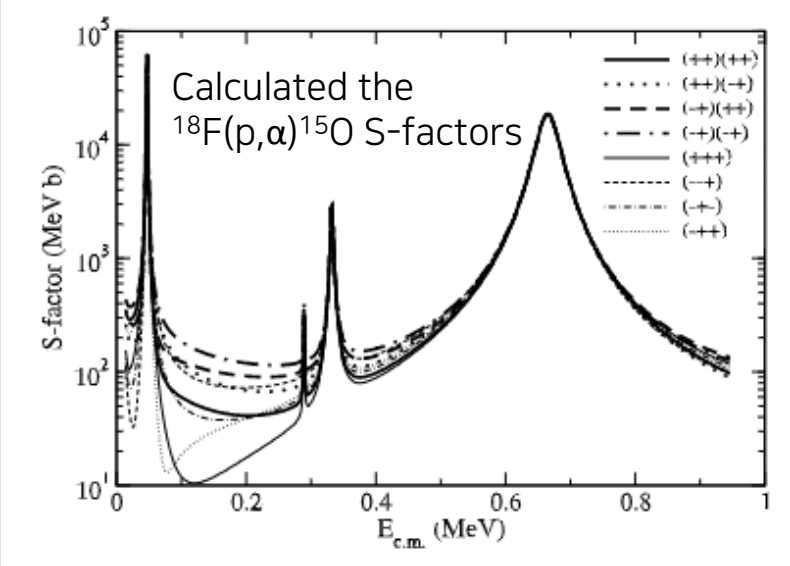
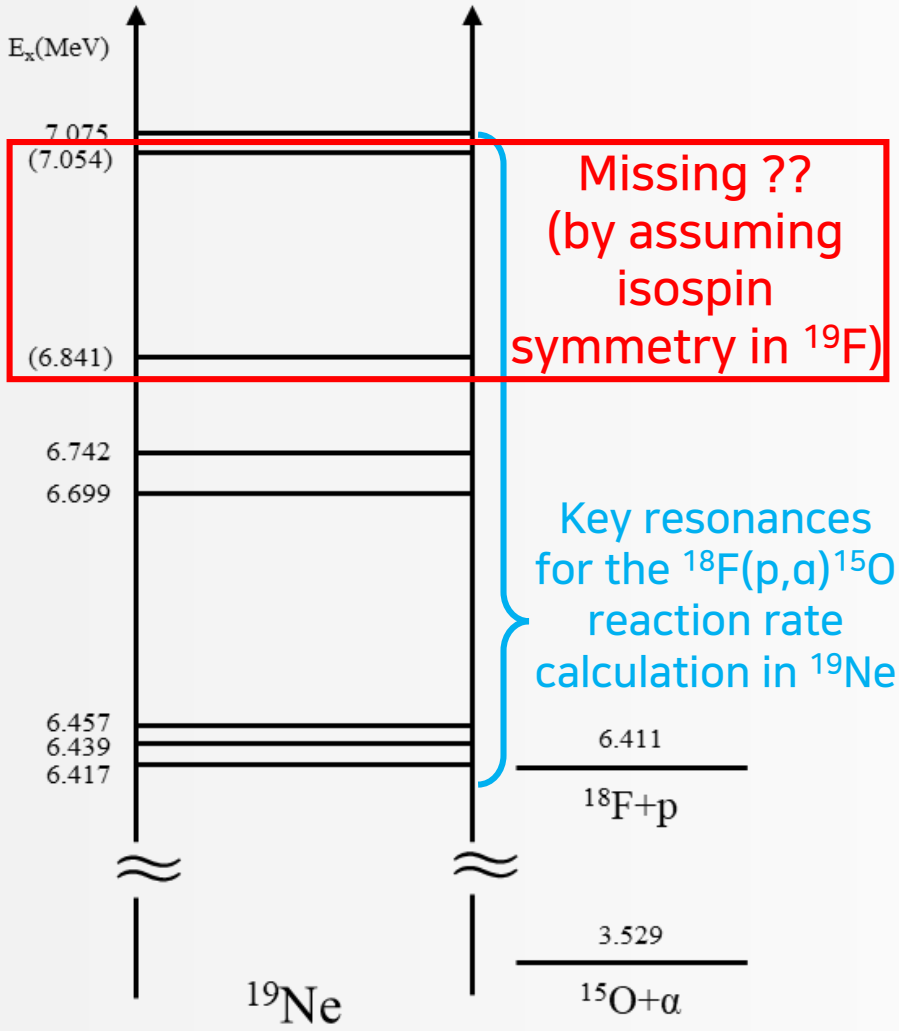
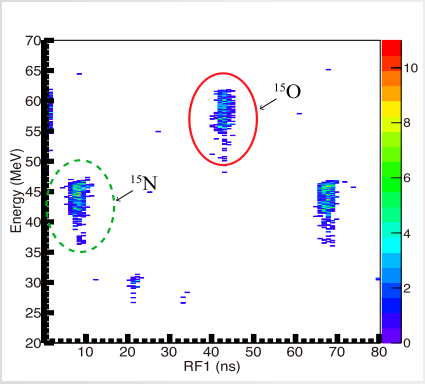
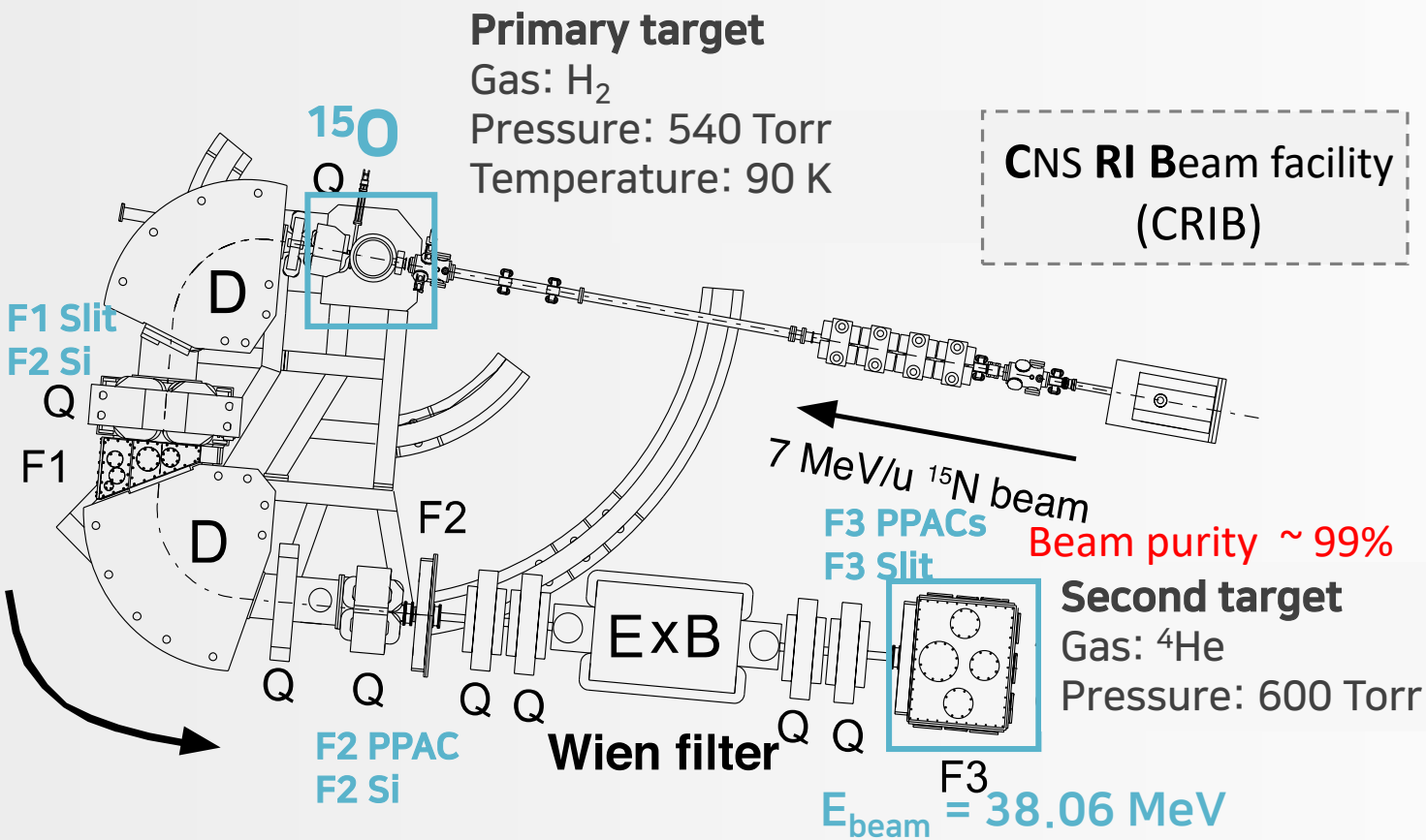



**It would reduce the reaction rate uncertainties at the nova temperature!**

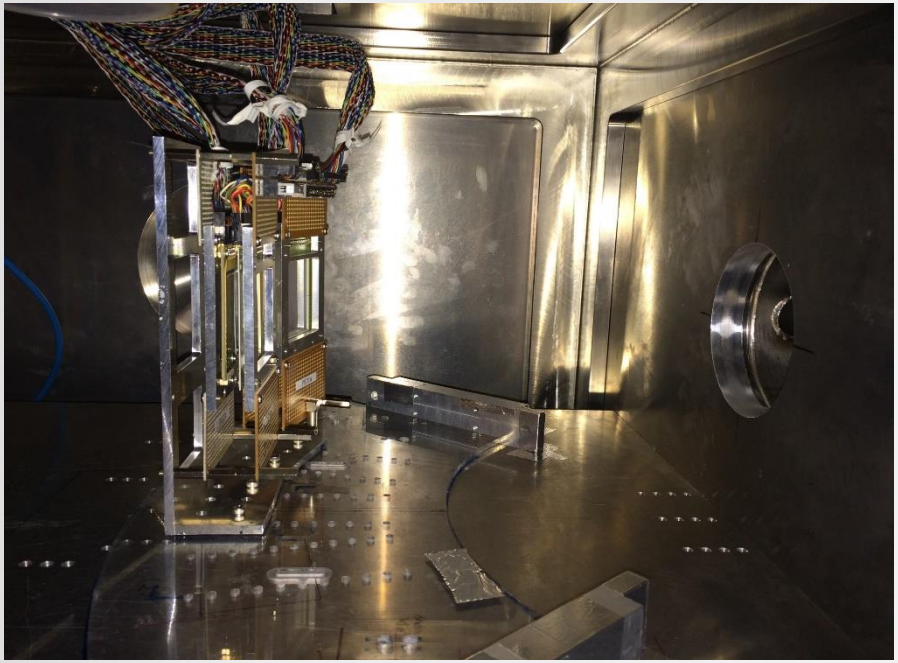
# CRIB facility

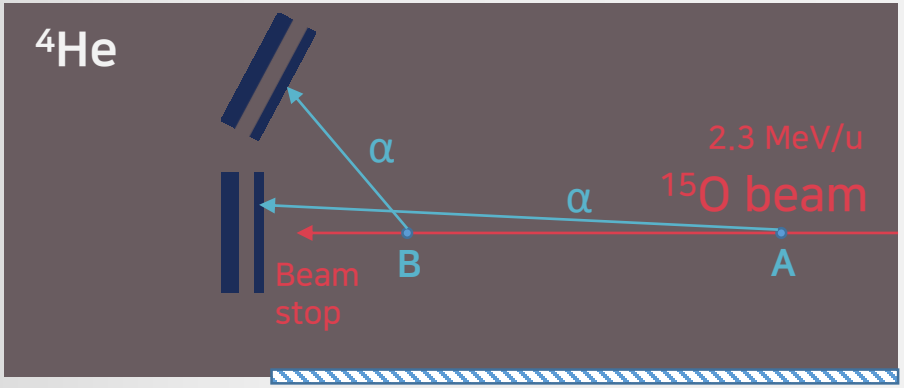


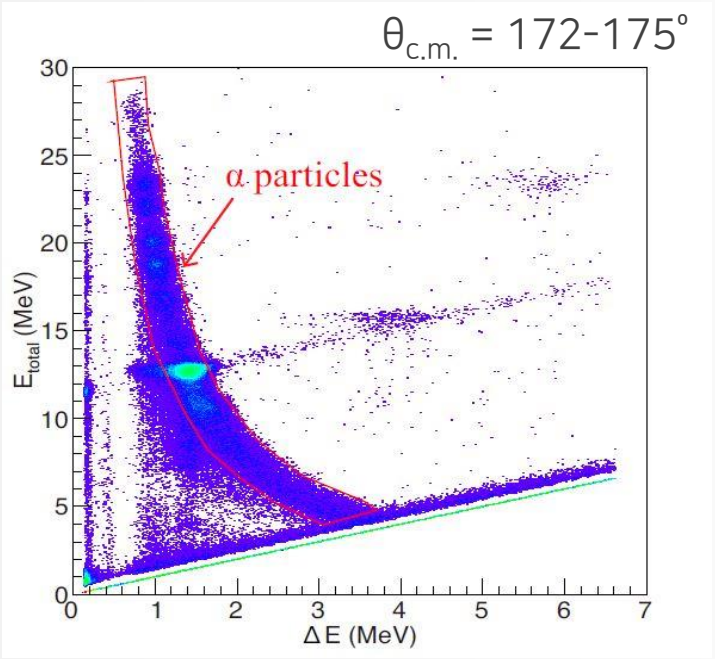

- Two experiments ($^{15}$N+α, $^{15}$O+α) were performed.
- $^{15}$N+α scattering:
  Providing indirect information and constraining on $^{19}$Ne resonance parameters

# Experimental set-up






Thick target inverse kinematics (TTIK)




**Particle identification with ΔE-E telescope**

- Two ΔE-E telescopes were installed for the particle identification.
  - Resolution: $E_{c.m.}$ = 40 keV
  - Thickness: ΔE ~ 20 μm, E ~ 480 μm
  - Angle coverage: $\theta_{c.m.}$ = 133-180°

# Results: $^{19}$Ne (extracted resonance parameters)

## Resonances which affect the $^{18}$F(p,α)$^{15}$O reaction rate

| This experiment | | | | Previous experiments | | | |
|---|---|---|---|---|---|---|---|
| $E_x$(MeV) | $\Gamma_\alpha$(keV) | $J^\pi$ | $\theta^2_\alpha$ | $E_x$(MeV) | $\Gamma_\alpha$(keV) | $J^\pi$ | Ref. |
| 5.652(20) | 59(3) | 1/2− | 0.87 | - | - | - | |
| 6.220(4) | 65(2) | 5/2− | 0.86 | 6.289(10) | - | - | [18, 19] |
| 6.340(12) | 182(9) | 1/2+ | 0.69 | - | - | - | |
| 6.426(4) | 250(15) | 1/2− | 0.51 | 6.437 | 220(20) | 1/2− | |
| 6.860(8) | 58(4) | (3/2−) | 0.20 | (6.841) | 25(18) | (3/2−) | [14, 18–20] |
| 7.055(4) | 25(2) | (7/2+) | 0.20 | (7.054) | 29(25) | (5/2+, 7/2+) | [9, 21] |
| 7.165(15) | 51(8) | (3/2+) | 0.05 | 7.203(31) | 35(12) | (3/2+) | |
| 7.320(4) | 130(3) | (7/2+) | 0.67 | 7.326(15) | - | - | |
| | | | | 7.335 | - | - | |
| 7.420(11) | 196(4) | (5/2+) | 0.89 | 7.378(7) | 121(9) | (7/2+) | |
| 7.790(4) | 205(6) | (5/2−) | 0.21 | 7.775(10) | - | - | |
| 7.850(4) | 81(7) | (1/2+) | 0.05 | 7.863(39) | 292(107) | (1/2+) | [22, 23] |
| **8.120(4)** | 114(3) | (7/2−) | 0.74 | 8.063(15) | | | |
| 8.400(4) | 86(3) | (9/2−) | 0.39 | 8.442(9) | | | |
| 8.840(7) | 110(5) | (5/2−) | 0.05 | 8.810(25) | | | |
| **9.150(4)** | 49(15) | (5/2−) | 0.02 | - | | | |
| 9.250(8) | 648(11) | (5/2+) | 0.47 | 9.240(20) | | | |
| 9.310(4) | 254(6) | (7/2+) | 0.18 | - | | | |
| **9.590(4)** | 49(5) | (5/2+) | 0.03 | - | | | |
| **9.610(4)** | 32(2) | (11/2−) | 0.90 | - | | | |
| **9.830(8)** | 120(3) | (11/2+) | 0.49 | - | | | |
| 9.880(8) | 133(5) | (9/2+) | 0.53 | 9.875(50) | | | |
| **10.270(4)** | 107(2) | (9/2−) | 0.09 | - | | | |
| **10.290(4)** | 113(3) | (7/2−) | 0.10 | - | | | |
| **10.510(4)** | 73(3) | (11/2−) | 0.75 | - | | | |
| **10.865(4)** | 216(9) | (7/2−) | 0.14 | - | | | |
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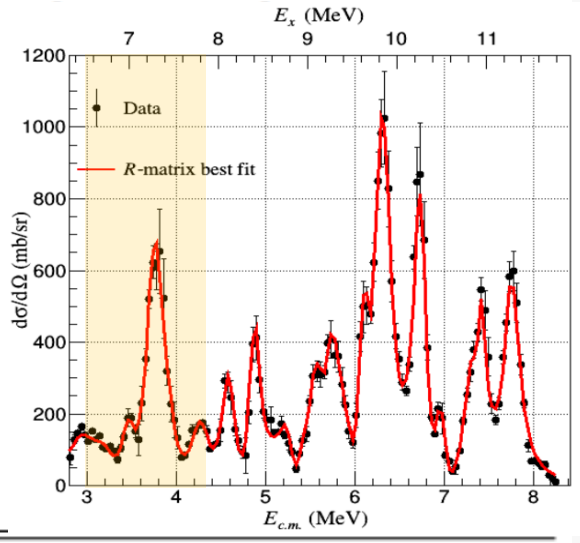


**~ 28 resonances were identified in $E_x$ = 6.0~11.5 MeV**

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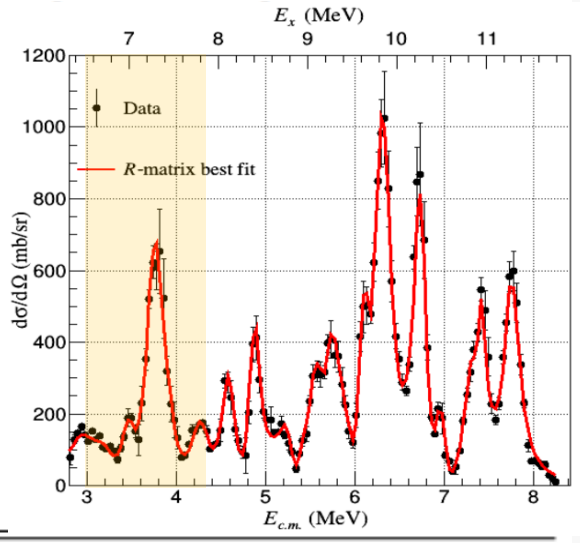
Predicted missing states

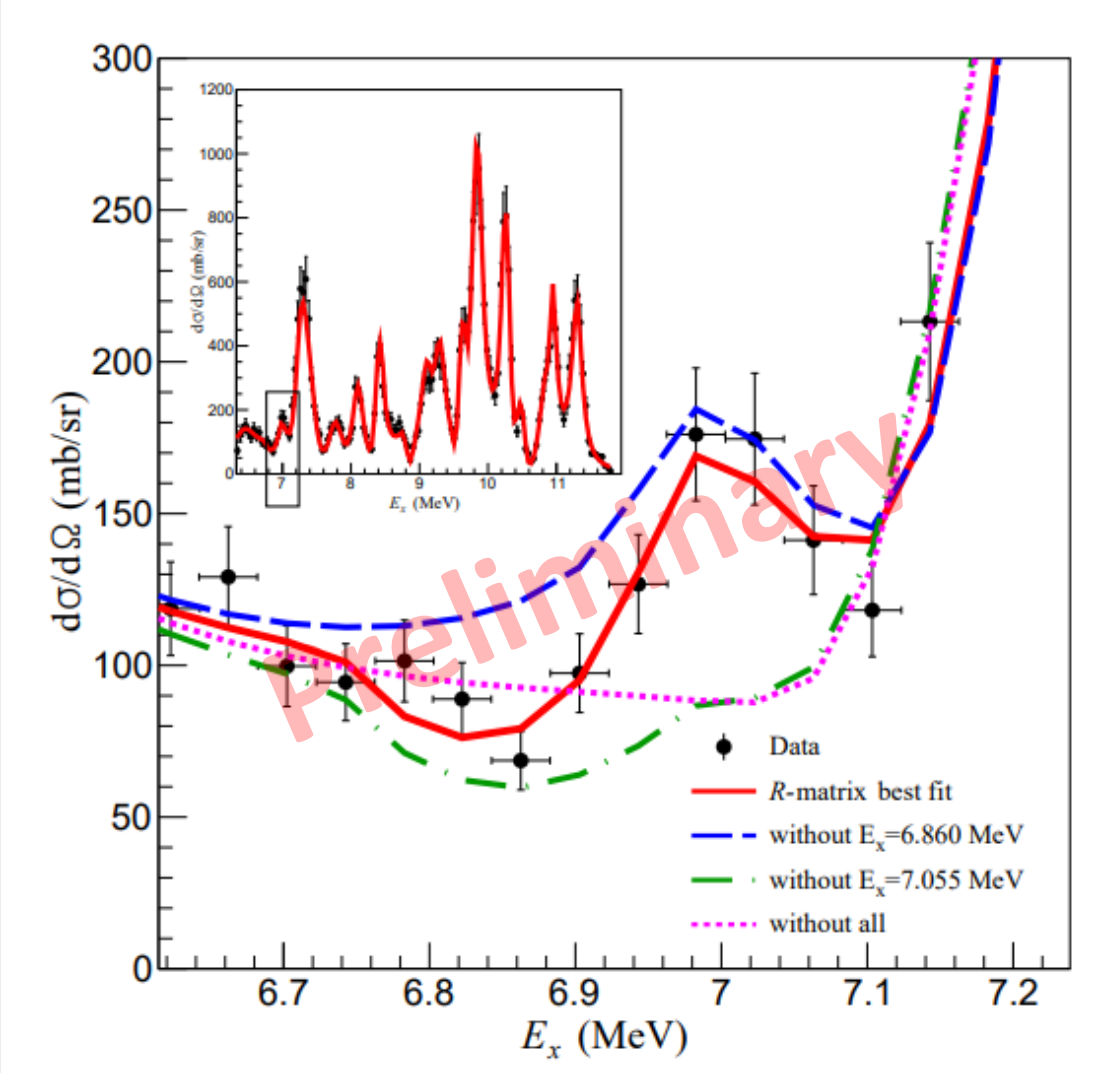





**~ 28 resonances were identified in $E_x$ = 6.0~11.5 MeV**

# Results: Identify two missing states

- Enlarged area of the excitation function of $^{19}$Ne in $E_x$ = 6.6-7.2 MeV



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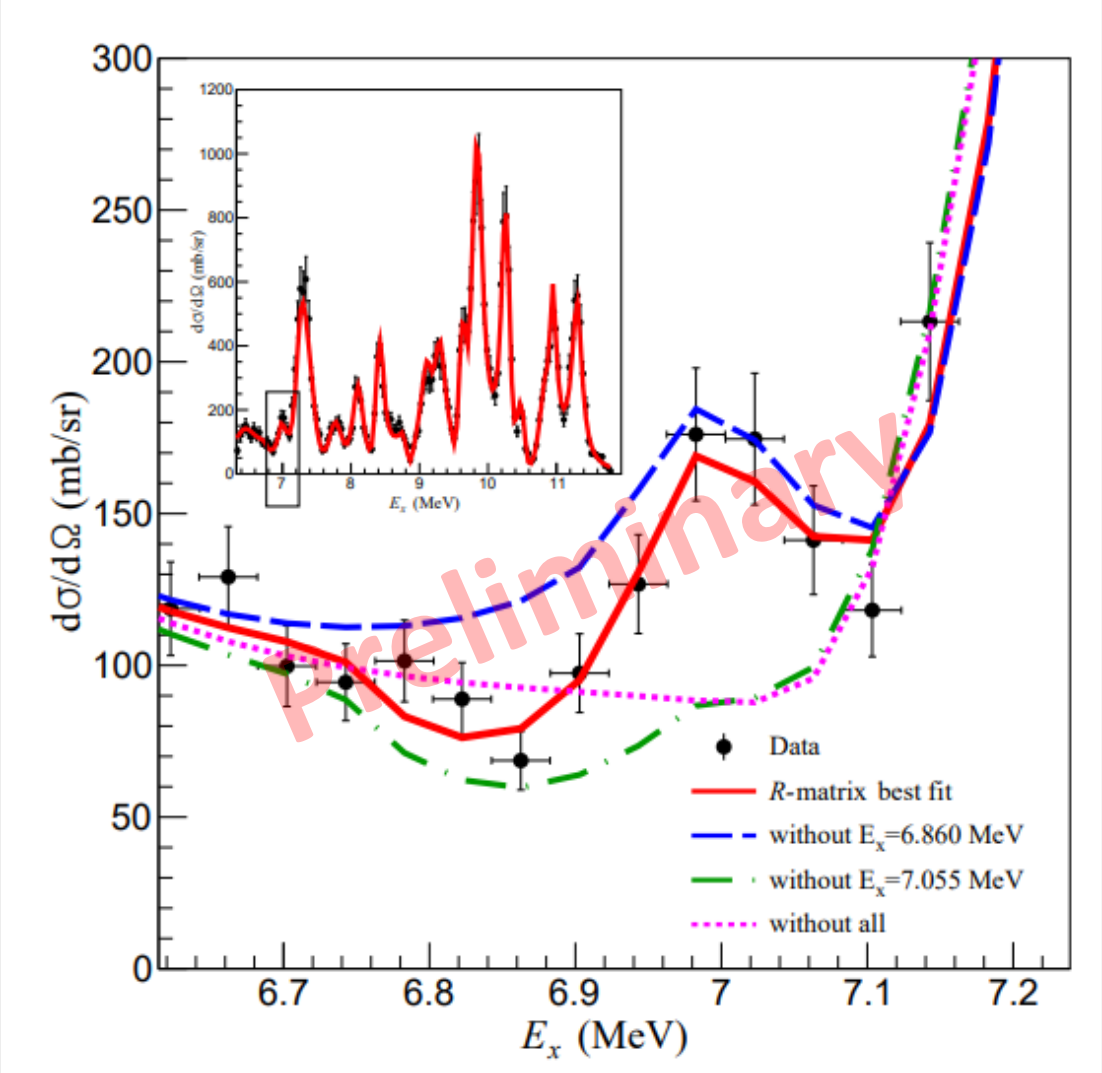


**Two missing states are required for the R-matrix fitting of $^{19}$Ne excitation function!**

# Results: Updated S-factor calculation

- Updated S-factor including two missing states (6. 860 and 7.055 MeV states)

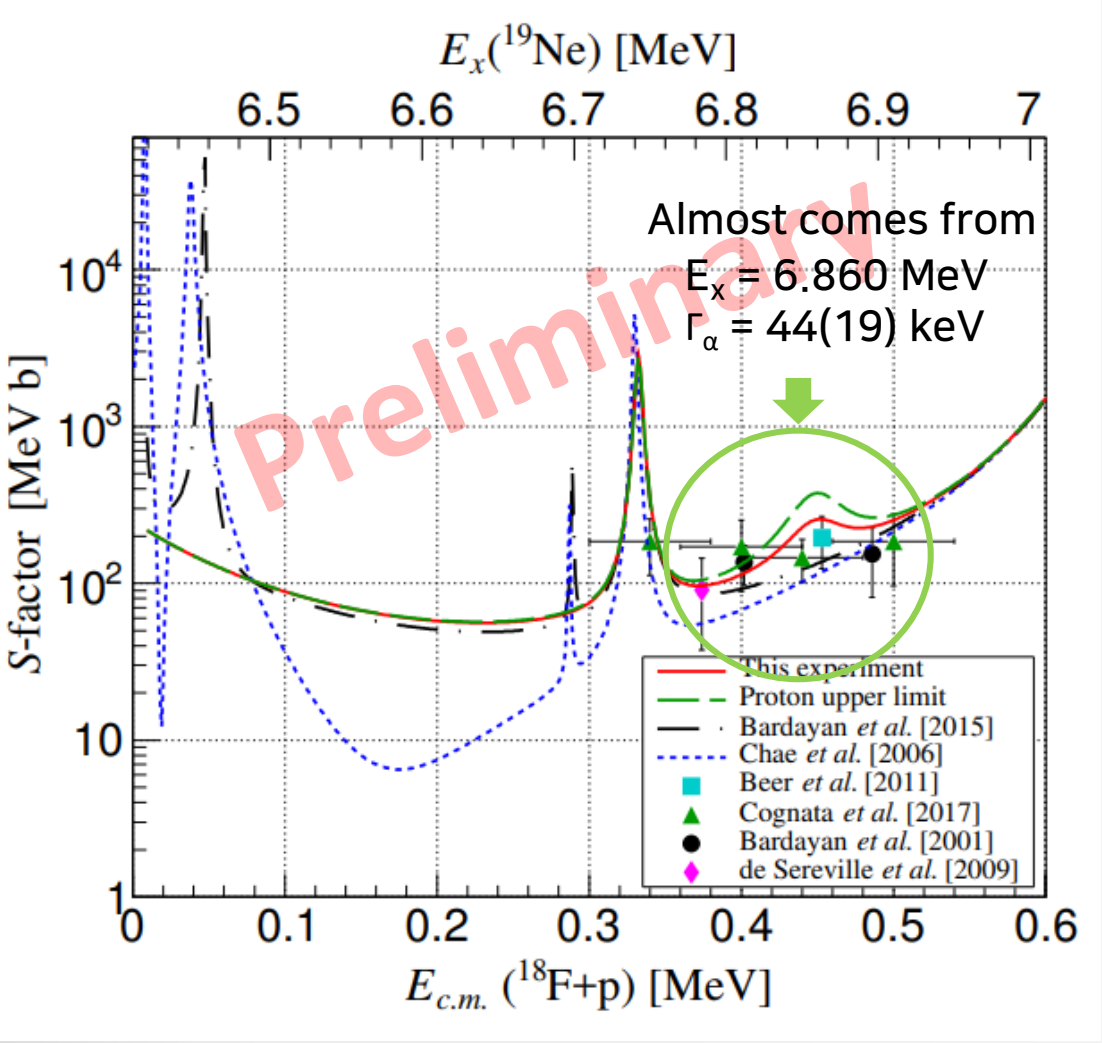


TABLE I: Resonance state energies and widths, including those for the two newly observed states for the $S$-factor calculation.

| $E_x$(MeV) | $\Gamma_\alpha$(keV) | $\Gamma_p$(keV) | $J^\pi$ | Ref. |
|---|---|---|---|---|
| 6.132(5) | 0.74 | ≤6 | (3/2+) | [11, 25] |
| 6.286(4) | 11.7 | 83.5 | (1/2+) | [26–28] |
| 6.742(2) | 5.2 | 0.0022 | 3/2− | [6, 12, 29] |
| 6.860(27) | 44(19) | 0.007 | 3/2− | this work |
| 7.055(25) | 42(11) | 0.047 | (5/2+,7/2+) | this work, [12, 29] |
| 7.075(17) | 23.8 | 15.2 | 3/2+ | [30] |
| 7.845(25) | 71(27) | 59 | 1/2+ | this work, [11] |

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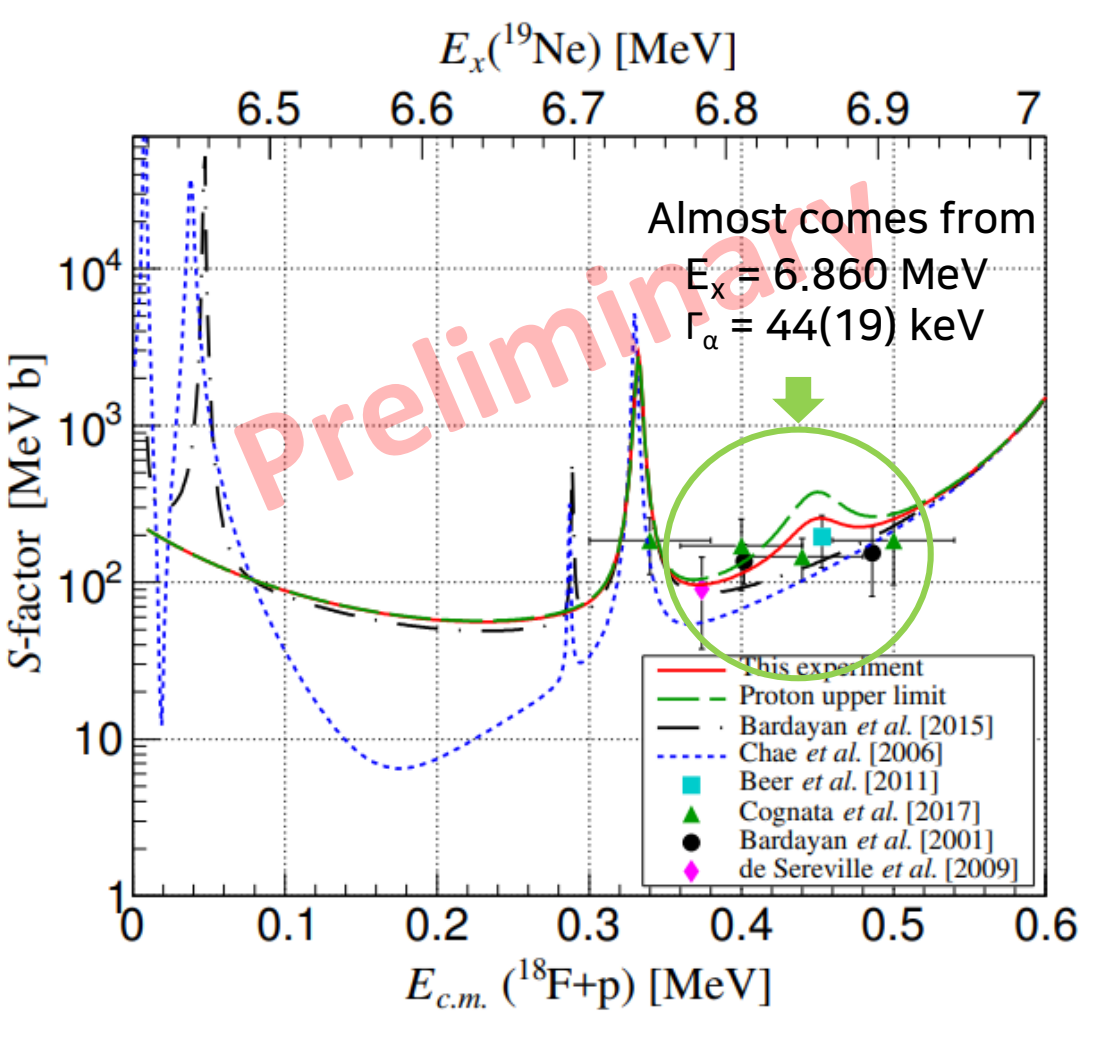


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**The missing state at $E_x$=6.860 MeV affect the S-factor calculation by several factors difference around the astrophysically important energy range!**

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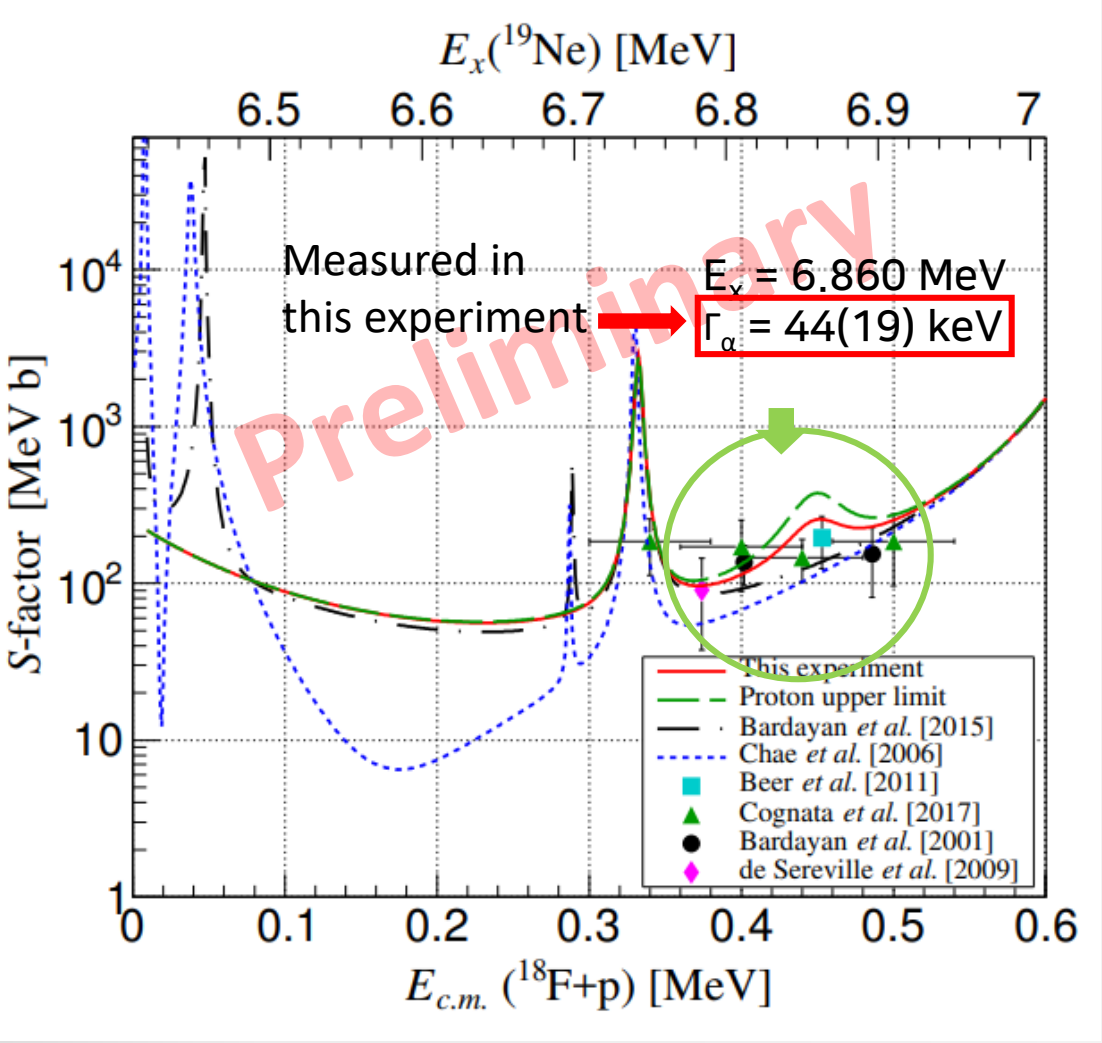


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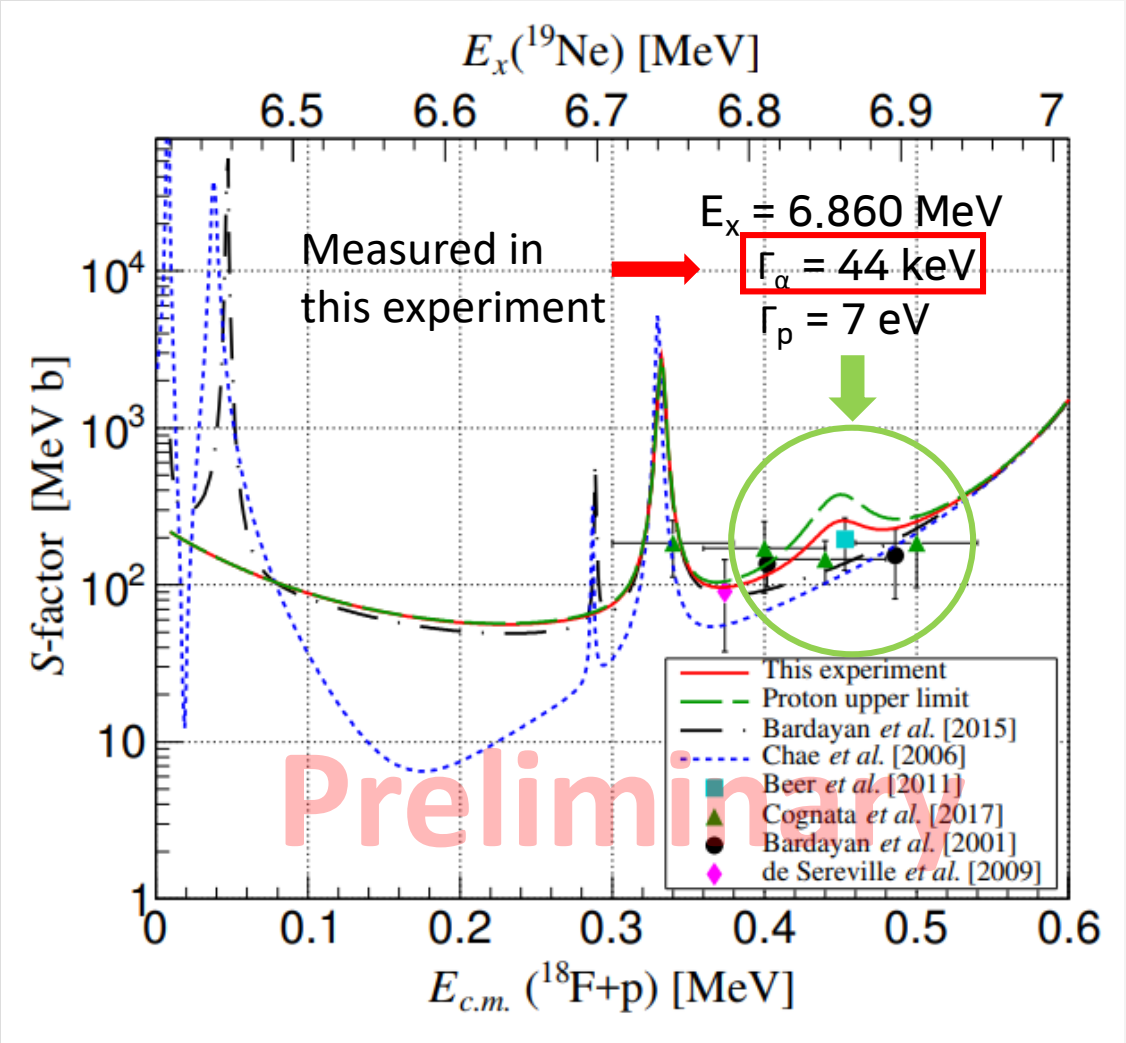
|---|---|---|---|---|
| 6.132(5) | 0.74 | ≤6 | (3/2+) | [11, 25] |
| 6.286(4) | 11.7 | 83.5 | (1/2+) | [26–28] |
| 6.742(2) | 5.2 | 0.0022 | 3/2− | [6, 12, 29] |
| 6.860(27) | 44(19) | 0.007 | 3/2− | this work |
| 7.055(25) | 42(11) | 0.[illegible]7 | (5/2+,7/2+) | this work, [12, 29] |
| 7.075(17) | 23.8 | 1[illegible]2 | 3/2+ | [30] |
| 7.845(25) | 71(27) | [illegible] | 1/2+ | this work, [11] |

Never been measured!

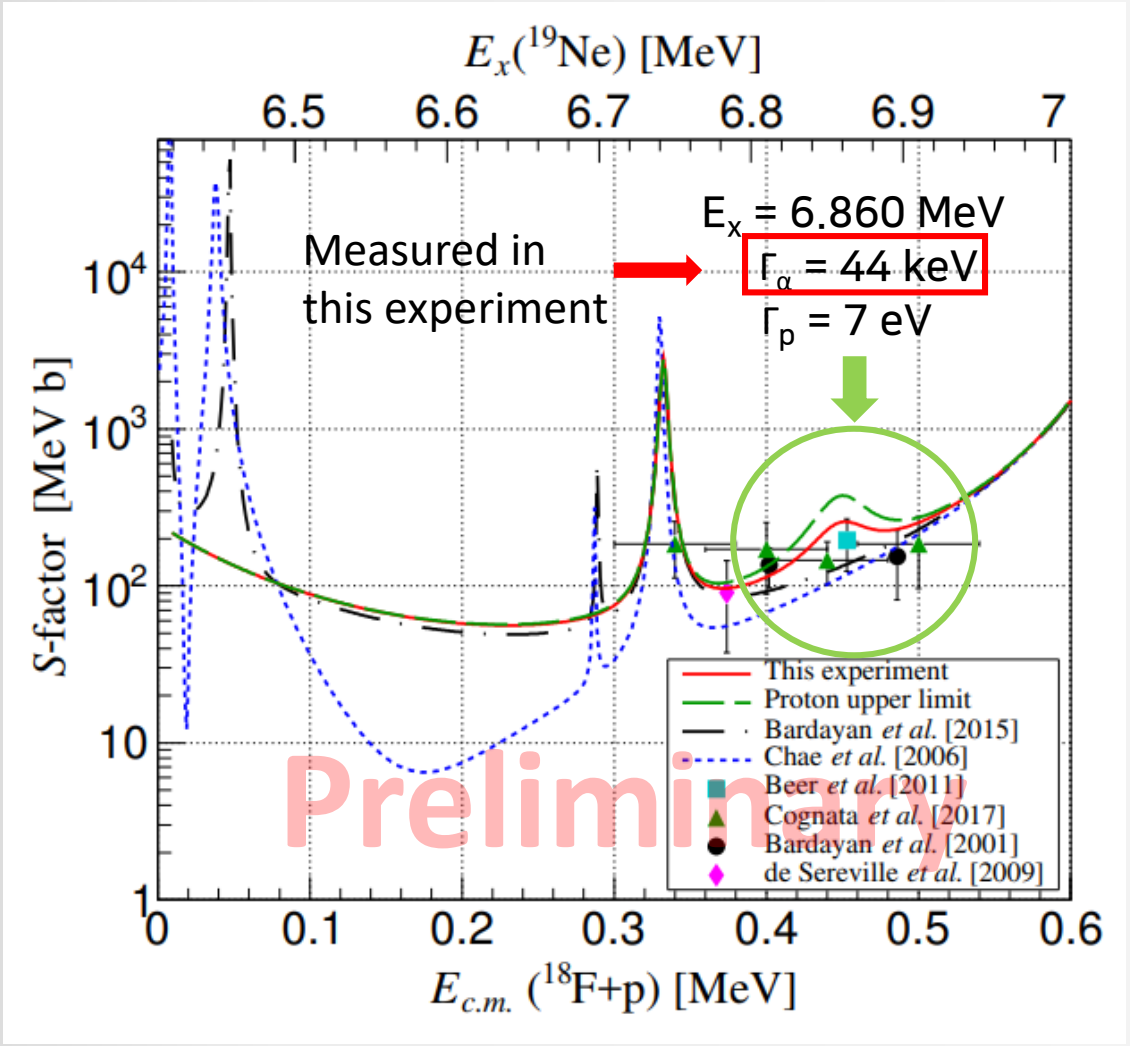
# Results: Proton width calculation




Finding the minimum kai-square between experimental value and the calculation result by varying the proton width value.

| $E_x$(MeV) | $\Gamma_\alpha$(keV) | $\Gamma_p$(keV) | $J^\pi$ |
|---|---|---|---|
| 6.132(5) | 0.74 | ≤6 | (3/2+) |
| 6.286(4) | 11.7 | 83.5 | (1/2+) |
| 6.742(2) | 5.2 | 0.0022 | 3/2− |
| 6.860(27) | 44(19) | 0.007 | 3/2− |
| 7.055(25) | 42(11) | 0.047 | (5/2+,7/2+) |
| 7.075(17) | 23.8 | 15.2 | 3/2+ |
| 7.845(25) | 71(27) | 59 | 1/2+ |

# Results: Proton width calculation

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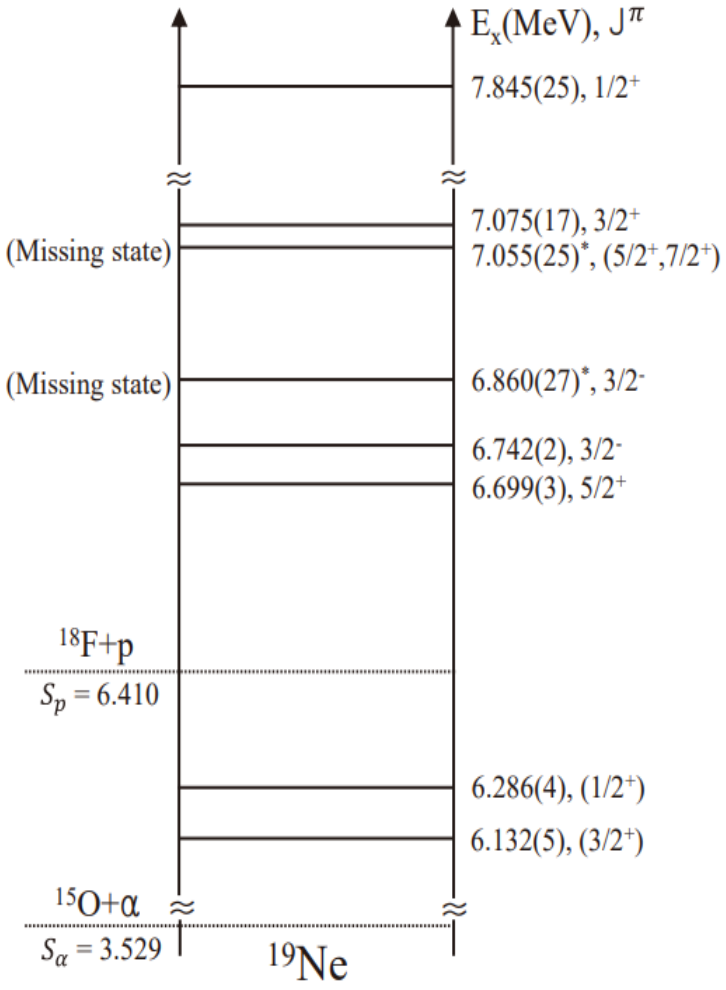
| 7.075(17) | 23.8 | 15.2 | 3/2+ |
| 7.845(25) | 71(27) | 59 | 1/2+ |

- Proton width upper limit of the missing state at $E_x$ = 6.860 MeV in $^{19}$Ne with 1σ confidence level is ~ 14 eV.

Very close to the deduced value (12 eV) from the mirror state in $^{19}$F!

# Summary




- Studied missing states in $^{19}$Ne near proton threshold ($E_x$=6.410 MeV) for the $^{18}$F(p,α)$^{15}$O reaction rate which is a nuclear astrophyiscally important reaction in a classical nova.
- Identified ~ 28 resonances in $^{19}$Ne including 12 new resonances via the $^{15}$O+alpha elastic scattering experiment in $E_x$ = 6.0 ~ 11.5 MeV.
- Observed two missing states near the proton threshold.
- Calculated proton width for one of the missing state at $E_x$ = 6.860 MeV, and which would change the S-factor by several factors at $E_{c.m.}$ = 0.4-0.5 MeV region and contribute to the $^{18}$F(p,α)$^{15}$O reaction rate at nova temperature.

# Collaboration list

**$\alpha$-cluster States Observed in $^{19}$Ne Affecting the $^{18}$F$(p, \alpha)^{15}$O Reaction Rate in Novae**


D. Kim,[1,2,*] K. I. Hahn,[1,2,†] A. Kim,[3] S. Y. Park,[4] G. W. Kim,[4] E. K. Lee,[4] S. W. Hong,[5] K. Y. Chae,[5] S. M. Cha,[1] M. S. Gwak,[6] E. J. Lee,[5] J. H. Lee,[5] J. Y. Moon,[6] S. H. Choi,[7] S. H. Bae,[1] H. Yamaguchi,[8] S. Hayakawa,[8] Y. Sakaguchi,[8] K. Abe,[8] N. Imai,[8] N. Kitamura,[8] O. Beliuskina,[8] Y. Wakabayashi,[9] S. Kubono,[9] V. Panin,[9] N. Iwasa,[10] D. Kahl,[11] and A. A. Chen[12]

[1] *Center for Exotic Nuclear Studies (CENS), Institute for Basic Science (IBS), Daejeon, Korea*
[2] *Ewha Womans University, Seoul, Korea*
[3] *Center for Extreme Nuclear Matters (CENuM), Korea University, Seoul, Korea*
[4] *Center for Underground Physics (CUP), Institute for Basic Science (IBS), Daejeon, Korea*
[5] *Department of Physics, SungKyunKwan University, Suwon, Korea*
[6] *RISP, Institute for Basic Science (IBS), Daejeon, Korea*
[7] *Department of Physics and Astronomy, Seoul National University, Seoul, Korea*
[8] *Center for Nuclear Study, University of Tokyo, Wako, Japan*
[9] *RIKEN, Nishina Center, Wako, Japan*
[10] *Department of Physics, University of Tohoku, Sendai, Japan*
[11] *Extreme Light Infrastructure Nuclear Physics, Horia Hulubei National Institute for RD in Physics and Nuclear Engineering(IFIN-HH), Bucharest-Magurele, Romania*
[12] *Department of Physics and Astronomy, McMaster University, Hamilton, Canada*

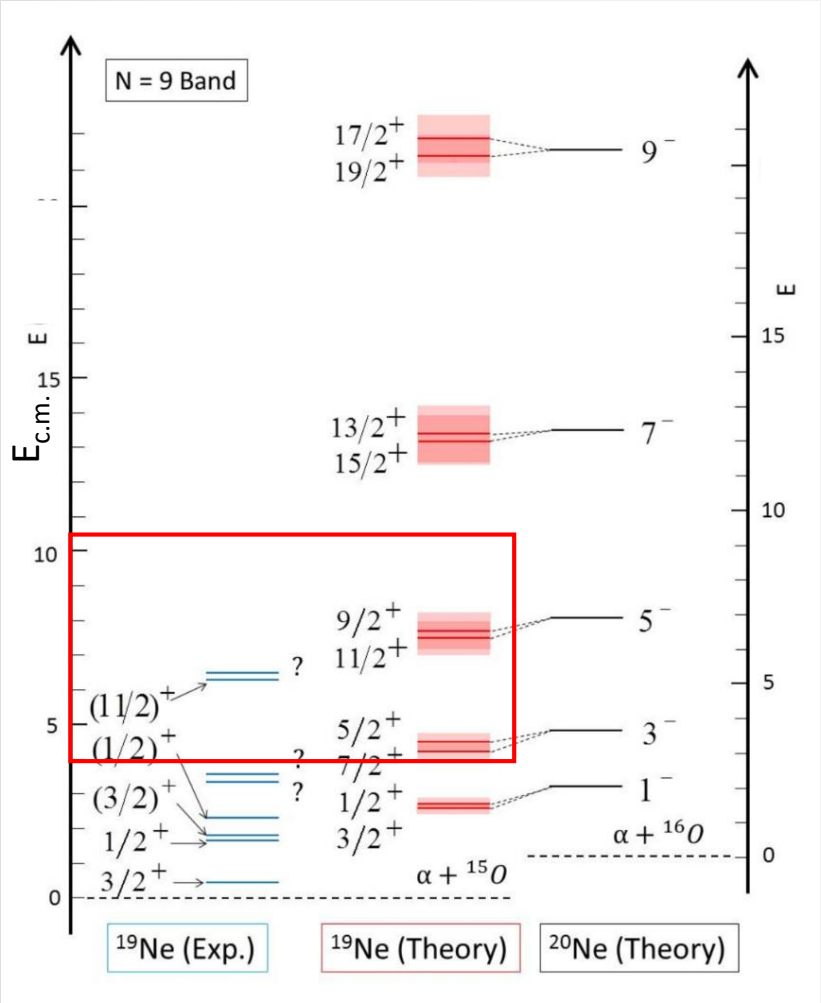

# Acknowledges


D. W. Bardayan (Notre Dame University, US)
S. Ahn, J. Park (Center for Exotic nuclear Studies, Korea)
S. L. Olsen, D. Leonard (Center for Underground Physics, Korea)


Thank you for your attention

# Results: $^{19}$Ne (Alpha cluster states)

- Predicted alpha cluster states using the simple potential model

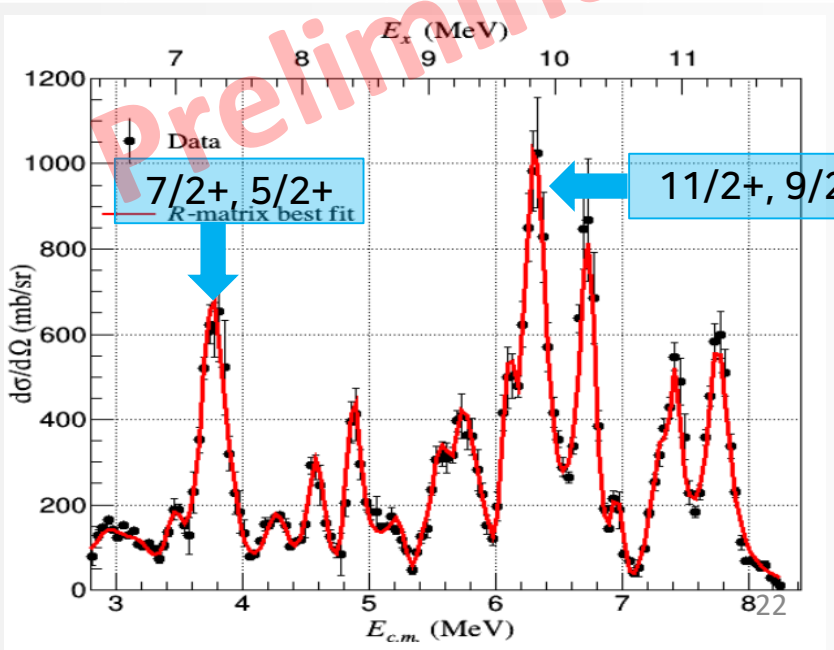



R. Otani et al., Phys. Rev. C 90, 034316 (2014)

- Resonance parameters of alpha cluster state candidates from this experiment

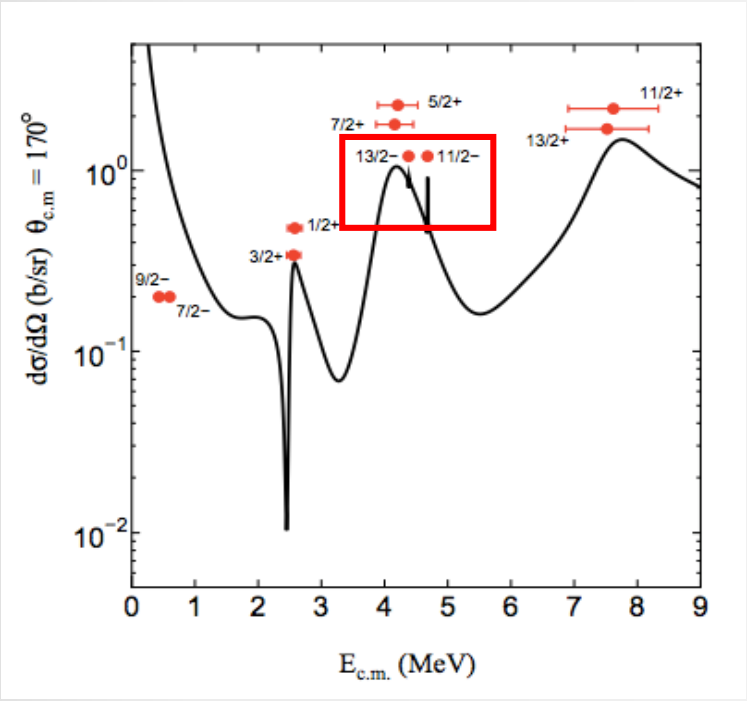
($\theta^2 > 0.1$) : alpha cluster state

| $E_x$ | $J^\pi$ | $\Gamma_\alpha$ (keV) | $\theta^2$ |
|---|---|---|---|
| 7.320(8) | $(7/2^+)$ | 130(3) | 0.67 |
| 7.420(8) | $(5/2^+)$ | 196(4) | 0.89 |
| 9.830(8) | (11/2+) | 120(3) | 0.49 |
| 9.880(4) | (9/2+) | 133(5) | 0.53 |



# Motivation: Alpha cluster states in A=19 isotopes

R. Otani et al., PRC 90, 034316 (2014)




D. Torresi et al., PRC 96, 044317 (2017)

TABLE II. Comparison of the calculated and measured $\alpha + {}^{15}O$ rotational levels.

| Expt. | | | Calc.[a] | |
|---|---|---|---|---|
| $E_x$ (MeV) | $I^\pi$ | $\theta_\alpha^2$ | $E_x$ (MeV) | $I^\pi$ |
| 0.27509(13)[b] | $1/2^-$[a] | (bound) | 0.52 | $1/2^-$ |
| 1.51756(3)[b] | $5/2^-$[a] | (bound) | 1.56 | $5/2^-$ |
| 1.6156(5)[b] | $3/2^-$[a] | (bound) | 1.66 | $3/2^-$ |
| 4.140(4)[b] | $(9/2^-)$ | $\leqslant 1$[c] | 3.98 | $9/2^-$ |
| 4.197(2)[b] | $(7/2^-)$ | $\leqslant 0.1$[c] | 4.18 | $7/2^-$ |
| 8.428(2)[d] | $(13/2^-)$[b] | 0.31(4)[d] | 7.98 | $13/2^-$ |
| (8.790)[d] | $(11/2^{-/+})$[b] | 0.10(3)[d] | 8.26 | $11/2^-$ |
| 14.2(3)[b] | — | — | 13.67 | $17/2^-$ |
| 14.5(3)[b] | — | — | 14.26 | $15/2^-$ |

[a]There is an uncertainty of ≈50 keV on the calculated energies for $9/2^-$ and above, from extracting the values from Fig. 3 of Ref. [45].

- Theoretical calculation result using simple potential model on the excitation energies of the cluster structure states in $^{19}$Ne.
- The $^{15}$O+α excitation function fitting result ($\theta_{c.m}$ = 180°). The states with negative alpha cluster states, $J^\pi$ = 13/2- and 11/2-, were measured.

**Finding positive alpha-cluster states which were predicted by theoretical calculation.**