THE 12th APCTP-BLTP JINR JOINT WORKSHOP

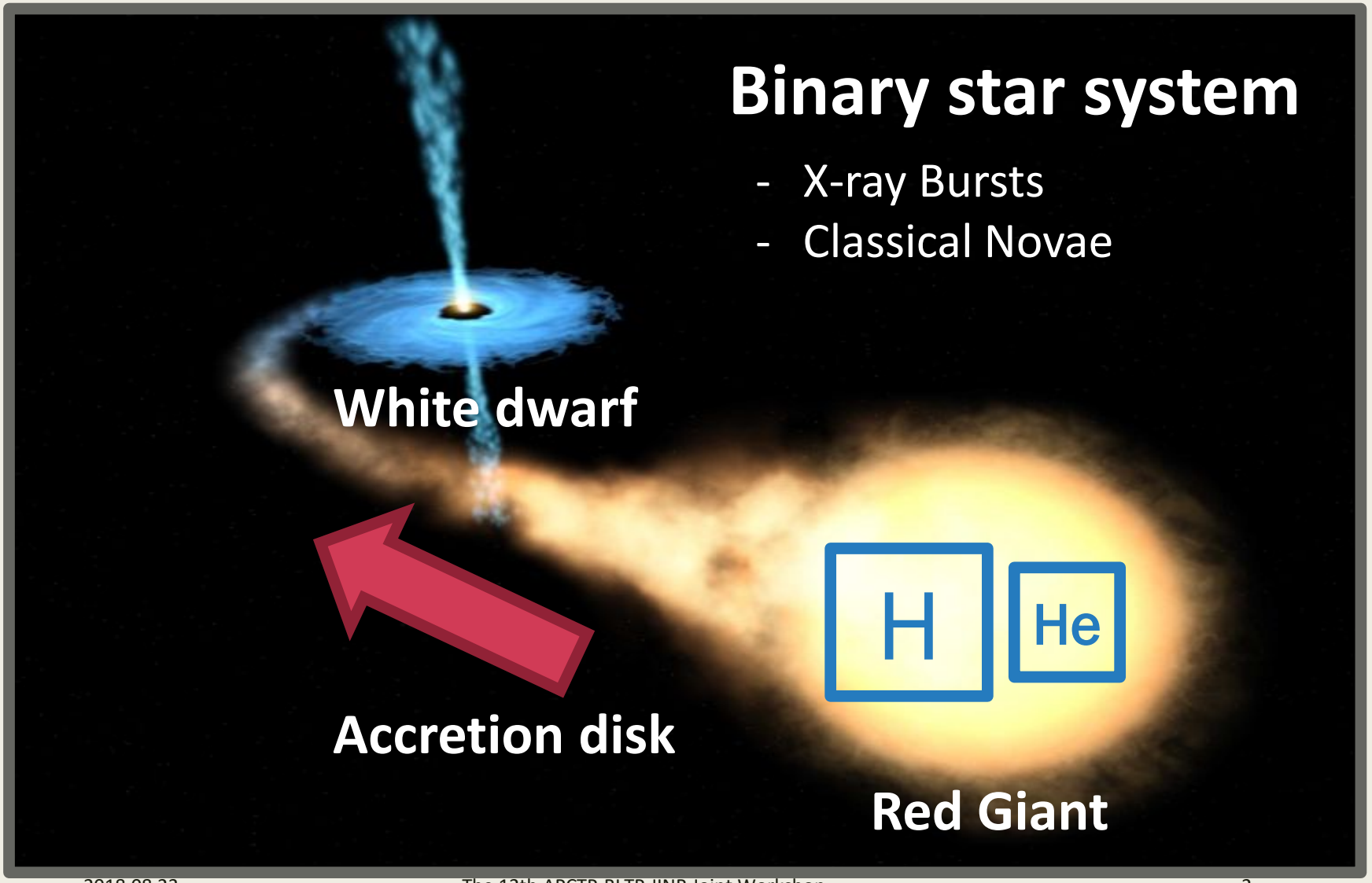
Study of ^{19}Ne and ^{19}F structures for astrophysical implication

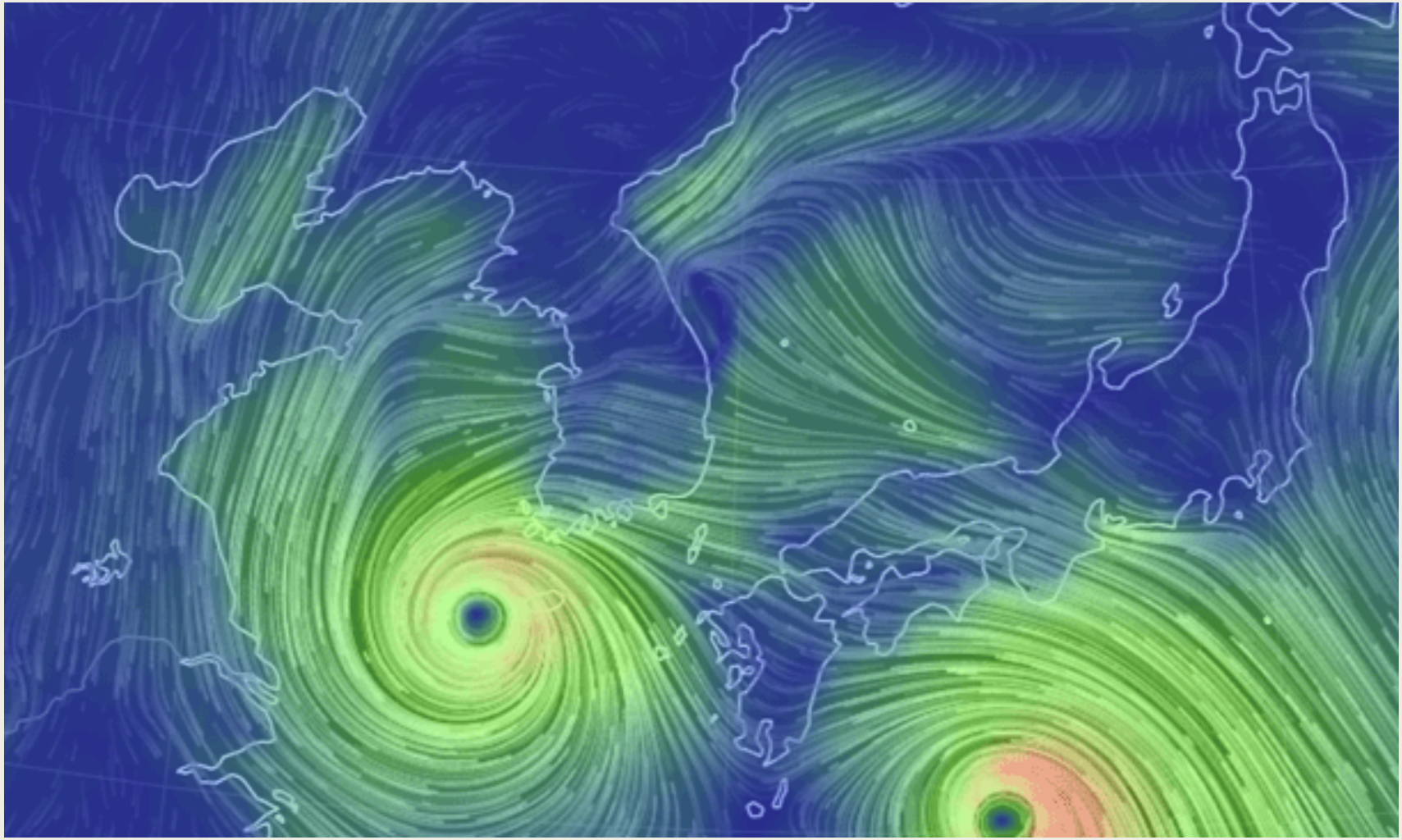
Kevin Insik Hahn
Ewha Womans University

Ph.D. thesis work by Dahee Kim

Motivation

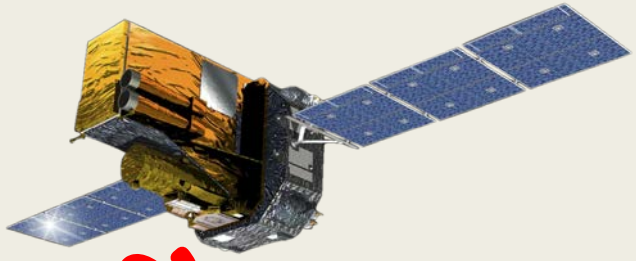
- **Classical nova**





Motivation

- **Properties of ^{18}F**



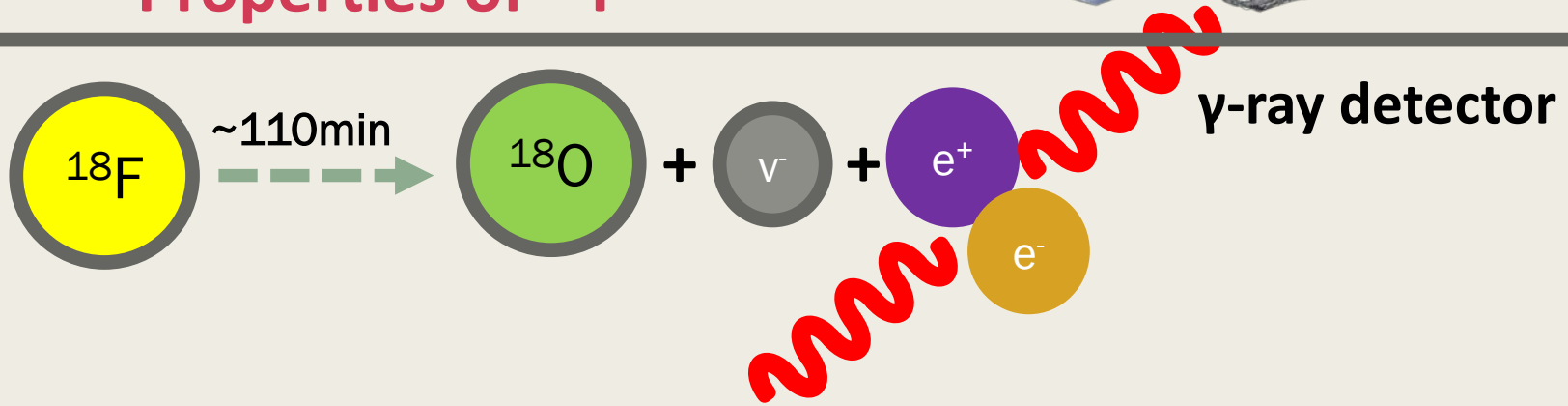
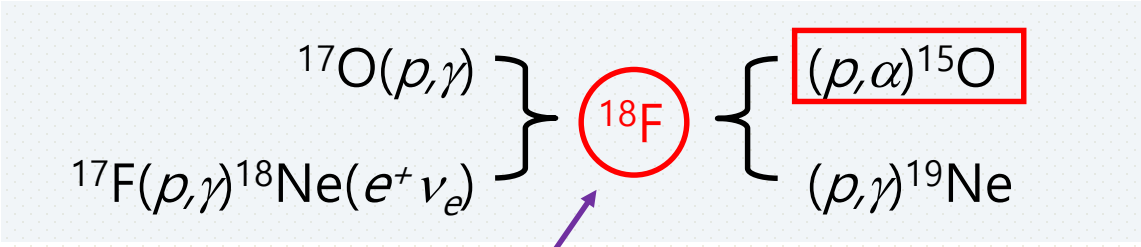


Table 1.1. List of γ-ray emission types for CO and ONe nova [7].

Nova type	Isotope	Mean lifetime	Main emission type
CO & ONe	^{13}N	9.965 min	511 keV line & continuum
CO & ONe	^{18}F	109.77 min	511 keV line & continuum
CO	^{7}Be	77 days	478 keV line
ONe	^{22}Na	2.6018 yr	1275 keV line
ONe	^{26}Al	10^6 yr	1809 keV line

$^{18}F(p,\alpha)^{15}O$ reaction in nova explosion



τ ~ 2hrs, β^+-decay

Important positron annihilation source

$^{18}F(p,a)^{15}O$ reaction rate is dominated by

1. $3/2^-$ resonance at E_{cm} = 330keV $\Rightarrow$ clearly measured.
2. the interference of $3/2^+$ states at E_{cm}= 8 and 38 keV and broad resonance at E_{cm}= 665 keV $\Rightarrow$ still controversial !!

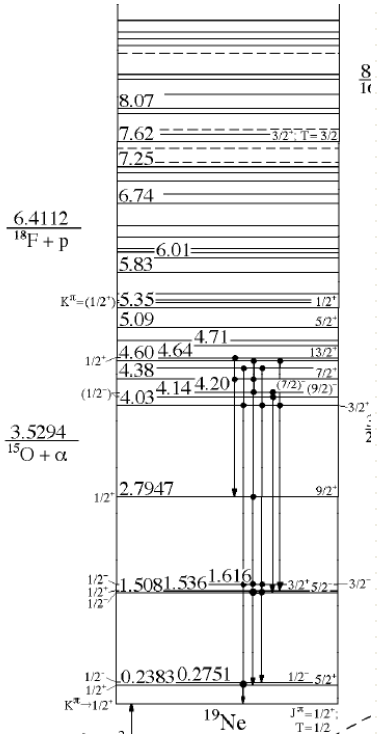
Is γ-Ray Emission from Novae Affected by Interference Effects in the $^{18}F(p, \alpha)^{15}O$ Reaction?

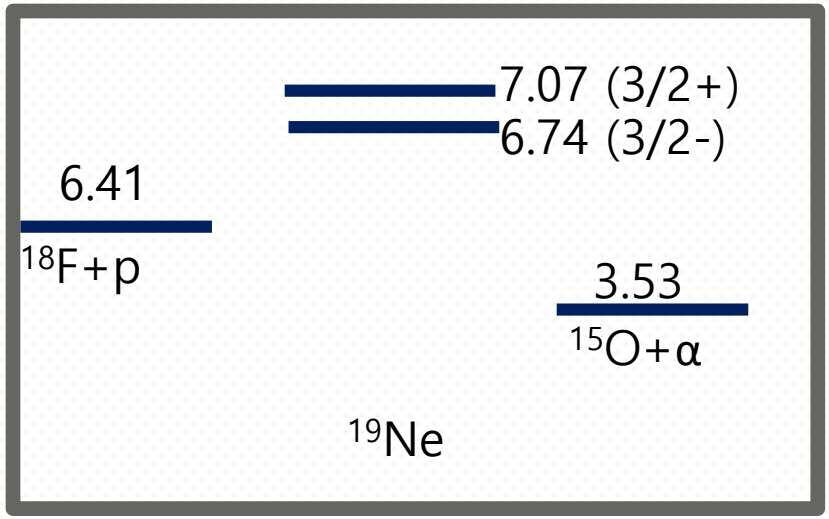
A. M. Laird,[1,*] A. Parikh,[2,3] A. St. J. Murphy,[4] K. Wimmer,[5,6] A. A. Chen,[7] C. M. Deibel,[8,9] T. Faestermann,[10,11] S. P. Fox,[1] B. R. Fulton,[1] R. Hertenberger,[11,12] D. Irvine,[7] J. José,[2,3] R. Longland,[2,3] D. J. Mountford,[4] B. Sambrook,[7] D. Seiler,[10,11] and H.-F. Wirth[11,12]

Present work				
E_x (MeV)	E_{cm} (keV)	J^π	Γ_p (keV)[b]	Γ_α (keV)[b]
6.014(2)	−397	$3/2^-$	···	···
6.072(2)	−339[c]	$(3/2^+, 5/2^-)$	0.143	6×10^{-4}
6.097(3)	−314	$(7/2, 9/2)^+$	···	···
6.132(3)	−282[c]	$(3/2^+, 5/2^-)$	0.143	7×10^{-4}
6.289(3)	−122	···	···	···
6.416(3)	5[c]	$(3/2^-, 5/2^+)$	4.7×10^{-50}, 1.2×10^{-51}	0.5, 0.126
6.440(3)	29	$(11/2^+)$	···	···
6.459(3)	48[c]	$(5/2^-)$	8.4×10^{-14}	5.5
6.700(3)	289	···		
6.742(2)	331[c]	$(3/2^-)$	2.22×10^{-3}[d]	5.2[d]
6.862(2)	451	$(7/2^-)$	1.1×10^{-5}[d]	1.2[d]

None of three states just above the proton threshold are found to be consistent with 3/2+ assignment!

We need to decide the resonance energy and J^{π} of important states around the proton threshold for the determination of the reaction rate.





Low alpha threshold energy!
Easy to find the resonances around the proton threshold via $^{15}O + \alpha$!

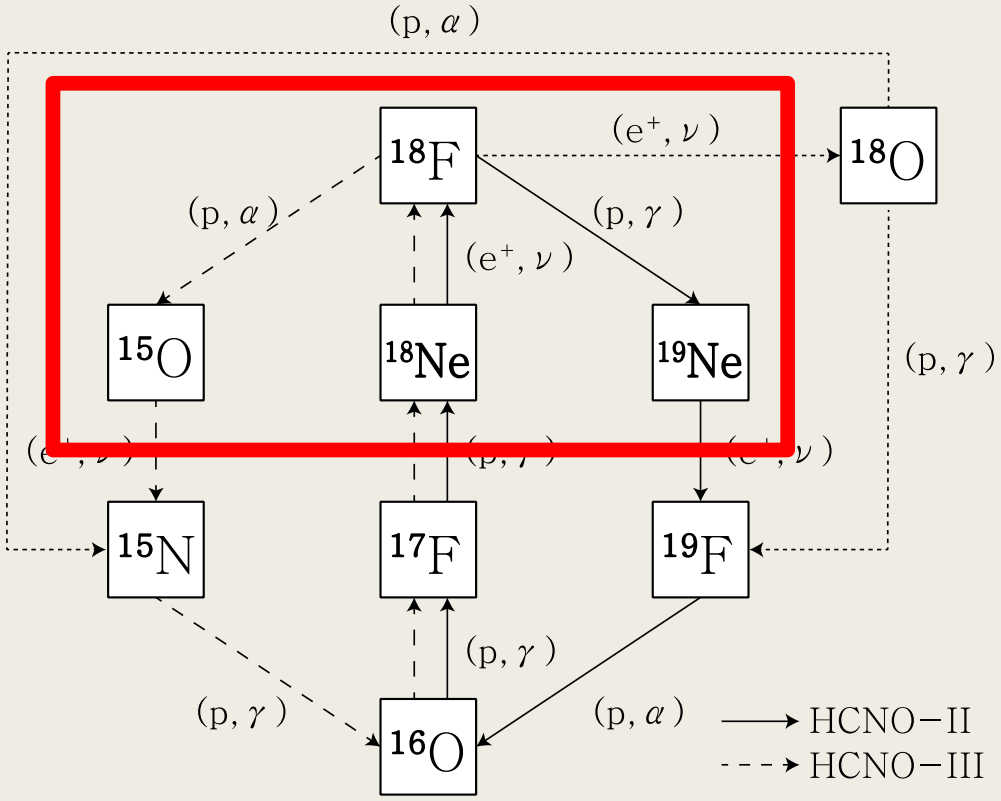
Motivation

- **^{18}F nucleosynthesis in the classical nova**

Destructive reactions of ^{18}F

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

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



Previous study

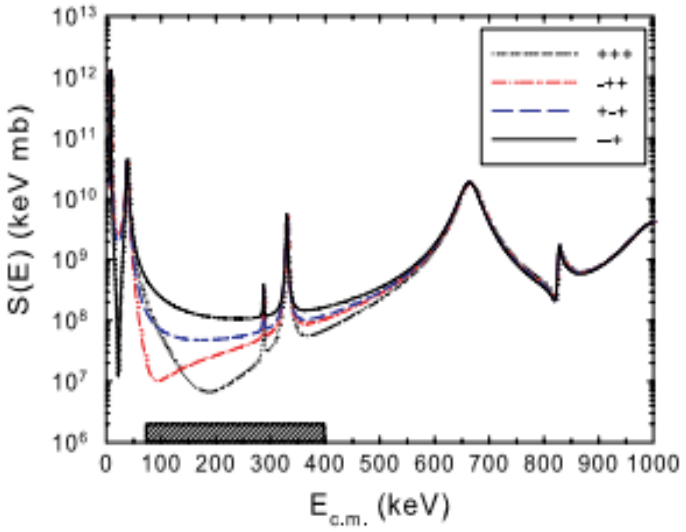
- **Interference effect**

K. Y. Chae et al.
Astrophysical S- factor of the $^{18}F(p,a)^{15}O$ reaction

- Several resonances near the proton threshold (E_x = 6.411 MeV) mainly affect the $^{18}F(p,\alpha)^{15}O$ reaction rate in T_9 = 0.04 ~ 0.4. These states were well investigated by many studies.

- However, the 3/2+ sub-threshold states and above the proton threshold have interference, and they affect the reaction rate between T_9 = 0.04 ~ 0.4.

E_r (keV)	J^π	Γ_p (keV)	Γ_α (keV)	Ref.
8	$3/2^+$	2.2×10^{-37}	0.5	[10]
26	$1/2^-$	1.1×10^{-20}	220.0	[10]
38	$3/2^+$	4.0×10^{-15}	4.0	[10]
287	$5/2^+$	1.2×10^{-5}	1.2	[10]
330	$3/2^-$	2.22×10^{-3}	2.7	[11]
450	$7/2^-$	1.6×10^{-5}	3.1	[12]
664.7	$3/2^+$	15.2	24.0	[8]
827	$3/2^+$	0.35	6.0	[12]
842	$1/2^+$	0.2	23.0	[12]
1009	$7/2^+$	27.0	71.0	[12]
1089	$5/2^+$	1.25	0.24	[12]
1122	$5/2^-$	10.0	21.0	[12]



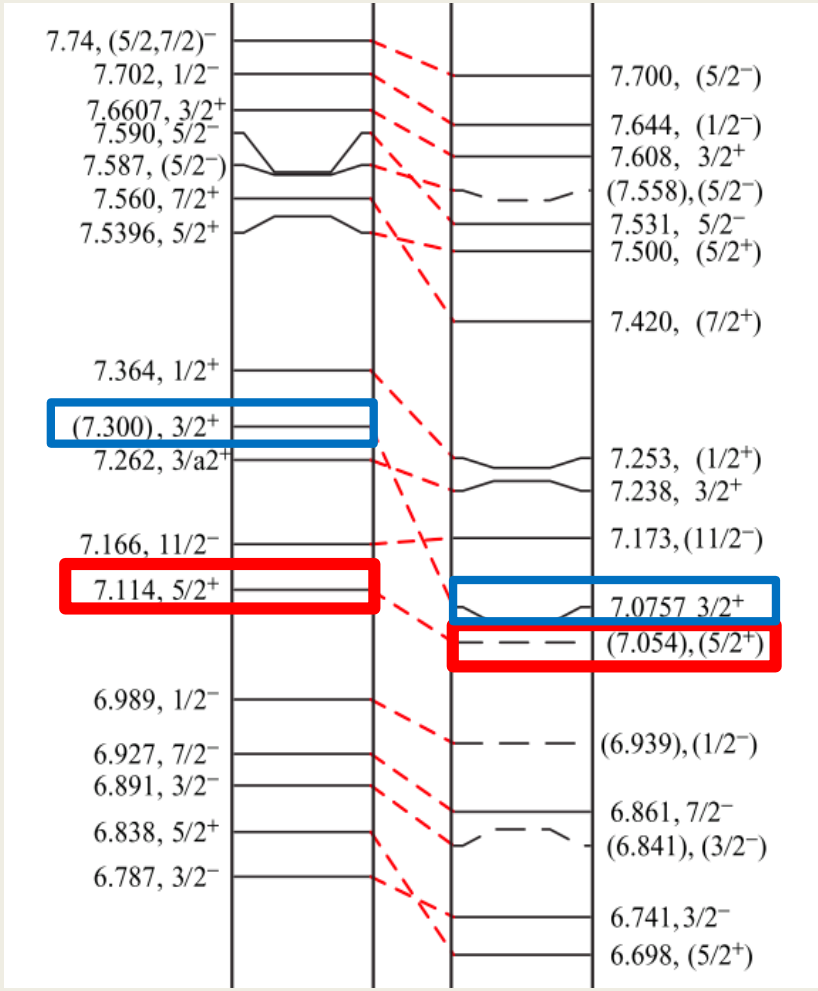
Previous study

- **Missing state**

C.D. Nesaraja et al.
^{19}Ne and ^{19}F mirror states

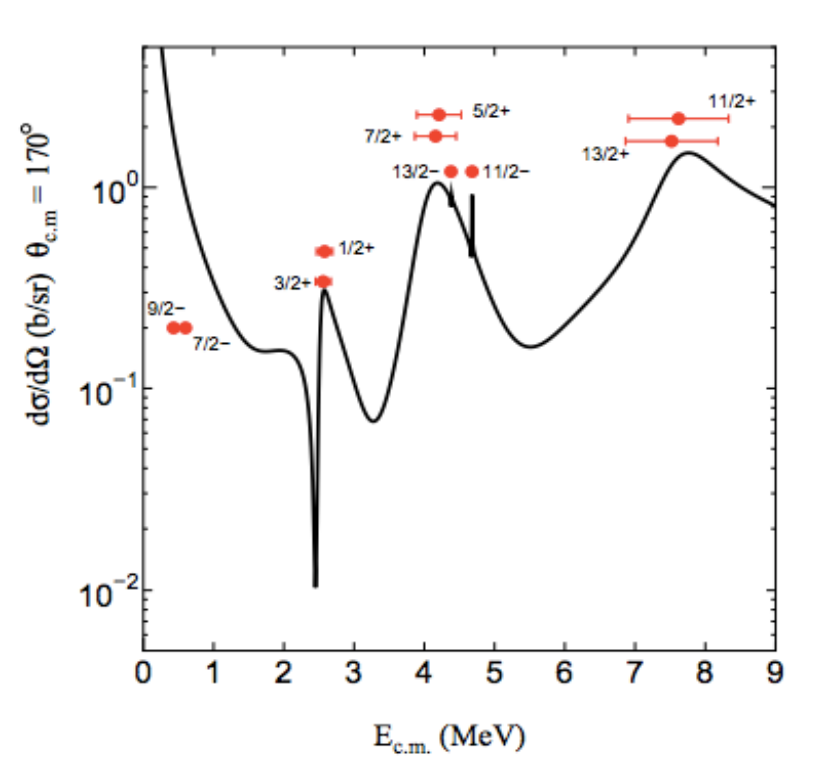
- Due to the insufficient experimental results in ^{19}Ne, important resonance parameters of ^{19}Ne were extracted from the mirror nucleus ^{19}F.

- The E_x = 7.054 MeV state in ^{19}Ne may affect the ^{18}F(p,α)^{15}O reaction rate. However, it has not been measured yet.

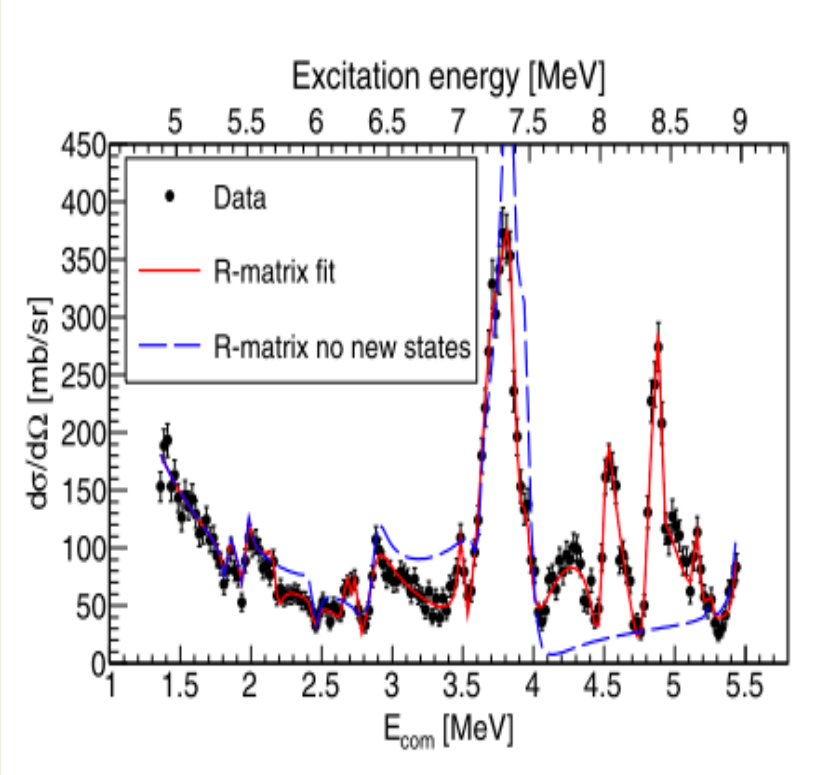


Previous study

- **Alpha cluster states**



Otani et al. (2016)
Theoretical calculation on the excitation energies of the cluster structure states in ^{19}Ne



D. Torresi et al. (2017)
^{15}O+alpha excitation function fitting result ($\theta_{c.m.}$ = 180°) Fitting result used R-matrix code (SAMMY)

Purpose

- To study the $^{18}F(p,\alpha)^{15}O$ reaction rate
  - Affects the abundance calculation model of ^{18}F in the classical nova

$$^{15}O+\alpha \rightarrow {}^{19}Ne^{*}$$

- Find accurate resonance parameters of ^{19}Ne near the proton threshold

6.419 MeV, 6.449 MeV,
(7.054 MeV), 7.0757 MeV, 7.420 MeV
…

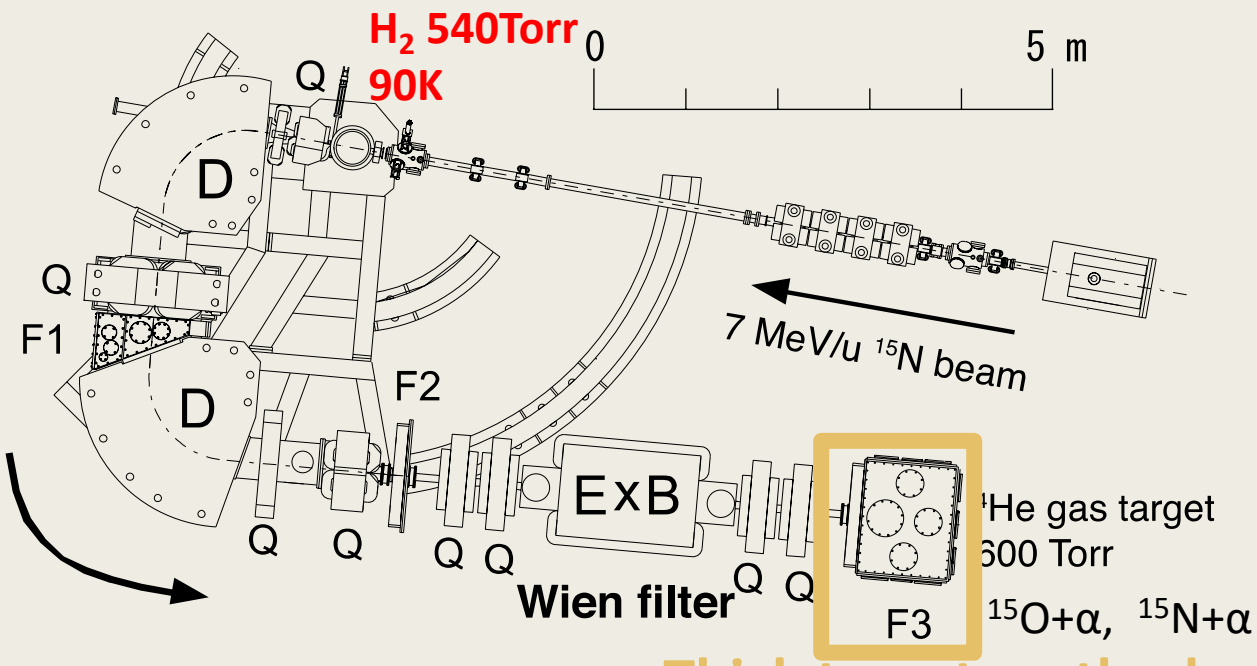
Spin, Parity ?

Missing state

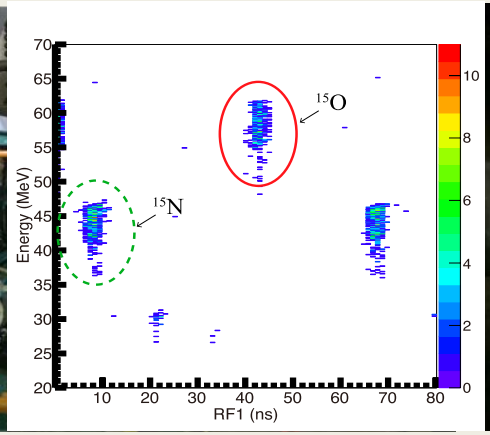
Existence ??

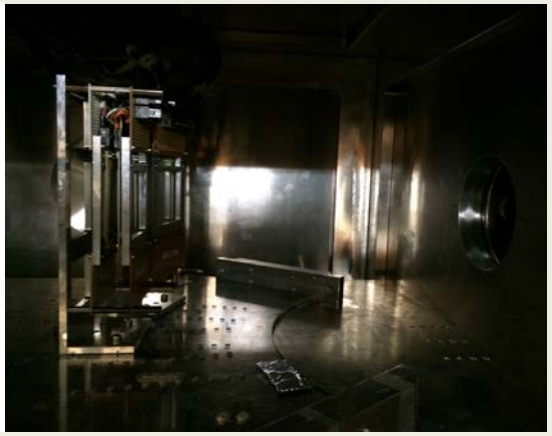
- To investigate the structures of ^{19}Ne and ^{19}F in a wide energy range

Experimental set-up



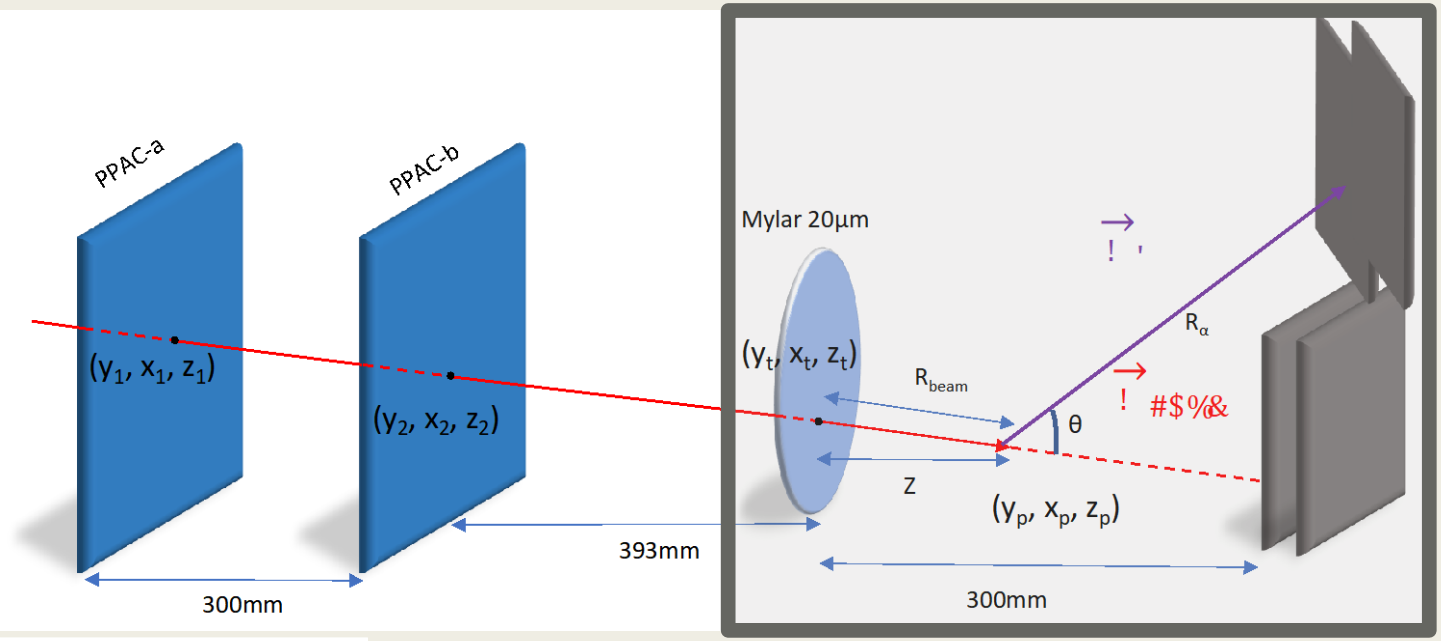
Thick target method

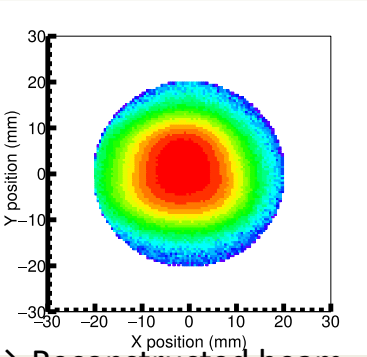




Reaction reconstruction

- **Reaction reconstruction**





→ Reconstructed beam position at the F3 window

$$cos\theta = \vec{V}_{beam} \cdot \vec{V}_{\alpha}$$

The reaction point depends on the detected α particle energy, α position, the beam direction, and energy loss in the target.

Reaction reproduction

- **Differential cross section**

$$\frac{d\sigma}{d\Omega} = \frac{Y M(^4He)}{N_{beam} N_A T_{eff} \Delta\Omega}$$

Y : yield (#/s)

M(^{4}He) : 4.003 g/mol

N_{beam} : number of ^{15}O beam particles

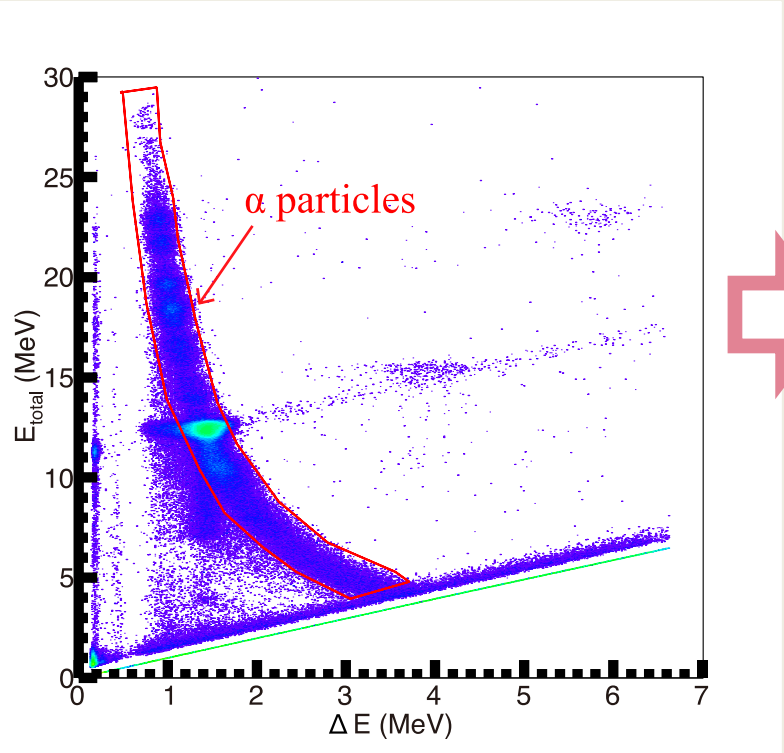
N_A : Avogadro number($6.02*10^{23}$#)

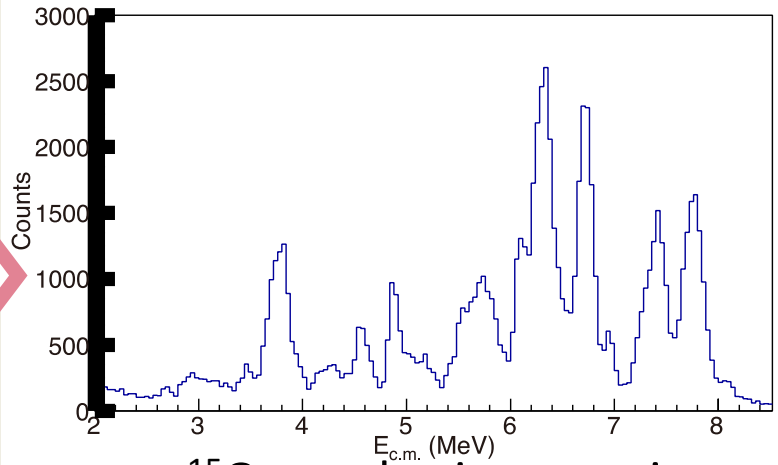
T_{eff} : Effective thickness (g/cm^2)

$\Delta\Omega$: solid angle (sr)

Data analysis

- **Background reduction**



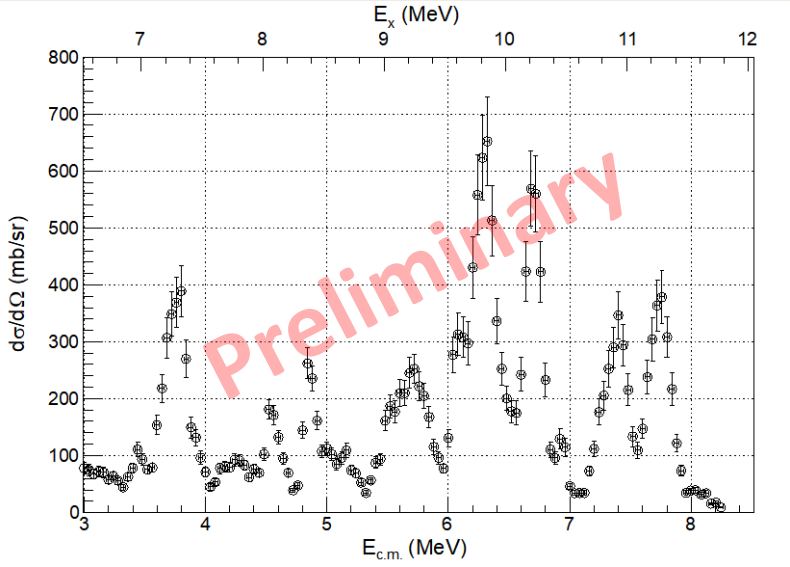


$^{15}O + \alpha$ elastic scattering

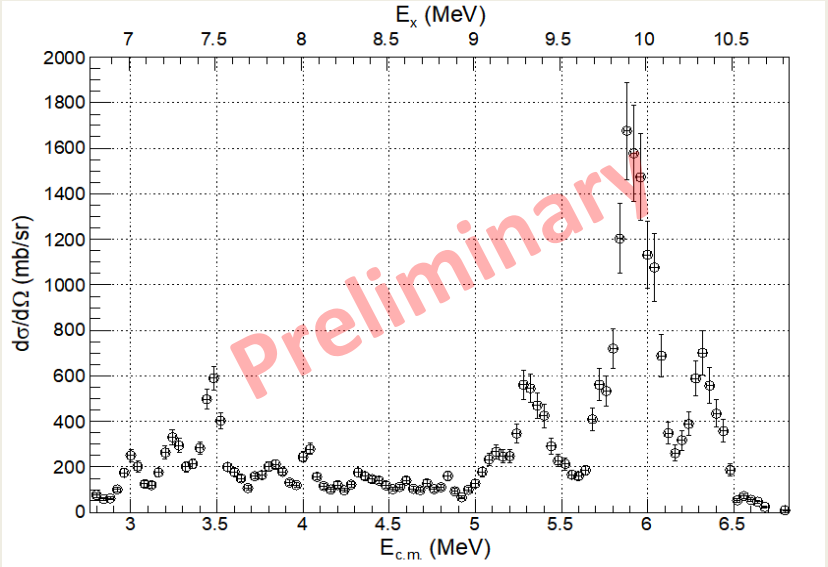
^{15}O + argon run

Result

- **Cross section**



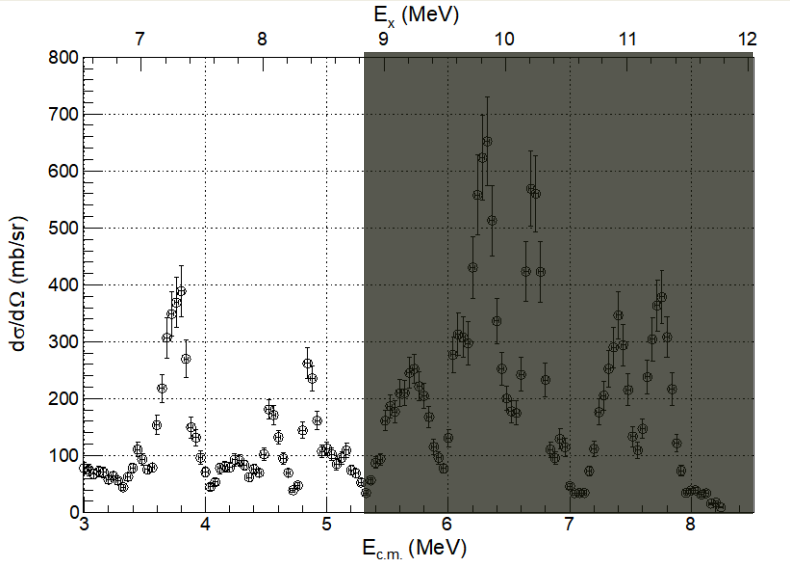
The excitation function for ^{19}Ne



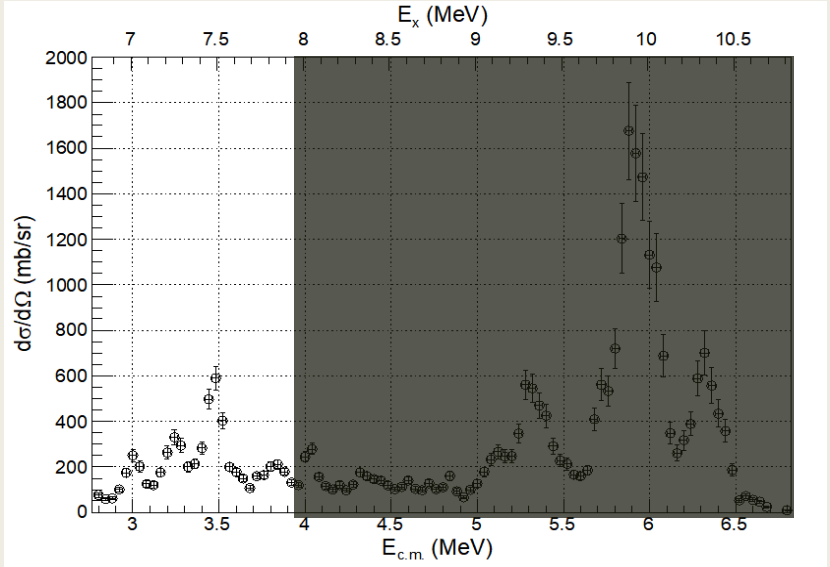
The excitation function for ^{19}F

Result

- **Cross section**



The excitation function for ^{19}Ne



The excitation function for ^{19}F

Result

- **The obtained ^{19}F resonance parameters**

TABLE I: Resonance parameters of the levels in ^{19}F with $E_x = 6.5 - 7.9$ MeV.

Previous study					This work				
E_x (MeV ± keV)	Γ_α (keV)	Γ (keV)	J^π	Ref.	$E_{c.m.}$ (MeV)	E_x (MeV)	Γ_α (keV)	l	J^π
6.536 ± 5[a]	245 ± 6	-	$\frac{1}{2}^-$	[19, 23, 25]					
6.838 ± 0.9[b]	1.2	-	$\frac{5}{2}^+$	[19, 23]	2.82	6.83	2.4 ± 0.6	3	$\frac{5}{2}^+$
6.989 ± 3[b]	96 ± 6	-	$\frac{1}{2}^-$	[19, 23]	2.98	6.99	100 ± 32	0	$\frac{1}{2}^-$
7.114 ± 6[b]	∼ 30	-	$\frac{3}{2}^+$	[19, 21]	3.10	7.11*	32 ± 6	3	$(\frac{5}{2}^+)$
	25 ± 4	-	$\frac{5}{2}^+$	[23]			23 ± 4	3	$(\frac{7}{2}^+)$
	32	-	$\frac{7}{2}^+$	[15, 19]					
7.353[a]	65	-	$\frac{7}{2}^+$	[19, 23]	3.32	7.33	69 ± 10	3	$(\frac{5}{2}^+)$
							39 ± 8	3	$(\frac{7}{2}^+)$
7.56 ± 10[b]	-	< 90	$\frac{7}{2}^+$	[19]	3.53	7.56*	78 ± 7	3	$\frac{7}{2}^+$
7.587	$\Gamma_{lab} < 50$	-	$(\frac{5}{2}^-)$	[29]	3.58	7.59	49 ± 13	2	$\frac{5}{2}^-$
7.702 ± 5	-	< 30	$\frac{1}{2}^-$	[29]	3.68	7.69	59 ± 25	2	$(\frac{3}{2}^-)$
7.88[c]	-	< 260	-	[19]					

[a] from Ref. [23]

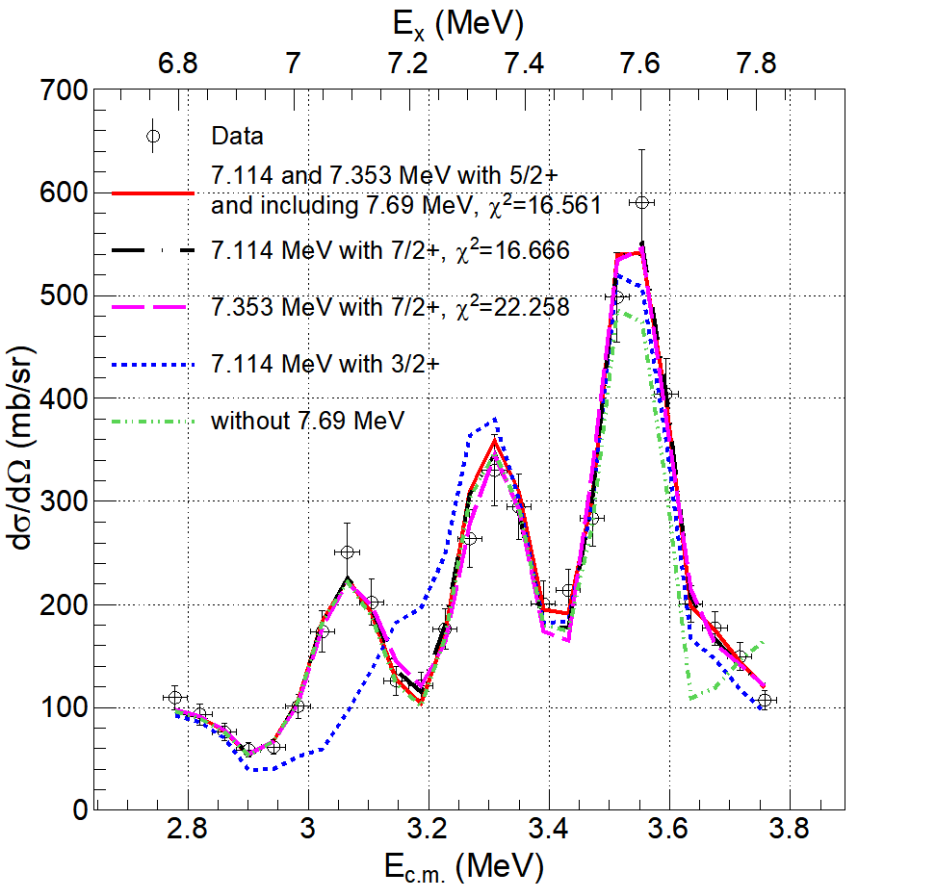
[b] from Ref. [29]

[c] from Ref. [19]

* used for the calibration

Discussion (^{19}F)

- We successfully reproduce the previous experimental result of ^{19}F.
- The E_x = 7.114 MeV state J^π could be assigned with 7/2+ and 5/2+. We obtained the best fit with 5/2+, and the J^π =3/2+ was ruled out.
- The E_x = 7.353 MeV state spin assignment was changed from 7/2+ to 5/2+.
- The E_x = 7.56 and 7.58 MeV states were newly determined the alpha width.
- The E_x = 7.69 MeV state can be a newly found state in ^{19}F because we could not find the corresponded J^π and Γ_α in the previous results.



Result

- **The obtained ^{19}Ne resonance parameters**

Table 3.3. Summary of ^{19}Ne resonance parameters compared with previous studies.

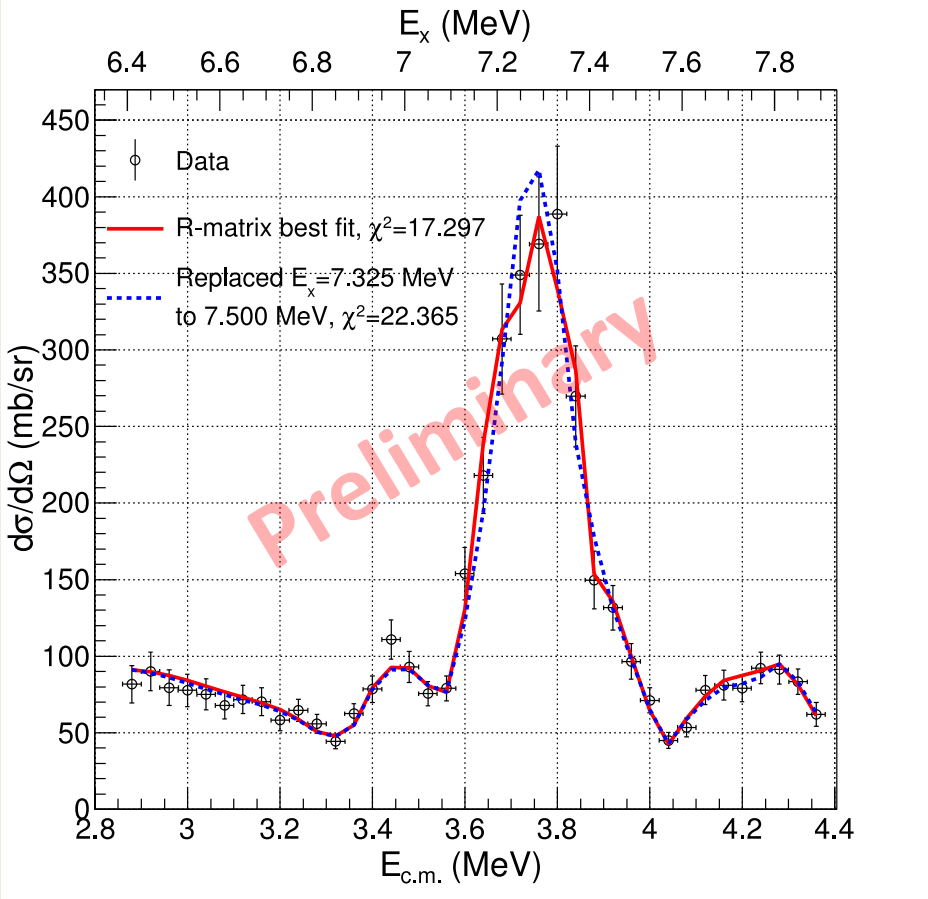
Previous study					This work		
E_x[a] (MeV ± keV)	E_γ[a] (keV)	Γ_α (keV)	J^π	Ref.	E_x (MeV)	Γ_α (keV)	J^π
6.437	26 ± 9	216 ± 19	$\frac{1}{2}^-$	[26, 49]			
6.939	528 ± 30 9	99 ± 69	$\frac{1}{2}^-$	[51]	6.94	138	$\frac{1}{2}^-$
(7.054)	643 ± 30	29 ± 25	$(\frac{5}{2}^+,\frac{7}{2}^+)$	[15, 51]	7.03	20	$\frac{5}{2}^+$
7.076	664.7 ± 16	23.8 ± 1.2	$\frac{3}{2}^+$	[4, 10, 14, 15, 18, 19, 21, 22, 23]	7.11	38	$\frac{3}{2}^+$
7.326	915 ± 11	46 ± 40	$\frac{1}{2}^+$	[14, 42, 49]	7.24	38	$(\frac{5}{2}^+)$
7.420	1009 ± 14	71 ± 11	$(\frac{7}{2}^+)$	[15, 23]	7.35	72	$\frac{7}{2}^+$
7.531	1120 ± 11	21 ± 11	$\frac{5}{2}^-$	[4, 23, 49]	7.35	25	$\frac{5}{2}^-$
7.608	1197 ± 11	43 ± 15	$\frac{3}{2}^+$	[4, 51]	7.49	46	$(\frac{3}{2}^-)$
7.644	1233 ± 12	16 ± 6	$(\frac{1}{2}^-,\frac{3}{2}^-)$	[4, 22, 51]			
7.758	1347 ± 5	5 ± 2	$\frac{3}{2}^+$	[22]	7.78	308	$(\frac{5}{2}^-)$

[a] from Ref. [51]

Preliminary

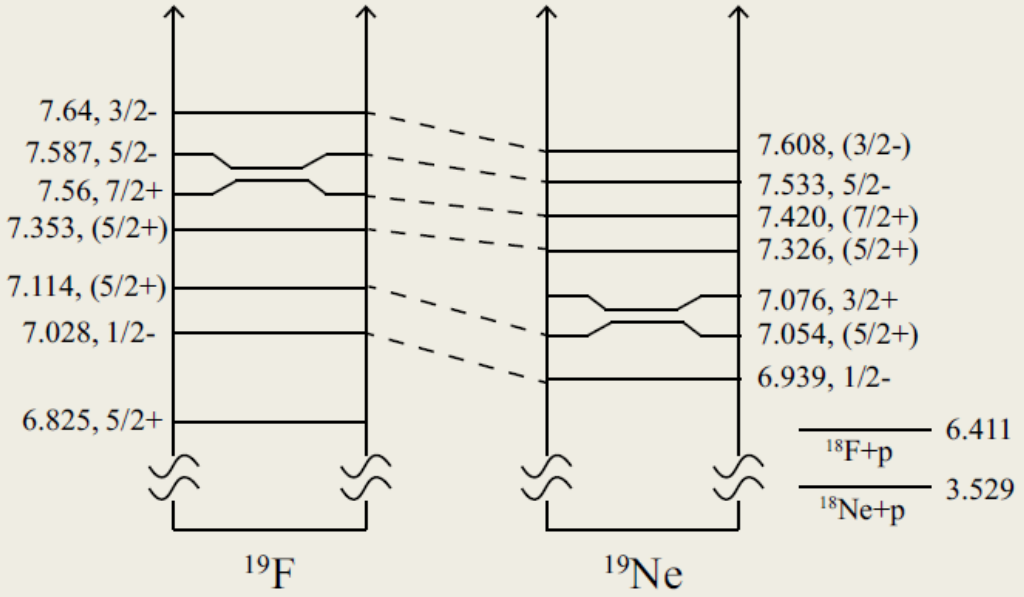
Discussion (^{19}Ne)

- The 7.076 MeV state was identified and assigned the J^{π} with 3/2+.
- The strong peak was found at E_x ~ 7.3 MeV which may consist with four resonances , E_x = 7.326, 7.420, 7.531, and 7.644 MeV.
- The 7.326 MeV state was ruled out for the ^{18}F(p,α)^{19}Ne reaction rate calculation due to the weak evidence. However, we found the state with a large alpha width, so we suggest that the 7.326 MeV state should be considered to the reaction calculation.



Result

- **Mirror states**

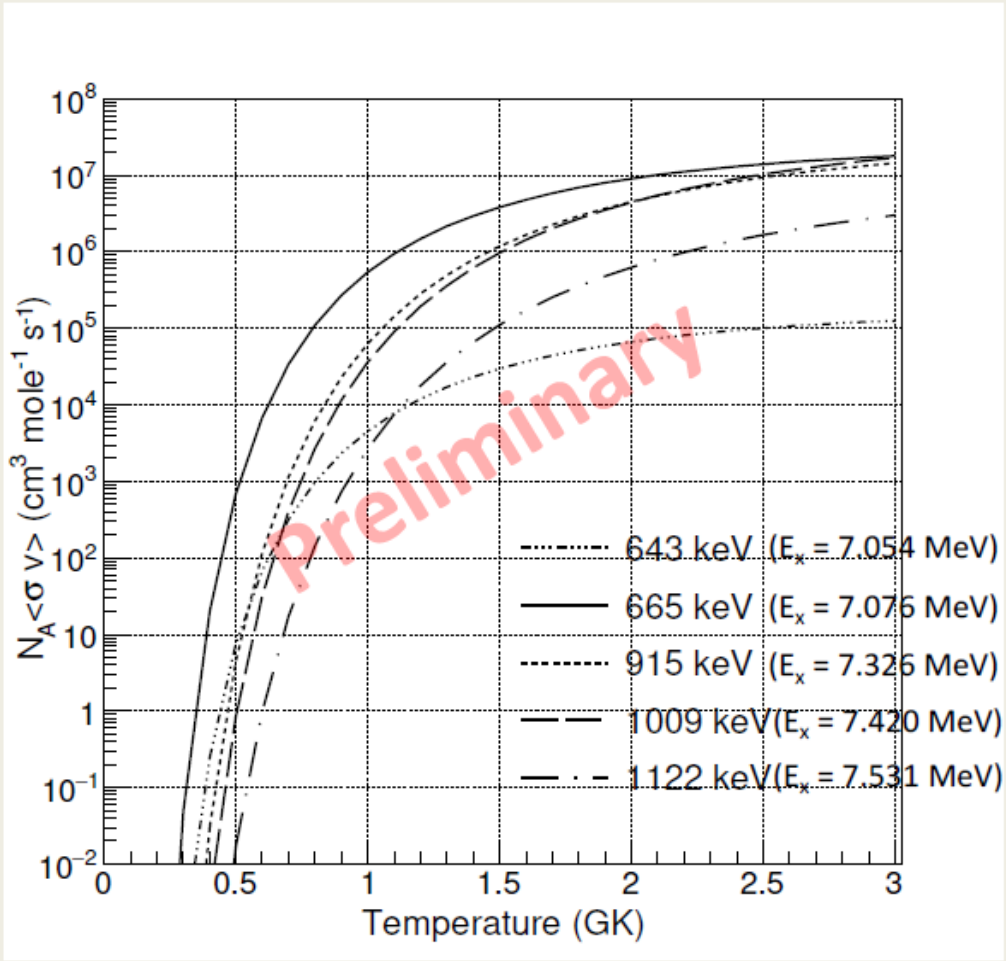


This diagram shows the presumed mirror states using our analysis results.

- The mirror state of 7.076 MeV state in ^{19}Ne is still missing.
- The missing state at E_x = 7.054 MeV was measured in the present experiment. This state can be corresponded to E_x = 7.114 MeV state in ^{19}F.
- The mirror state of E_x = 7.56 MeV in ^{19}F was found at E_x = 7.420 MeV in ^{19}Ne.
- For the E_x = 7.608 MeV state, which may be a new state in ^{19}Ne, we found the candidate of a mirror state at E_x = 7.64 MeV.

Result : $^{18}F(p,\alpha)^{15}O$ reaction rate

- The $^{18}F(p,\alpha)^{15}O$ reaction rate was calculated using our results.
- The E_x = 7.076 MeV state is still dominant in the reaction rate.
- We found newly determined E_x = 7.420 and 7.326 MeV states, and these states also affect the $^{18}F(p,\alpha)^{15}O$ reaction rate



Conclusions

- Experimental data for ^{19}F, which is the mirror nuclei of ^{19}Ne, were also taken for the analysis of ^{19}Ne data

- More than 8 peaks in ^{19}Ne were shown in silicon telescopes with energy resolution of $E_{c.m.}$ = 40 keV.

- The $^{18}F(p,\alpha)^{15}O$ reaction rate was calculated using our data, and we found newly observed states which affect the reaction rate.

- Investigation of alpha cluster structures in ^{19}Ne and ^{19}F are in progress.

Thank you for your attention