Experimental study on astrophysically important ^{22}Mg nucleus via resonant scattering of ^{18}Ne+α

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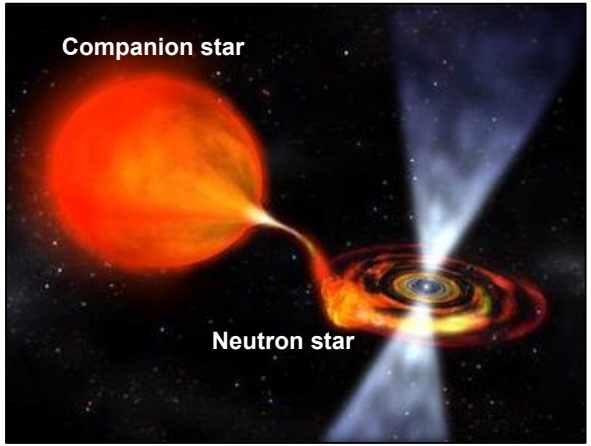
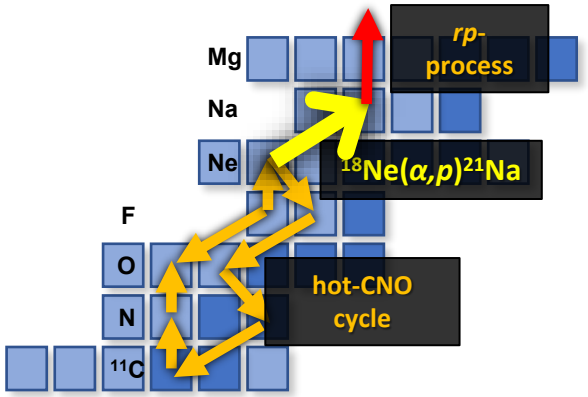
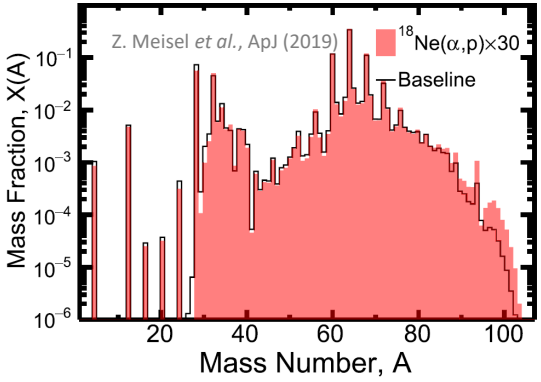
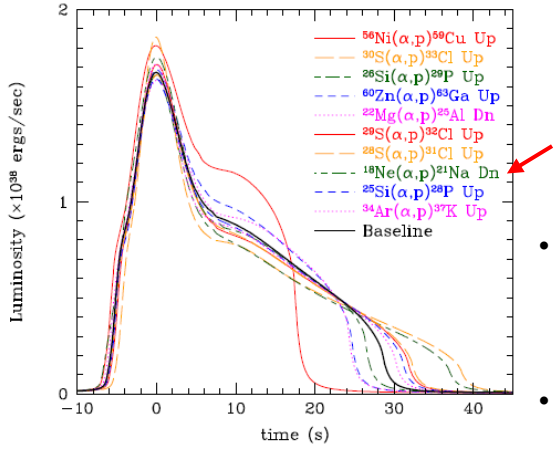
Background Image:
Courtesy of J. DePasquale.

^{18}Ne(α,p)^{21}Na reaction









Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{15}O(α, γ)^{19}Ne	D	16	1
2	^{56}Ni(α, p)^{59}Cu	U	6.4	1
3	^{59}Cu(p, γ)^{60}Zn	D	5.1	1
4	^{61}Ga(p, γ)^{62}Ge	D	3.7	1
5	^{22}Mg(α, p)^{25}Al	D	2.3	1
6	^{14}O(α, p)^{17}F	D	5.8	1
7	^{23}Al(p, γ)^{24}Si	D	4.6	1
8	^{18}Ne(α, p)^{21}Na	U	1.8	1
9	^{63}Ga(p, γ)^{64}Ge	D	1.4	2
10	^{19}F(p, α)^{16}O	U	1.3	2
11	^{12}C(α, γ)^{16}O	U	2.1	2
12	^{26}Si(α, p)^{29}P	U	1.8	2
13	^{17}F(α, p)^{20}Ne	U	3.5	2
14	^{24}Mg(α, γ)^{28}Si	U	1.2	2
15	^{57}Cu(p, γ)^{58}Zn	D	1.3	2
16	^{60}Zn(α, p)^{63}Ga	U	1.1	2
17	^{17}F(p, γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p, γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p, γ)^{49}Mn	D	1.2	2

R. H. Cyburt *et al.*, ApJ (2016)

- **one of the break-out candidates from the hot-CNO cycle, fueling the *rp*-process**

  R. Wallace & S. Woosely, ApJ. S. (1981)

- **affects on the characteristics of X-ray burst (light curve, ash composition)**

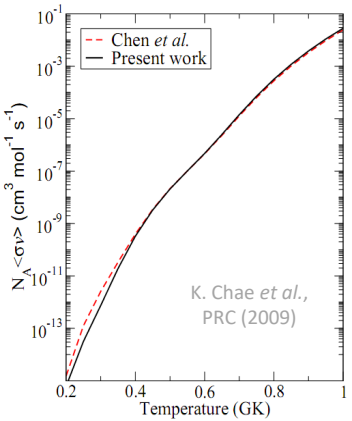
Previous studies on the ^{18}Ne(α,p)^{21}Na reaction

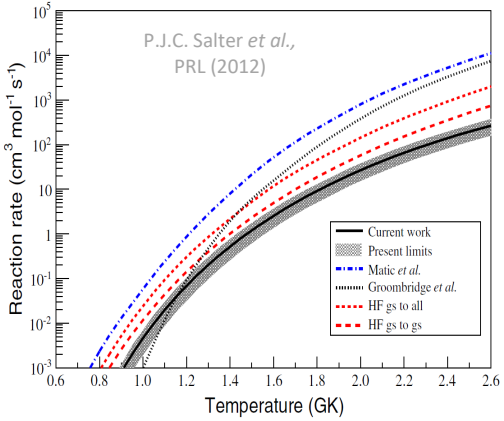
Indirect measurements

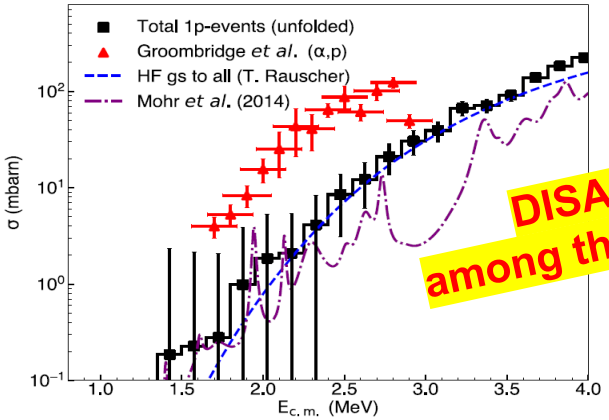
- **studies of the structure of ^{22}Mg**
  - ^{24}Mg(p,t)^{22}Mg, ^{12}C(^{16}O,^{6}He)^{22}Mg, ^{25}Mg(^{3}He,^{6}He)^{22}Mg, …
  - several resonance parameters obtained
- **time reversal reaction : ^{21}Na(p,a)^{18}Ne**
  - Salter *et al.*, PRL(2012) : E_{cm} = 1.19-2.57 MeV
  - only (a,p_0) measured → considered as a lower limit

Direct measurements

- **two measurements at Louvain-la-Neuve**
  - Bradfield-Smith *et al.*, PRC (1999) : E_{cm} = 2.0-3.0 MeV
  - Groombridge *et al.*, PRC (2002) : E_{cm} = 1.7-2.9 MeV
- **recent measurement at FSU**
  - Anastasiou *et al.*, PRC (2022) : E_{cm} = 2.5-4 MeV



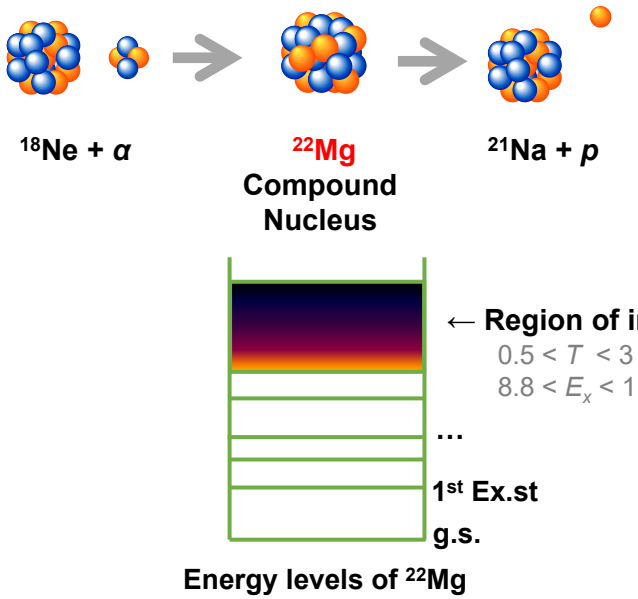


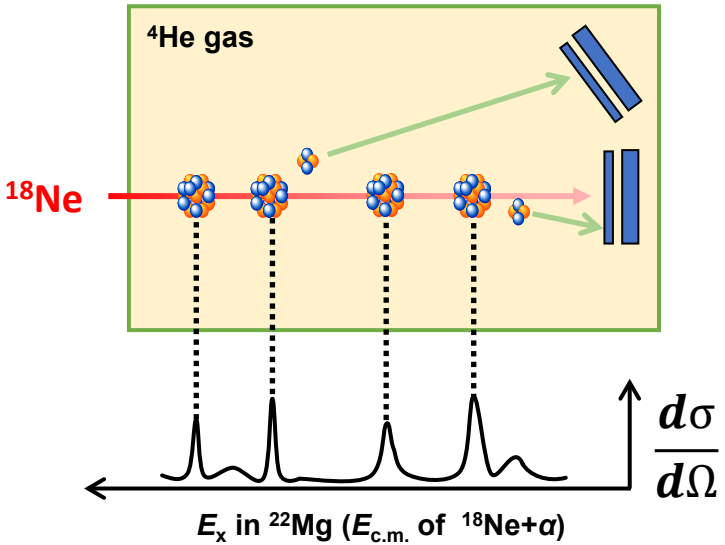


DISAGREEMENT among the measurements!

M. Anastasiou *et al.*, PRC (2022)

Experiment – Goals & Strategies





- Energy level properties of ^{22}Mg above the $E_{\alpha\text{-thres.}}$ dominates the ^{18}Ne(α,p)^{21}Na reaction
- ^{18}Ne+α resonant scattering can populate the energy levels of ^{22}Mg !
- Thick target method in inverse kinematics adopted.

K. P. Artemov *et al.*, Sov. J. Nucl. Phys. 52, 408 (1990)

α-cluster structure in ^{22}Mg nucleus

Theoretical Prediction

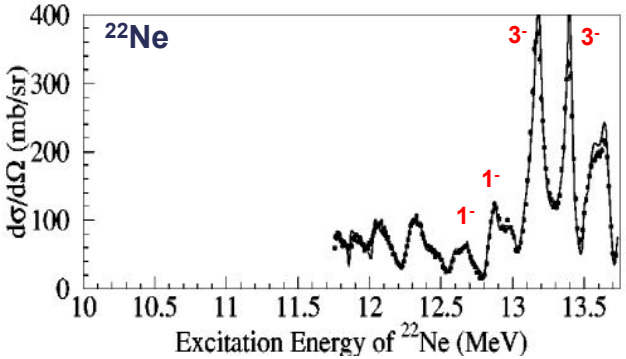
M. Dufour & P. Descouvemont, NPA (2003)

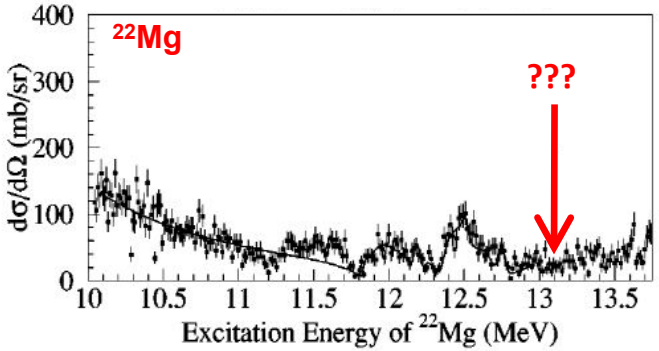
ETCM calculation : ^{22}Ne		
J^{π}	E_x (MeV)	θ_α^2 (%)
1^-	12.58	13
1^-	13.53	8
3^-	12.92	13
3^-	13.69	11

GCM calculation : ^{22}Mg		
J^{π}	E_x (MeV)	θ_α^2 (%)
1^-	12.14	11.5
1^-	13.04	6.7
3^-	12.46	11.6
3^-	13.19	11.7

Experiment

G.V. Rogachev *et al.*, PRC (2001)
V. Goldberg *et al.*, PRC (2004)





- **Predicted 1^- and 3^- doublets arose from the α-cluster structure in ^{22}Mg**
- **Not observed in the previous experiment**

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1^-	12.14	11.5

^{18}Ne+α resonant scattering

1. To enhance our knowledges on the ^{18}Ne(α,p)^{21}Na reaction
2. Observation of 1^- and 3^- states could be the evidence of the α-cluster states in ^{22}Mg nucleus.
3. Investigating wide energy range will provide the first spectroscopic study for E_x > 14 MeV !

Excitation Energy of ^{22}Ne (MeV)

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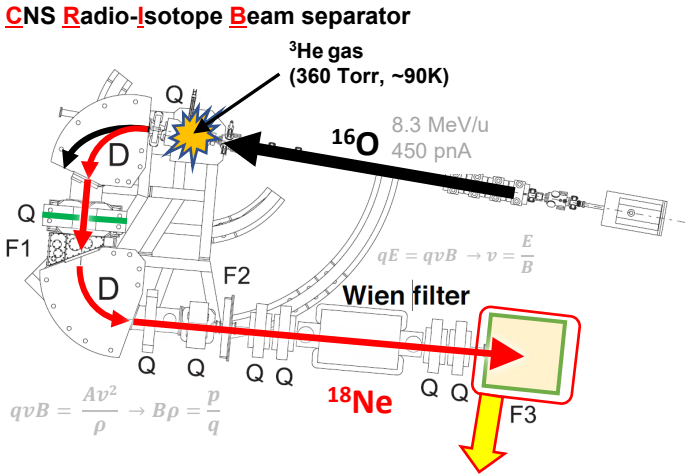
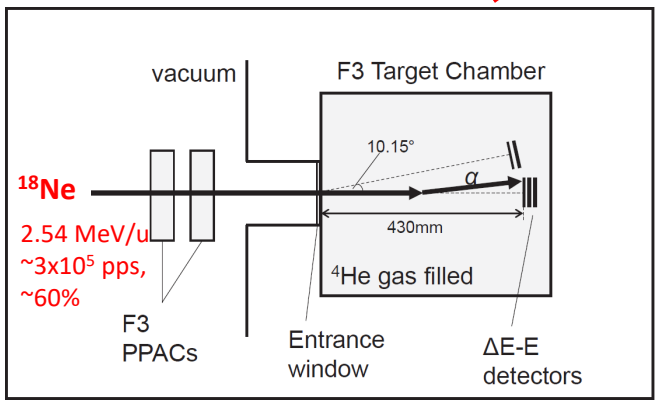
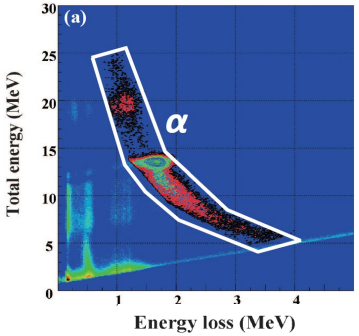
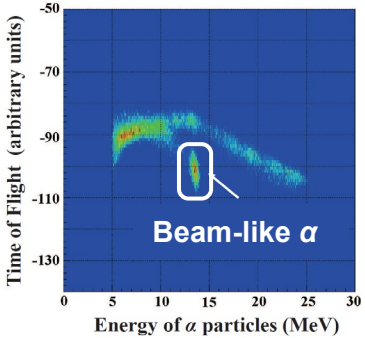
^{18}Ne(α,α)^{18}Ne measurement at CRIB





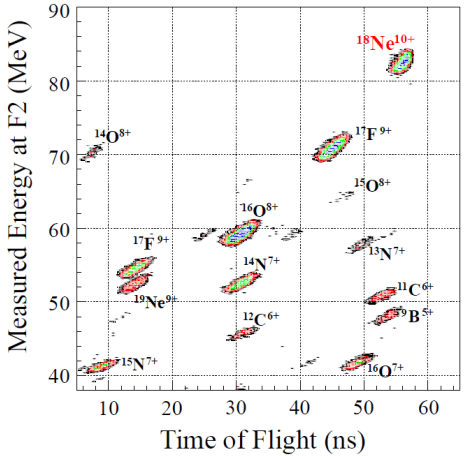
- ^{18}Ne beam produced by In-flight fragment : ^{16}O(^{3}He,n)^{18}Ne
- recoiling α particle measurement by silicon detector telescopes (energy, position)



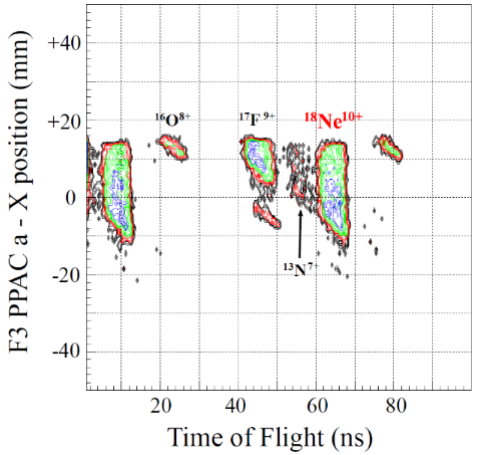


- Tracks of ^{18}Ne beam particles obtained by two PPACs (extrapolation)
- kinematics reconstruction by considering the energy loss of the beam and recoiling α particles
- **Excitation function of ^{22}Mg extracted !**

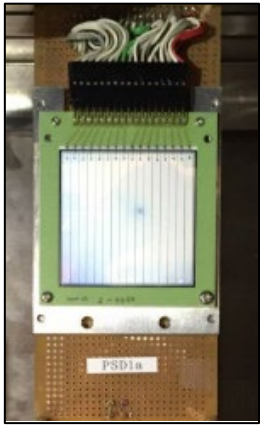
$^{18}Ne(\alpha,\alpha)^{18}Ne$ measurement at CRIB



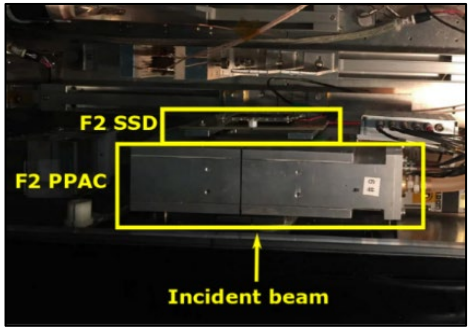
F2 : RI beam ID



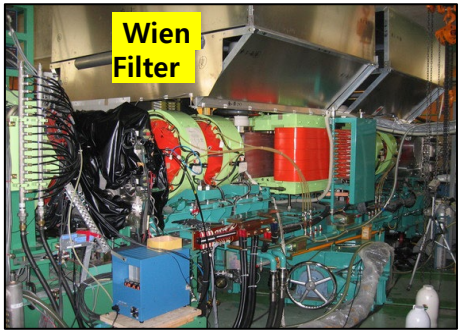
F3 : purified ^{18}Ne beam !



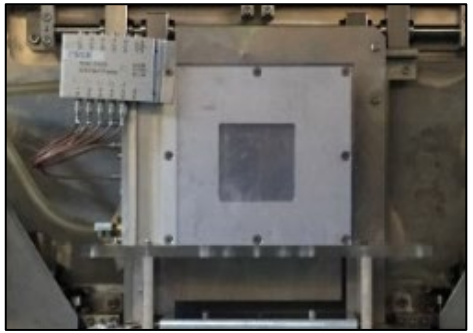
Silicon detector telescopes for energy and position measurement



A bird eye's view of F2 focal plane



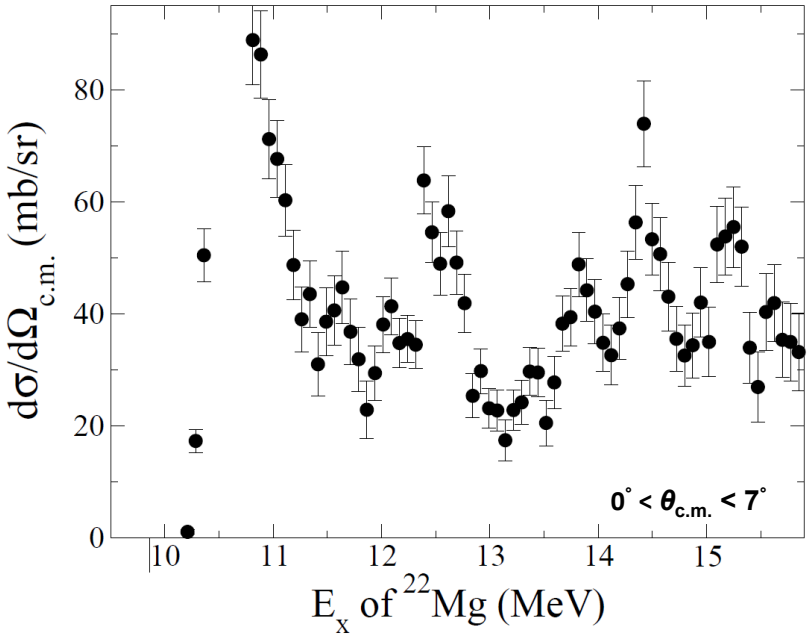
CRIB Wien Filter



Beam monitoring /Beam trajectory extrapolation by two F3 PPACs

Excitation function of ^{18}Ne+α system (^{22}Mg)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} = \frac{1}{4\cos\theta_{\text{lab}}}\left(\frac{d\sigma}{d\Omega}\right)_{\text{lab}} = \frac{1}{4\cos\theta_{\text{lab}}}\frac{Y}{IN\Delta\Omega_{\text{lab}}}$$



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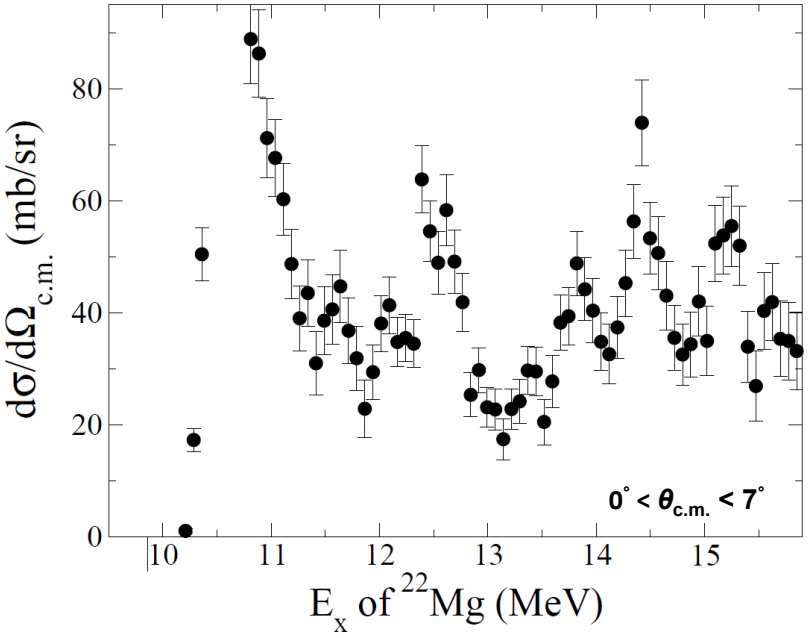

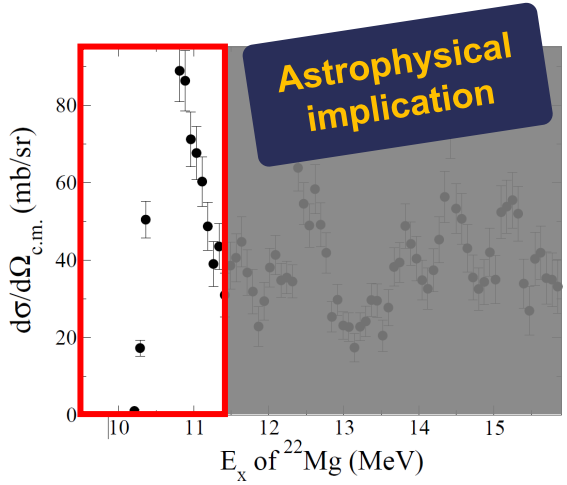

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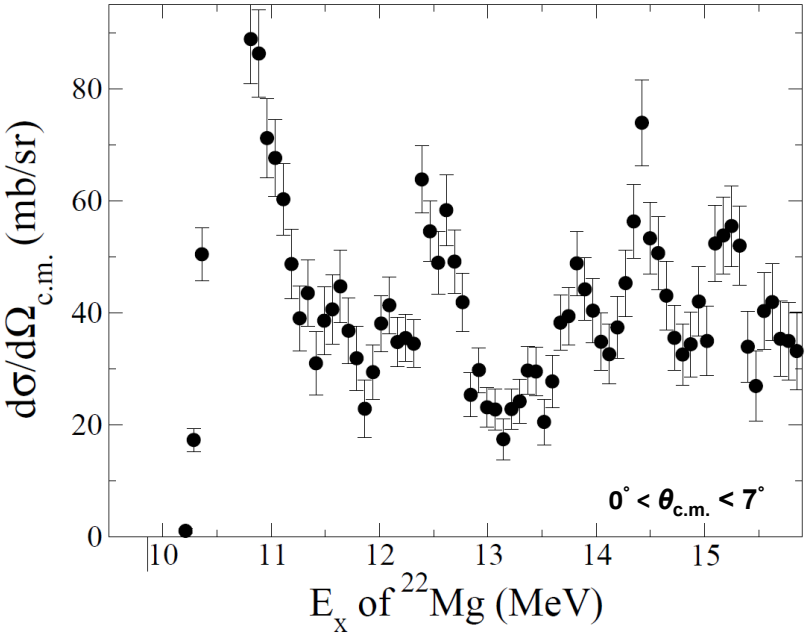
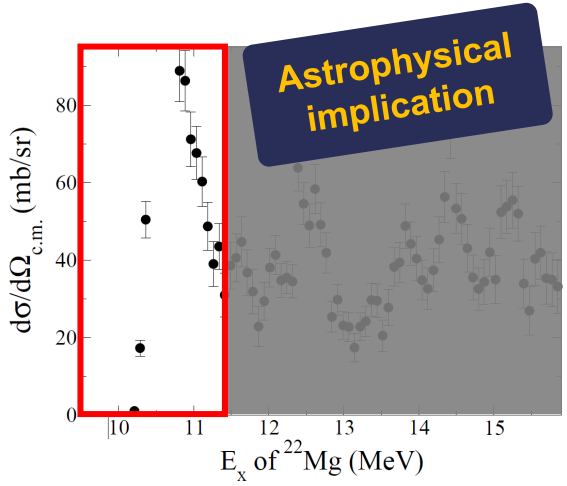
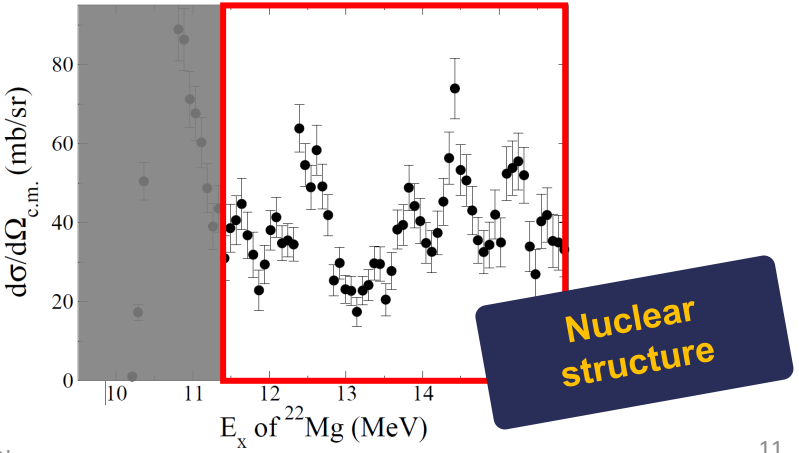
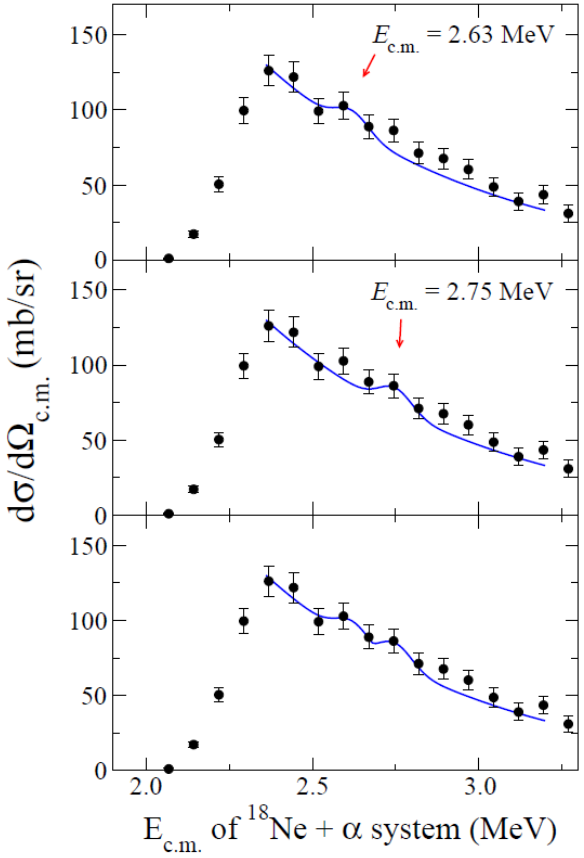






Astrophysical implication



- **Two small bumps were observed at the astrophysically important energy range (T_9 < 2 GK ↔ E_x < 2.9 MeV)**
- **Two energy levels have been reported in the previous direct measurement.**

Present Work	Groombridge *et al.*
$E_{c.m.}$ (MeV)	$E_{c.m.}$ (MeV)
2.63	2.52 ± 0.14
2.75	2.72 ± 0.14

dE_{cm}=50-100keV

- **The existence of these resonances is not obvious in our data possibly due to the insufficient statistics.**

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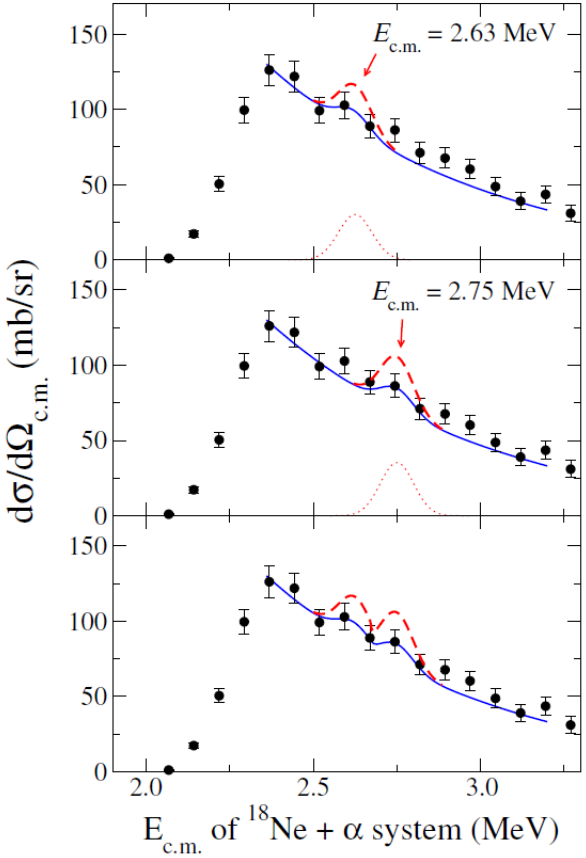

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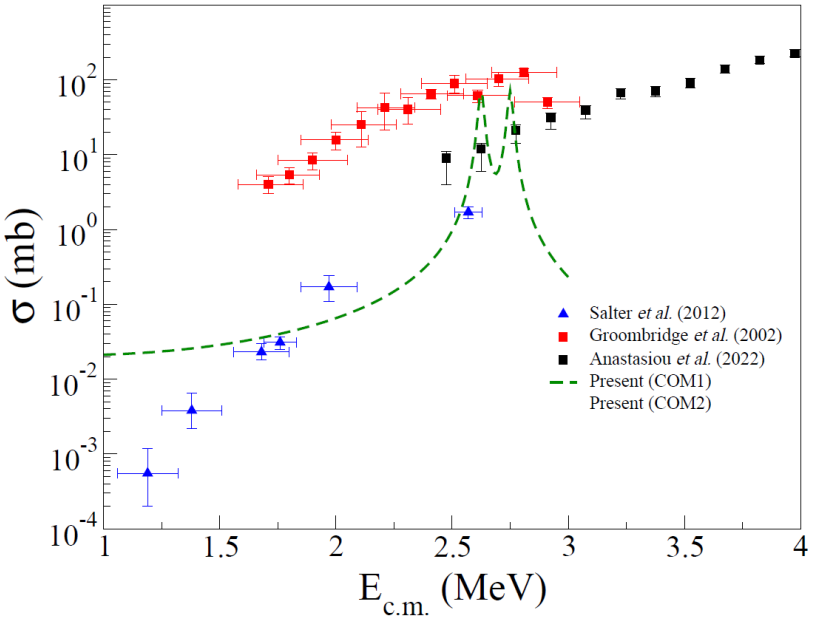
- **Upper limits on the ^{18}Ne(α,α)^{18}Ne cross section were set (one-sigma confidence level).**

Astrophysical implication



	E_r	J^π	Γ_α	Γ_p	Γ_{tot}
COM1	2.63	0^+	0.015	0.01	0.025
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COM2	2.63	0^+	0.015	0.085	0.1
	2.75	0^+	0.015	0.195	0.21

- **^{18}Ne(α,p)^{21}Na reaction cross section was calculated using the Breit-Wigner formula.**

$$\sigma_{BW}(E) = \frac{\lambda^2}{4\pi}\frac{(2J_r+1)}{(2J_{\mathrm{Ne}}+1)(2J_\alpha+1)}\frac{\Gamma_\alpha\Gamma_p}{(E-E_r)^2+(\Gamma_{\mathrm{tot}}/2)^2}$$

- ***E$_r$*, Γ_α adopted from the two observed bumps**
- ***J$^\pi$* adopted as 0^+** D. Groombridge *et al.*, PRC (2002)
- **Γ_p in this energy region has not been reported**

  → approximated Γ_p by two different approaches!

  considering the Wigner limit, global mean reduced proton width, ...

  assuming $\Gamma_{tot} = \Gamma_\alpha + \Gamma_p$ & Γ_{tot} adopted from Groombridge *et al.*

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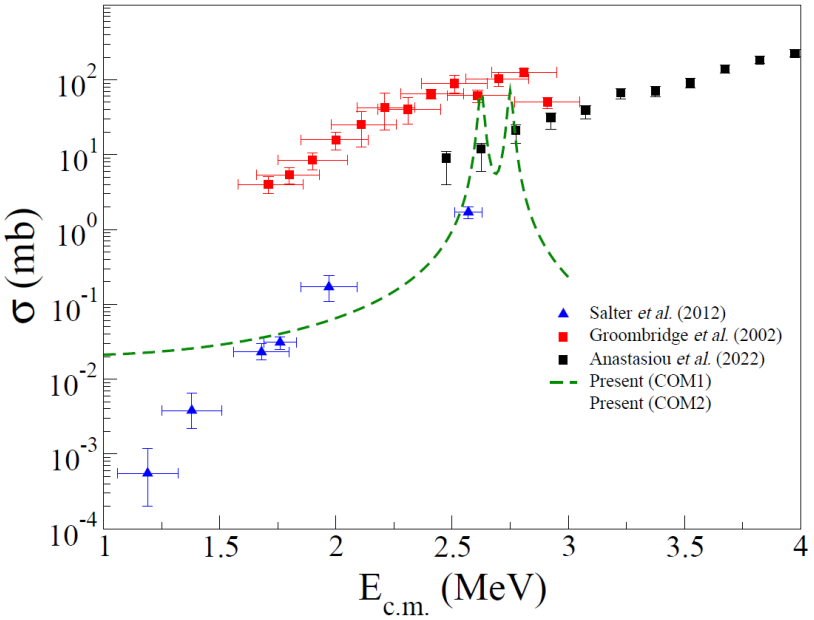

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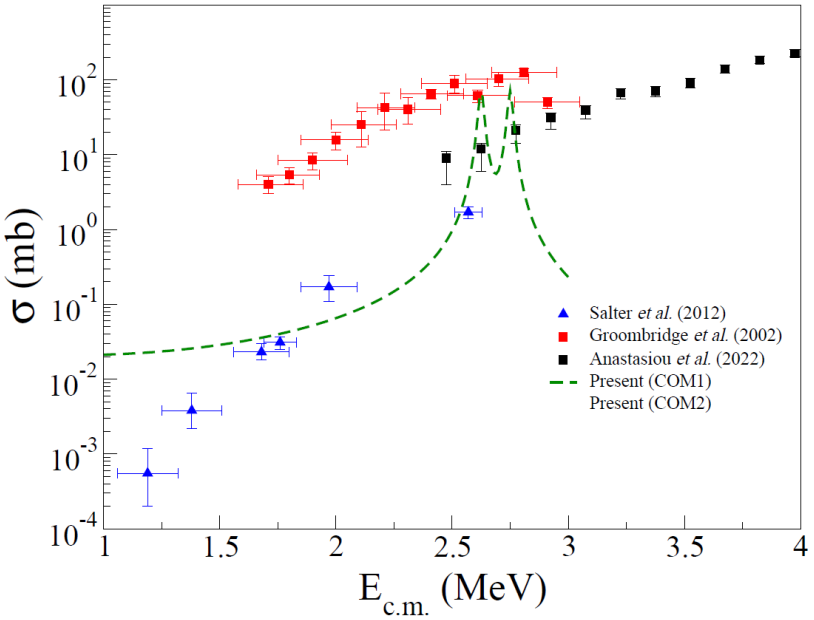

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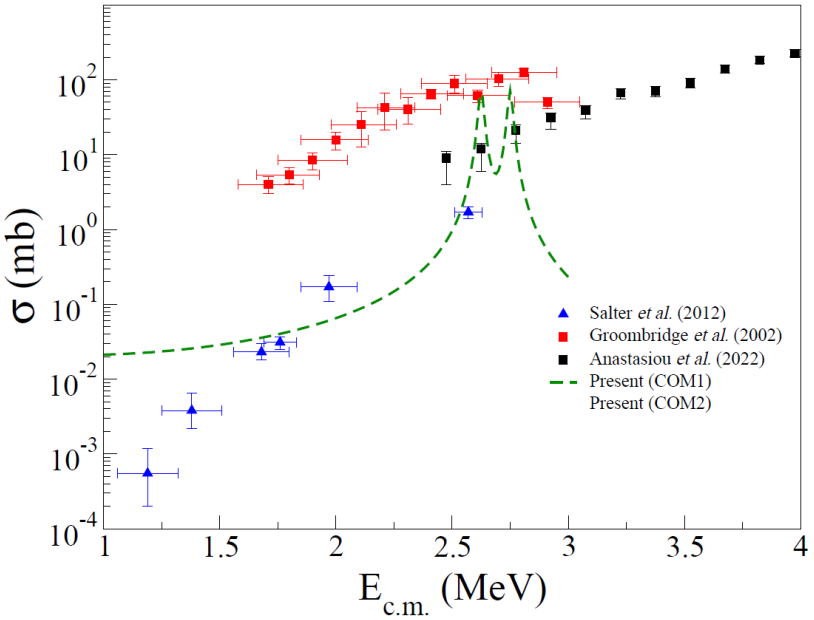

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- **^{18}Ne(α,p)^{21}Na reaction cross section was calculated using the Breit-Wigner formula.**

$$\sigma_{BW}(E) = \frac{\lambda^2}{4\pi}\frac{(2J_r+1)}{(2J_{\mathrm{Ne}}+1)(2J_\alpha+1)}\frac{\Gamma_\alpha\Gamma_p}{(E-E_r)^2+(\Gamma_{\mathrm{tot}}/2)^2}$$

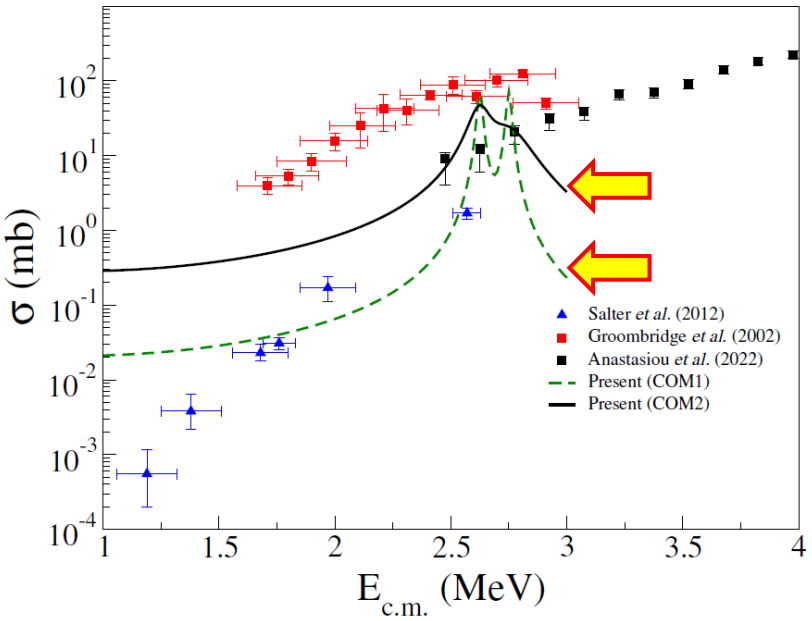
- ***E$_r$*, Γ_α adopted from the two observed bumps**
- ***J$^\pi$* adopted as 0^+** D. Groombridge *et al.*, PRC (2002)
- **Γ_p in this energy region has not been reported**

  → **approximated Γ_p by two different approaches!**

  considering the Wigner limit, global mean reduced proton width, ...

  assuming $\Gamma_{tot} = \Gamma_\alpha + \Gamma_p$ & Γ_{tot} adopted from Groombridge *et al.*

Astrophysical implication



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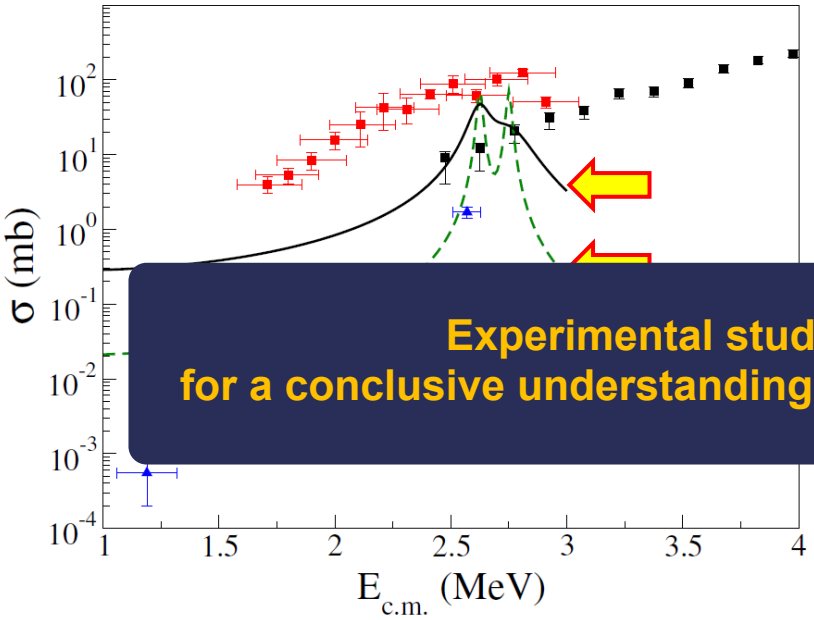
  assuming $\Gamma_{tot} = \Gamma_\alpha + \Gamma_p$ & Γ_{tot} adopted from Groombridge *et al.*

	E_r	J^π	Γ_α	Γ_p	Γ_{tot}
COM1	2.63	0^+	0.015	0.01	0.025
	2.75	0^+	0.015	0.01	0.025
COM2	2.63	0^+	0.015	0.085	0.1
	2.75	0^+	0.015	0.195	0.21

^{18}Ne(α,p)^{21}Na reaction cross section strongly depend on the proton widths of the resonances !

Astrophysical implication



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$$\sigma_{BW}(E) = \frac{\lambda^2}{4\pi}\frac{(2J_r+1)}{(2J_{\mathrm{Ne}}+1)(2J_\alpha+1)}\frac{\Gamma_\alpha\Gamma_p}{(E-E_r)^2+(\Gamma_{\mathrm{tot}}/2)^2}$$

Experimental studies of the Γ_p are highly required for a conclusive understanding on the ^{18}Ne(α,p)^{21}Na reaction cross section !

S.M. Cha et al., Frontiers in Physics (2023)

→ approxim

considering the Wigner limit, global mean reduced proton width, ...
assuming $\Gamma_{tot} = \Gamma_\alpha + \Gamma_p$ & Γ_{tot} adopted from Groombridge *et al.*

	E_r	J^π	Γ_α	Γ_p	Γ_{tot}
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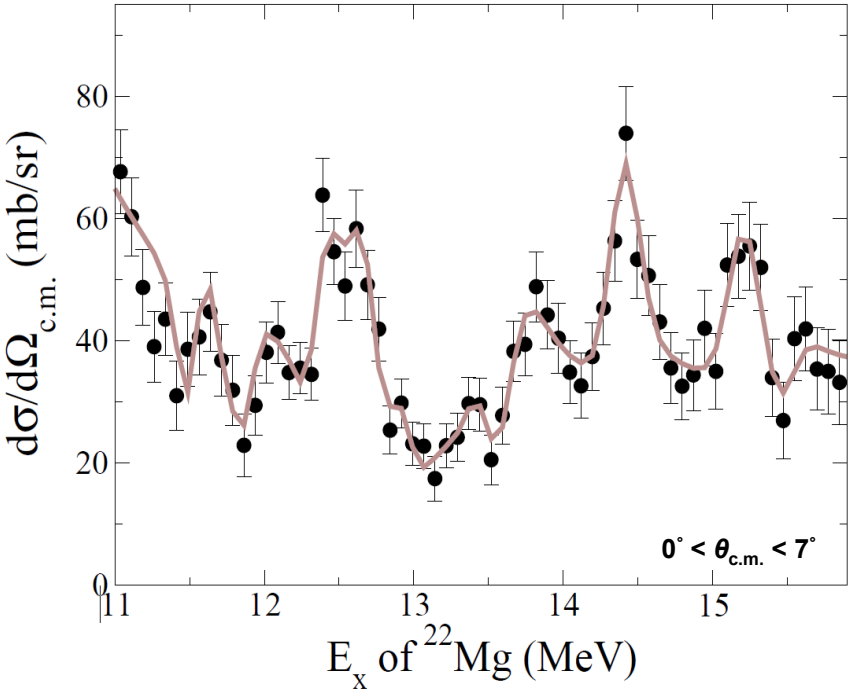
	2.75	0^+	0.015	0.195	0.21

^{18}Ne(α,p)^{21}Na reaction cross section strongly depend on the proton widths of the resonances !

R-matrix analysis

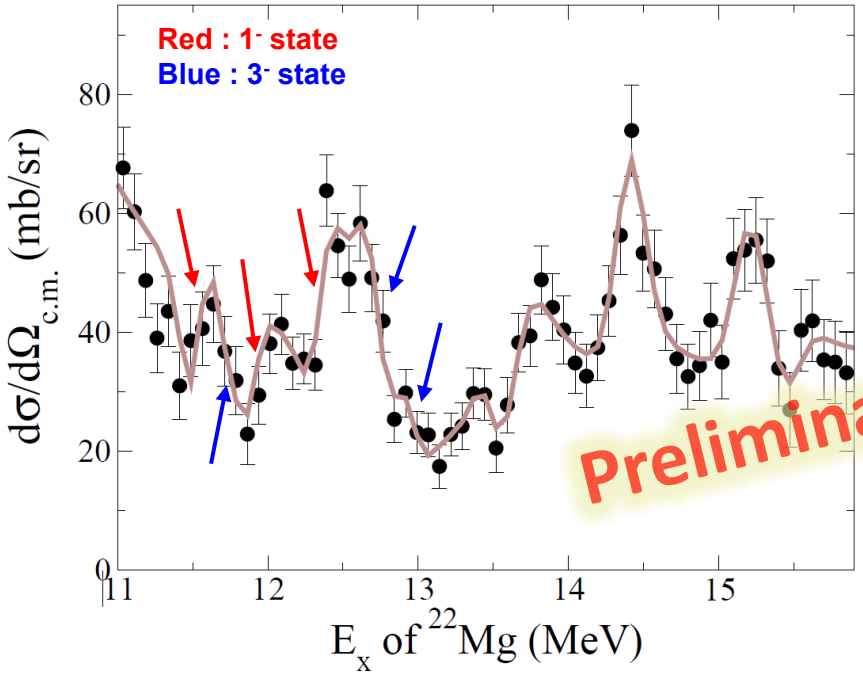


- **Evident peaks observed at E_x ~ 11 – 16 MeV !**
- **Resonance parameters of ^{22}Mg nucleus (E_r, Γ_α, J^π) can be constrained by R-matrix analysis.**
- **performed R-matrix calculation using SAMMY8**
- **All possible spin and natural parity combinations was considered during the analysis.**
- **χ^2 analysis is performed to deduce possible resonance parameters for each peak.**

- **calculated the dimensionless partial width (θ_α^2) for each level to provide a direct comparison with theoretical prediction**

$$\theta_a^2 = \Gamma_\alpha / \Gamma_W$$
$$\Gamma_w = 2\hbar^2/\mu R^2 P_l$$

1⁻ and 3⁻ candidates ?

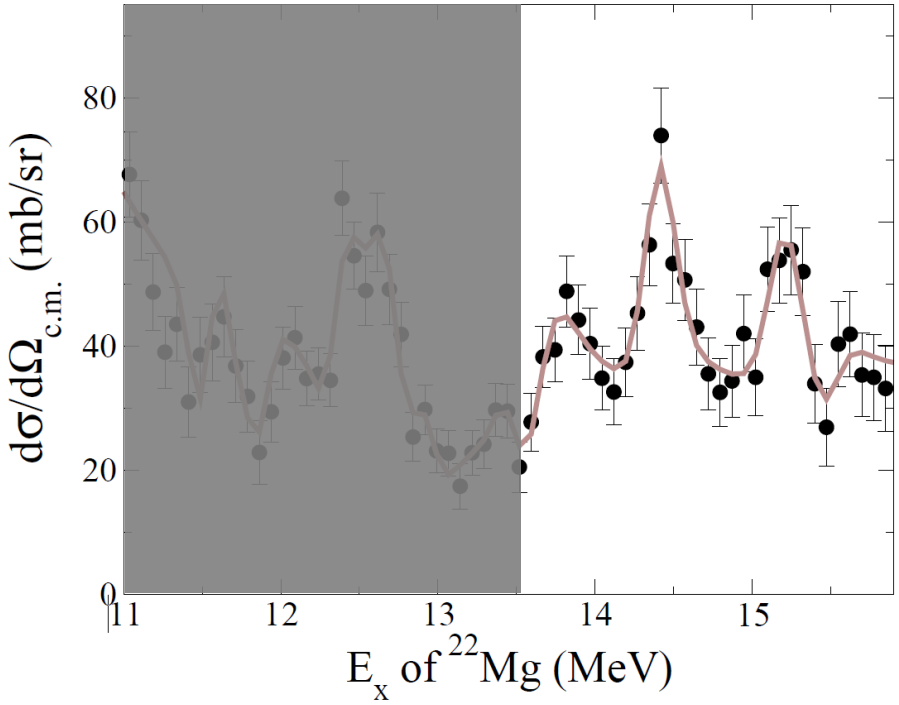


- Cluster model (CM) and Shell model (SM) calculation performed
- 1⁻ states obtained from both CM and SM calculation
- More discussions on 3⁻ states and reduction of *α*-widths required

Preliminary

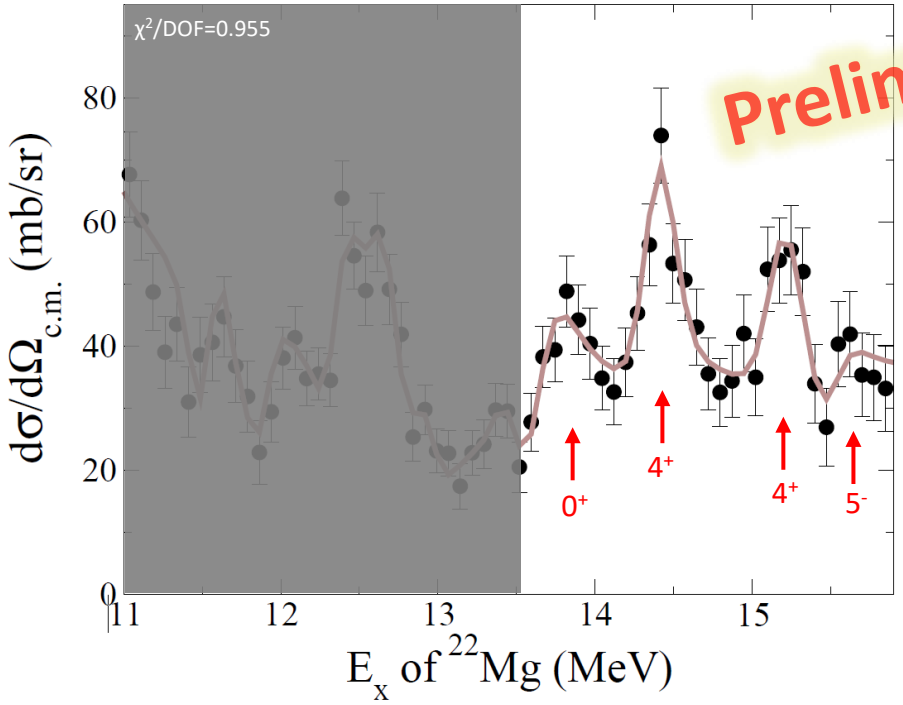
Present Work				Dufour & Descouvemont			Goldberg *et al.*	
E_x (MeV)	Γ_α (keV)	J^π	θ_α^2 (%)	E_x^{GCM} (MeV)	J^π	θ^2_{GCM} (%)	E_x (MeV)	J
11.493	7	1⁻	4.78	12.25	1⁻	11.5	11.462	1
11.705	3	3⁻	12.30	12.57	3⁻	11.6	11.798	2
11.869	6	1⁻	2.40	13.15	1⁻	6.7	11.842	1
12.352	19	1⁻ (4⁺)	3.72	13.30	3⁻	11.7	11.9	0
12.744	11	3⁻	6.80				12.362	1
12.974	8	3⁻	3.65					
13.456	4	3⁻ (0⁺,1⁻)	1.06					

First spectroscopic result of ^{22}Mg



- **No information from NNDC**
- **No information from the theory**

First spectroscopic result of ^{22}Mg



Present work			
E_x (MeV)	Γ_α (keV)	J^π	θ_a^2 (%)
13.644	177	0^+ $(1^-, 4^+, 5^-)$	11.0
14.381	16	4^+ $(2^+, 5^-)$	5.01
15.199	15	4^+ $(2^+, 3^-)$	2.49
15.477	4	5^- $(0^+$ to $7^-)$	1.59

- **Best fitting result : $J^\pi = 0^+, 4^+, 4^+$, and 5^- for four peaks**
- **cannot exclude other possibilities**

Summary

- The α resonant scattering on ^{18}Ne was measured in inverse kinematics to understand the astrophyscially important ^{18}Ne(α,p)^{21}Na reaction and the α-clustering of proton-rich ^{22}Mg nucleus.
- The measurement of ^{18}Ne + α scattering was done at CRIB in RIKEN by adopting the thick target method.
- The excitation function of ^{22}Mg was obtained for E_x= 10–16 MeV.
- Since energy levels were not clearly observed at the astrophysically important energy range, upper limits on the ^{18}Ne(α,α)^{18}Ne cross section were set.
- The astrophysical impact was also investigated by estimating the ^{18}Ne(α,p)^{21}Na cross section.
- R-matrix analysis was performed to constrain the energy level properties of ^{22}Mg.

Background Image:
Courtesy of Tervel Kutsev
Astronomical Photographer of the year 2023
“People and Space” category

List of collaborators

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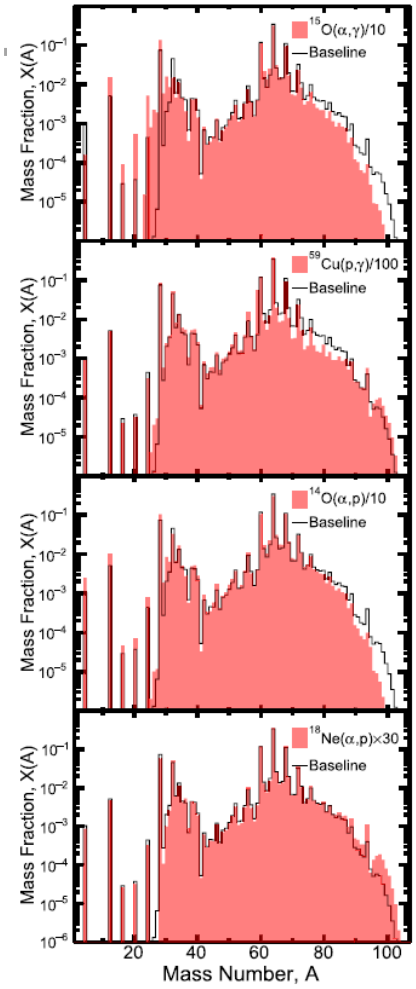
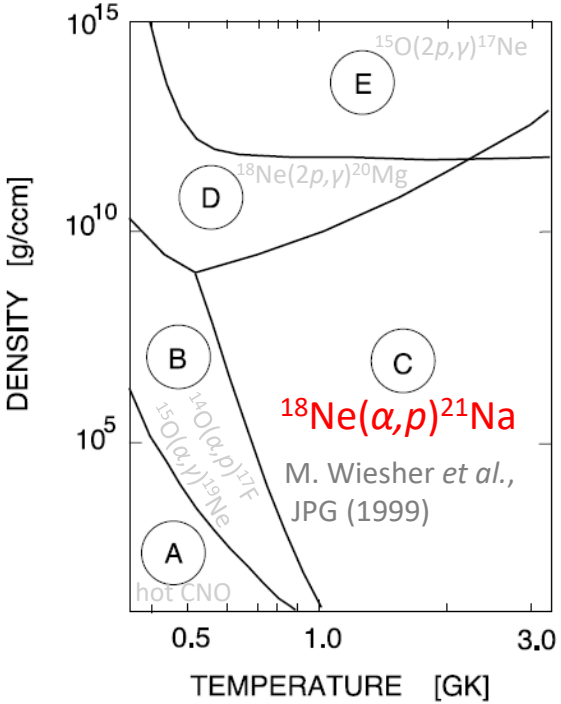
Energy levels of ^{22}Ne					
ETCM calculation			Experimental data		
J^π	E_x (MeV)	θ_α^2 (%)	J^π	E_x (MeV)	θ_α^2 (%)
1^-	12.58	13	1^-	12.58	10
1^-	13.53	8	1^-	12.84	20
3^-	12.92	13	3^-	13.19	19
3^-	13.69	11	3^-	13.41	11

As can be seen in Fig. 9 there are many anomalies in the ^{22}Mg spectrum at lower energies. The corresponding resonances were not observed in the mirror $\alpha+^{18}$O scattering due to the very small energies of the α particles. Generally speaking, a proper study of $\alpha+^{18}$Ne can bring information about the states in ^{22}Ne which are very close to the α-particle threshold, and maybe even below it.

TABLE II. Tentative spin assignment for ^{22}Mg levels.

Level	Spin	Energy (MeV)
1	2	2.87
2	2	3.055
3	0	3.18
4	1	3.32
5	2	3.656
6	1	3.70
7	0	3.76
8	1	4.02
9	0	4.021
10	2	4.085
11	1	4.22

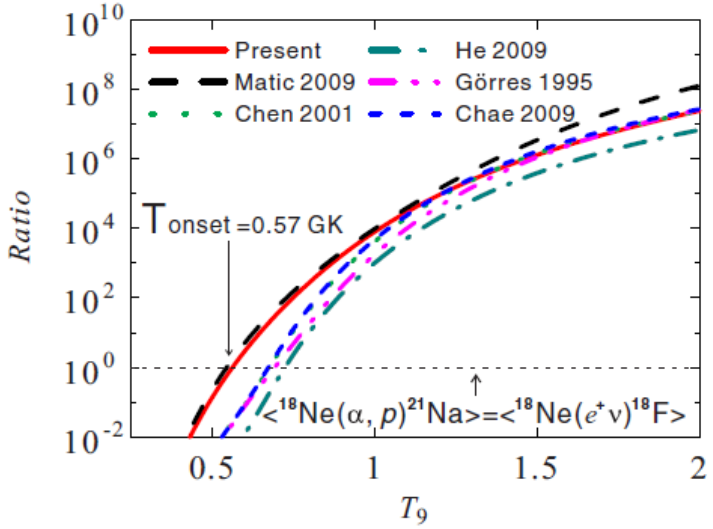




11410 *8*	A		
11499 *17*		K	[2+]
11594 *12*		KL	
11748 *17*		KL	[0+]
11914 *13*		KL	
12003 *20* ?		L	
12185 *17*		KL	[3-]
12474 *26*		K	[2+]
12665 *17*		K	[3-]
13014 *37*	A	K	
14012 *3*	A G		

TABLE I. Resonant parameters used in the present R-matrix analysis.

E_x (^{22}Mg)	J^π	s	ℓ	Γ_p (keV)
6.333	1^+	1	0	16
6.591	1^-	2	1	36
6.615	2^+	2	0	10
6.796	2^-	1	1	62
6.885	1^-	2	3	2
7.270	1^-	2	1	82
7.339	2^+	2	2	18
7.369	3^-	2	3	7
7.585	2^+	2	0	16
7.654	1^-	2	1	114
7.802	2^-	1	1	19
7.920	2^+	2	0	3
8.005	3^-	2	3	1
8.190	2^+	2	2	5
8.353	1^+	1	2	97
8.527	3^-	2	1	3
8.578	4^+	2	2	5
8.677	2^+	2	2	7
8.727	2^+	2	0	12
8.827	1^-	2	1	57
8.922	2^+	2	2	4
9.050	1^-	2	1	105
9.158	4^+	2	2	2



As discussed in the Introduction, the ^{18}Ne$(\alpha, p)^{21}$Na cross section was studied before by Bradfield-Smith *et al.* [9] and Groombridge *et al.* [10]. There, the experimental results were summarized as a table of resonance parameters and widths. Figure 14 displays the cross section derived from the resonance parameters of Ref. [10], in comparison to our result. Our experiment shows a much lower cross section, by close to an order of magnitude.

TABLE I. Resonant properties of excited states in ^{22}Mg deduced from the present work. The excitation energies from the previous work are listed for comparison. The uncertainties of energy, in units of keV, are included in parentheses. The observed proton partial widths are deduced from the R-matrix analysis with those spin-parity assignments as shown in Fig. 1.

E_x^{present}	E_x [7]	E_x [8]	E_x [9]	E_x [11]	Parity[a]	J^π (R matrix)[b]	$J^\pi;\ell$ (adopted)	Γ_p (keV)
6.61(15)[c]	6.606(9)	6.606(11)	6.616(4)		π = N [4]	$(2^+,1^+)$	$2^+;0$	23(7)
6.81(15)[d]	6.766(12)	6.767(20)	6.771(5)	6.760(90)		$(1^+,2^+)$	$(1^+,2^+);0$	64(20)
6.93(15)		6.889(10)	6.878(9)		π = N	$(2^+,1^+,3^-,2^-)$	$(2^+,3^-);0(1)$	27(7)
7.06(16)						$(1^+,3^-,2)$	$(1^+,3^-,2);0(1)$	49(20)
7.27(16)						$(2^+,1^+)$	$(2^+,1^+);0$	17(7)
7.42(17)		7.402(13)	7.373(9)			$(1,2^+)$	$(1,2^+);0(1)$	10(7)
7.59(17)	7.614(9)		7.606(11)			$(1^+,2^+)$	$(1^+,2^+);0$	23(7)
7.82(18)		7.784(18)	7.757(11)	7.840(90)	π = uN	$(1^- - 3^-)$	$(2^-);1$	27[g]
7.98(19)	7.938(9)	7.964(16)	7.986(16)	7.890(100)	π = N	$(1^+,2^+)$	$(2^+);0$	20[g]
8.18(19)	8.197(10)	8.203(23)	8.229(20)			(1^+-3^+)	$(1^+-3^+);2$	33[g]
8.31(20)				8.290(40)		(1^+-3^+)	$(1^+-3^+);2$	49[g]
8.51(20)[e]	8.512(10)	8.547(18)		8.550(90)	π = N	$(1^- - 3^-)$	$(3^-);1$	60(20)
8.62(21)[f]	(8.644(18))	8.613(20)	8.598(20)			(2^+)	$(2^+);2$	33(10)

[a]N, uN denote level of natural and unnatural parity, respectively.
[b]Present results deduced from the R-matrix analysis.
[c]$J^\pi = 2^+$ determined for the 6.616-MeV state [16].
[d]$J^\pi = (1^-, 2^-)$ determined for the 6.796-MeV state [16].
[e]$J^\pi = 2^+$ assumed in Chen *et al.* [8].
[f]$J^\pi = 3^-$ assumed in Chen *et al.* [8].
[g]The proton widths of these states are only roughly estimated from the R-matrix fits to the data.

Present work			
E_x (MeV)	Γ_α (keV)	J^π	θ_a^2 (%)
11.493	7	1^-	4.78
11.705	3	3^-	12.30
11.869	6	1^-	2.40
12.352	19	1^-	3.72
		(4^+)	
12.744	11	3^-	6.80
12.974	8	3^-	3.65
13.456	4	3^-	1.06
		$(0^+, 1^-)$	
13.644	177	0^+	11.0
		$(1^-, 4^+, 5^-)$	
14.381	16	4^+	5.01
		$(2^+, 5^-)$	
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		$(2^+, 3^-)$	
15.477	4	5^-	1.59
		$(0^+$ to $7^-)$	

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5	2	3.656
6	1	3.70
7	0	3.76
8	1	4.02
9	0	4.021
10	2	4.085
11	1	4.22

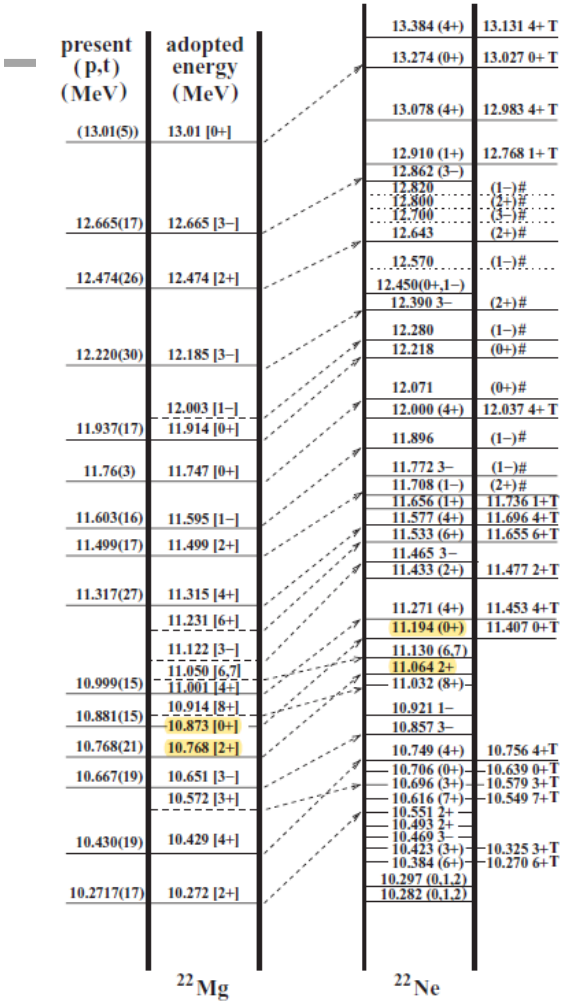
TABLE I. Summary of resonance parameters ($R = 5.0$ fm).

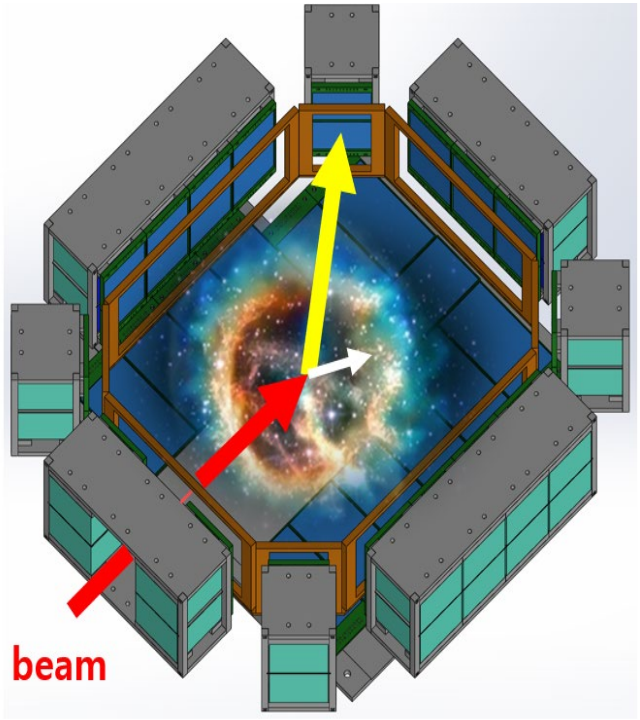
N	$E_{c.m.}$ (MeV)	E_x (MeV)	J^π	$\Gamma_{c.m.}$ (keV)	$\Gamma_\alpha/\Gamma_{tot}$ %	$\gamma^2{}_\alpha$ (kev)	$\gamma^2{}_\alpha/\gamma^2{}_W$ %
1	2.91	12.58	1^-	97	36	79	10
2	3.17	12.84	1^-	145	72	150	20
3	3.52	13.19	3^-	67	40	144	19
4	3.74	13.41	3^-	56	40	82	11
5	9.61	19.28	(7^-)	88	25	64	8
6	9.89	19.56	(7^-)	75	23	41	5
7	11.18	20.85	9^-	110	14.5	393	51
8	12.17	21.84	9^-	170	22.	441	57

TABLE VII. The spin values and resonance strengths of the levels at center-of-mass energies E_{res} (c.m.) used in the calculations of the rates for the ^{18}Ne$(\alpha,p)^{21}$Na reaction.

E_x (MeV)	E_{res} (c.m.) (MeV)	J^{π}[a]	S_α	Γ_α (eV)	$\omega\gamma$ (eV)
8.1812(16)	0.039	[2$^+$]	2.8×10^{-1}	1.7×10^{-65}	8.53×10^{-65}
8.385(7)	0.243	[2$^+$]	3.2×10^{-1}	2.7×10^{-18}	1.33×10^{-17}
8.5193(20)	0.377	[3$^-$]	4.0×10^{-3}	7.0×10^{-15}	4.87×10^{-14}
8.574(6)	0.432	[4$^+$]	6.0×10^{-2}	3.6×10^{-13}	3.26×10^{-12}
8.6572(17)	0.515	[0$^+$]	1.1×10^{-1}[b]	5.0×10^{-8}	4.97×10^{-8}
8.743(14)	0.601	[4$^+$]	2.2×10^{-2}	5.7×10^{-10}	5.15×10^{-9}
8.7832(22)	0.642	[1$^-$]	1.1×10^{-1}[b]	4.0×10^{-6}	1.21×10^{-5}
8.9318(27)	0.790	[2$^+$]	1.1×10^{-1}[b]	8.3×10^{-5}	4.13×10^{-4}
9.080(7)	0.938	[1$^-$]	1.1×10^{-1}[b]	7.7×10^{-3}	2.31×10^{-2}
9.157(4)	1.015	[4$^+$]	7.8×10^{-2}	9.7×10^{-5}	8.70×10^{-4}
9.318(12)	1.176	[2$^+$]	1.1×10^{-1}[b]	9.9×10^{-2}	4.97×10^{-1}
9.482(11)	1.342	[3$^-$]	1.5×10^{-2}	1.8×10^{-2}	1.25×10^{-1}
9.542(9)	1.401	[2$^+$]	2.8×10^{-2}	3.6×10^{-1}	1.78
9.709(19)	1.565	[0$^+$]	1.5×10^{-1}	5.2×10^{1}	5.18×10^{1}
9.7516(27)	1.610	[2$^+$]	1.9×10^{-2}	1.6	8.22
9.860(5)	1.718	[0$^+$]	1.9×10^{-2}	2.1×10^{1}	2.07×10^{1}
10.085(13)	1.944	[2$^+$]	5.0×10^{-2}	4.5×10^{1}	2.25×10^{2}
10.2715(17)	2.130	2$^+$	–[c]	–[c]	1.03×10^{4}[c]
10.429(13)	2.287	[4$^+$]	–[c]	–[c]	7.30×10^{3}[c]
10.651(13)	2.513	[3$^-$]	–[c]	–[c]	1.82×10^{4}[c]
10.768(13)	2.626	[2$^+$]	1.1×10^{-1}[b]	2.3×10^{3}	1.16×10^{4}
10.873(14)	2.734	[0$^+$]	–[c]	–[c]	4.52×10^{4}[c]
11.001(11)	2.859	[4$^+$]	–[c]	–[c]	8.10×10^{3}[c]
11.315(16)	3.173	[4$^+$]	3.0×10^{-2}[b]	2.0×10^{2}	1.83×10^{3}
11.499(17)	3.357	[2$^+$]	1.1×10^{-1}[b]	1.7×10^{4}	8.64×10^{4}
11.595(12)	3.455	[1$^-$]	5.4×10^{-2}	2.0×10^{4}	6.11×10^{4}
11.747(17)	3.607	[0$^+$]	1.1×10^{-1}[b]	7.1×10^{4}	7.13×10^{4}
11.914(13)	3.780	[0$^+$]	1.1×10^{-1}[b]	8.8×10^{4}	8.82×10^{4}
12.003(20)	3.861	[1$^-$]	2.1×10^{-1}	1.4×10^{5}	4.31×10^{5}
12.185(17)	4.050	[3$^-$]	1.8×10^{-1}	3.7×10^{4}	2.60×10^{5}
12.474(26)	4.332	[2$^+$]	1.1×10^{-1}[b]	7.8×10^{4}	3.89×10^{5}
12.665(17)	4.523	[3$^-$]	1.2×10^{-1}	4.9×10^{4}	3.45×10^{5}
(13.010(50))	4.865	[0$^+$]	1.1×10^{-1}[b]	2.2×10^{5}	2.16×10^{5}

[a]Spin for the mirror assignments given in Figs. 9 and 10.
[b]Constant S_α values as explained in the text.
[c]Resonance strengths are measured in Ref. [22].

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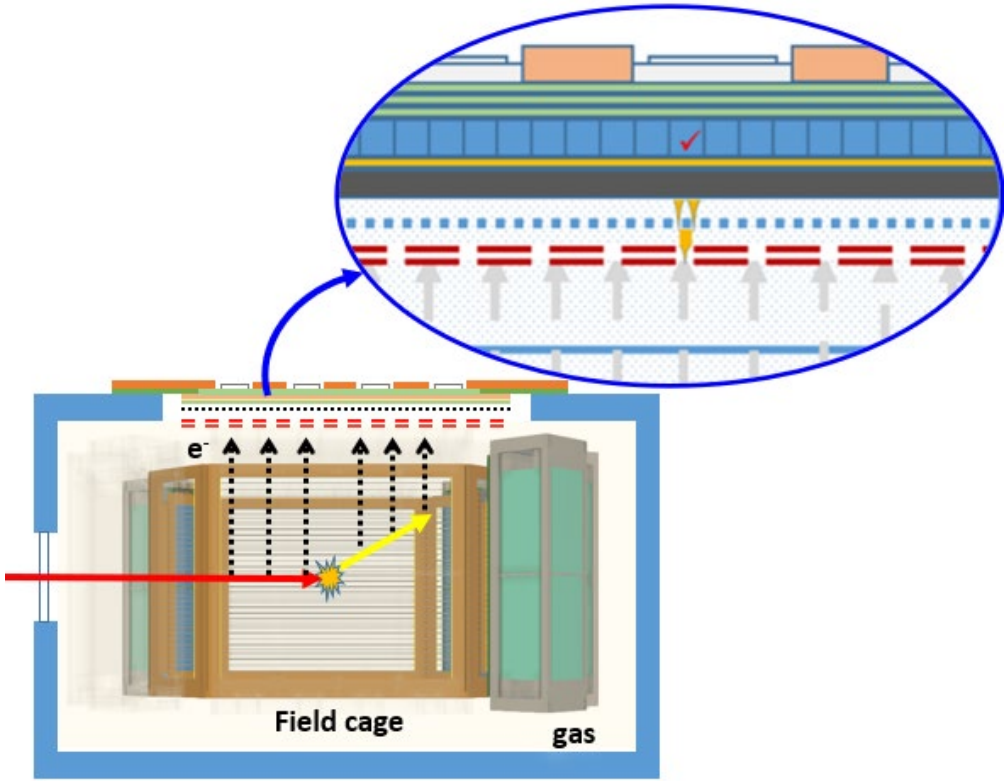
e-
Field cage
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