CENuM-RULiC Workshop
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Nuclear reactions with RI beams for X-ray burst

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Outline

Introduction

Experiments

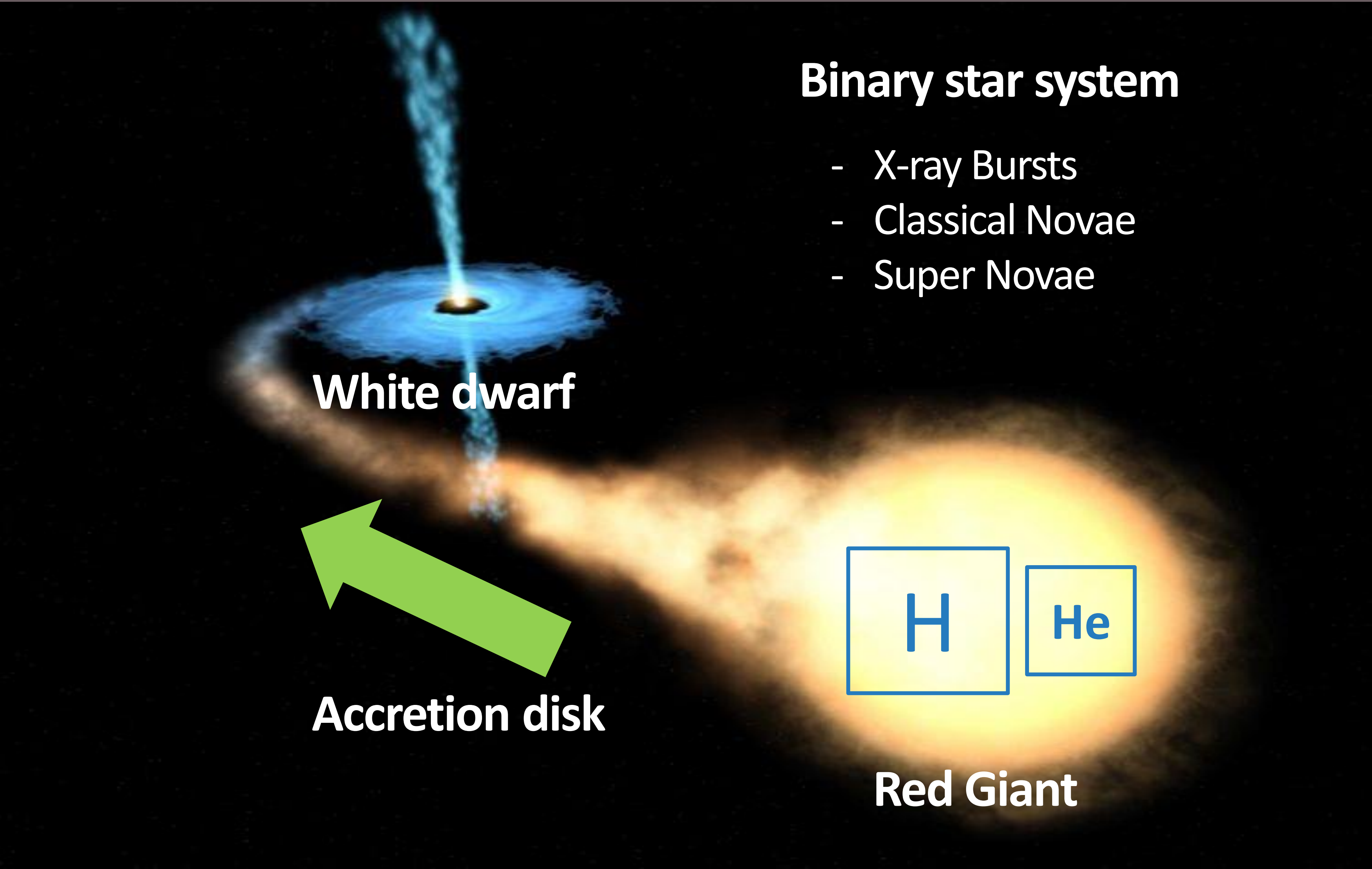
- The $^{14}O(a,p)\,^{17}F$ Experiment
- The $^{18}F(p,a)^{15}O$ Experiment
- SAMURAI experiments

Summary

Motivation

Binary star system

- X-ray Bursts
- Classical Novae
- Super Novae

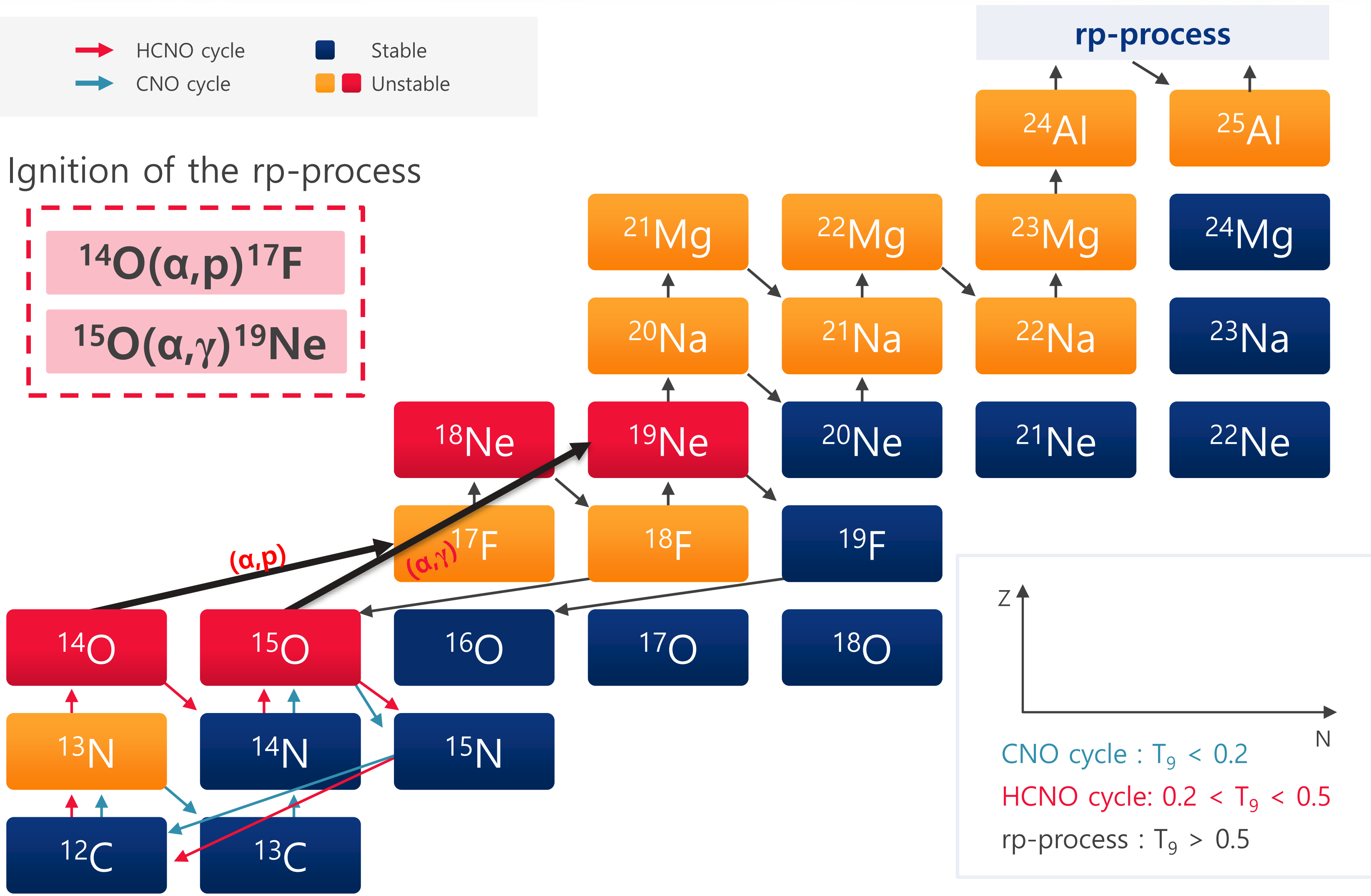


The breakout from the HCNO to the rp-process

Ignition of the rp-process

$^{14}O(\alpha,p)^{17}F$

$^{15}O(\alpha,\gamma)^{19}Ne$



CNO cycle : $T_9 < 0.2$

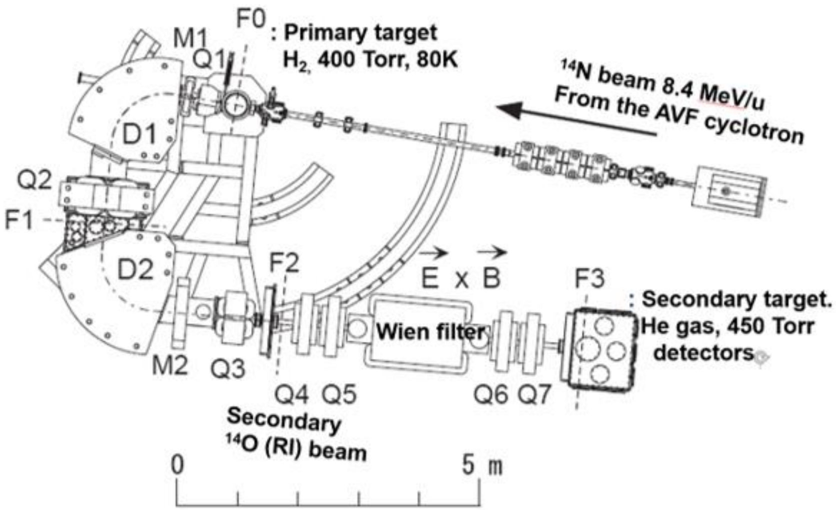
HCNO cycle: $0.2 < T_9 < 0.5$

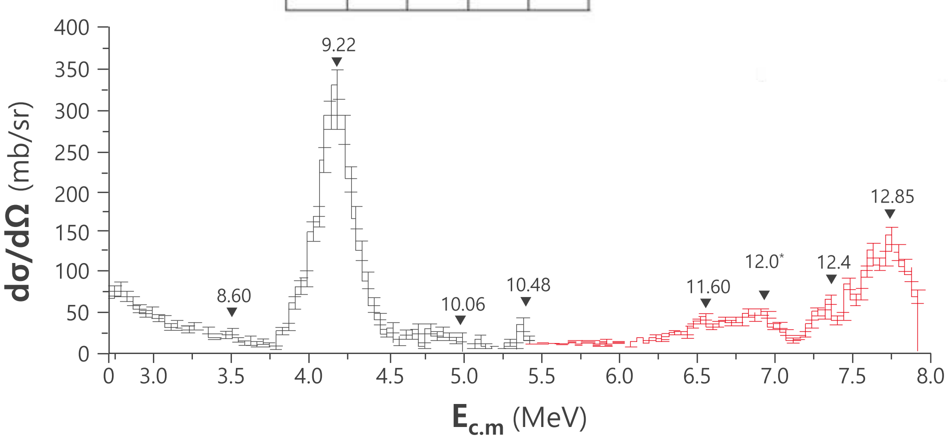
rp-process : $T_9 > 0.5$

D. Kim Ph.D. Thesis (2018)

D. Kim, A. Kim, K. I. Hahn *et al.* (to be submitted to PRL or PRC)

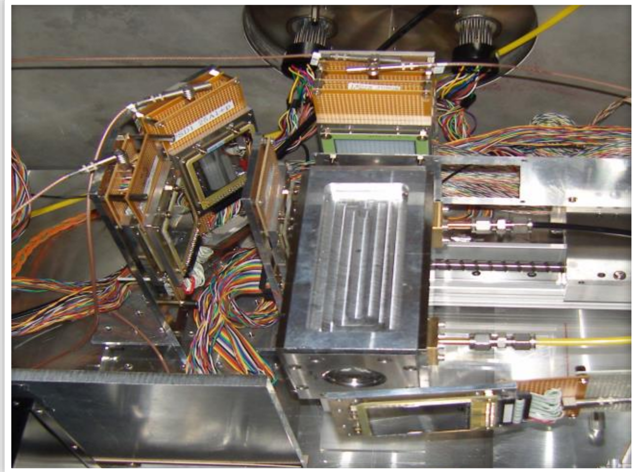
The $^{14}O(\alpha,p)^{17}F$ experiment at CNS

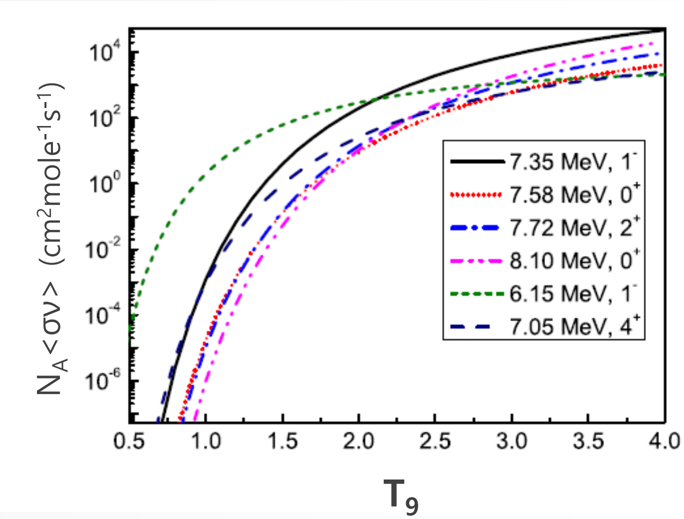




Excitation function of the $^{14}O(\alpha,\alpha)^{14}O$ reaction at the 0 degrees telescope. The level marked by * has not been seen before.

M. Notai, S. Kubono, T. Teranishi *et al.* Nucl. Phys. A738, 411 (2004)
I. S. Hahn, JKPS 45, 132 (2004)
A. Kim, N. H. Lee, I. S. Hahn, J. S. Yoo *et al.*, JKPS 57, 40 (2010)



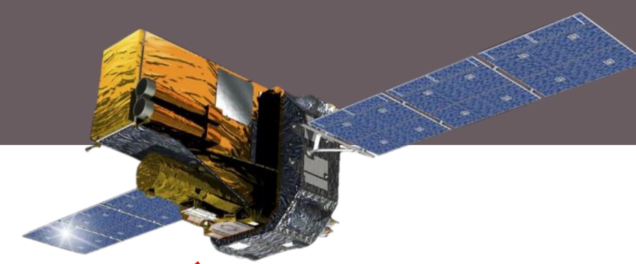


Direct measurement of the $^{14}O(\alpha,p)^{17}F$ cross section

A. Kim, K. I. Hahn *et al.*, Phys. Rev. C 92, 035801 (2015)

Motivation

❖ Properties of ^{18}F



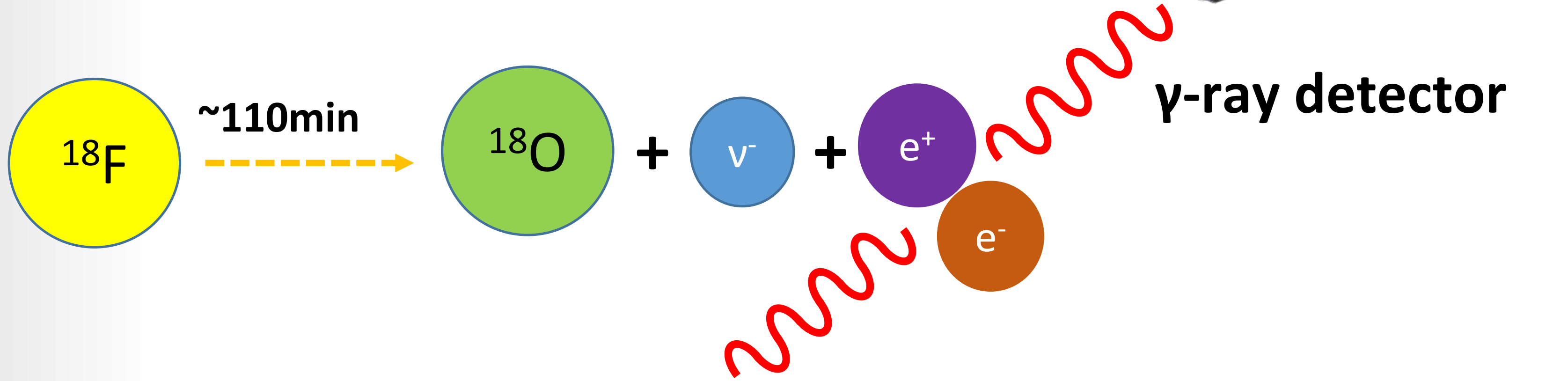


Table 1.1. List of γ-ray emission types for CO and ONe nova [7].

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

Motivation

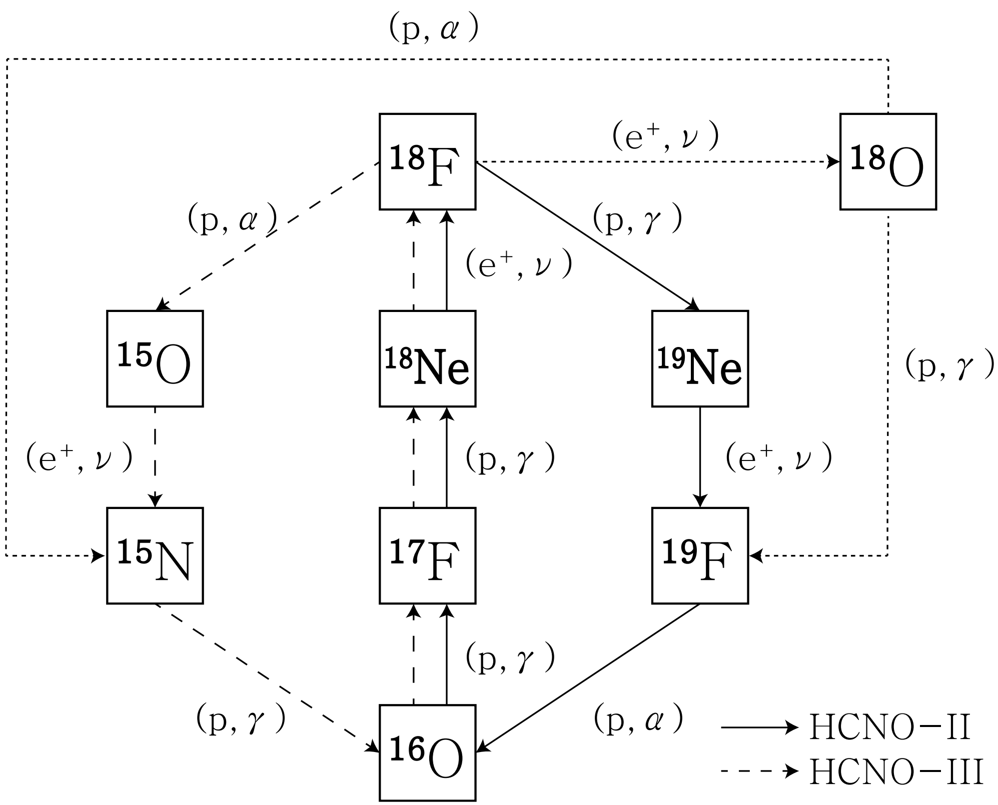
❖ ^{18}F nucleosynthesis in classical novae

The nova explosion initiation temperature : 20×10^6 K

HCNO-I : $T_9 < 0.2$

HCNO-II : $T_9 > 0.2$

HCNO-III : $T_9 < 0.4$



$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$$

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}(\beta^+)^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$$

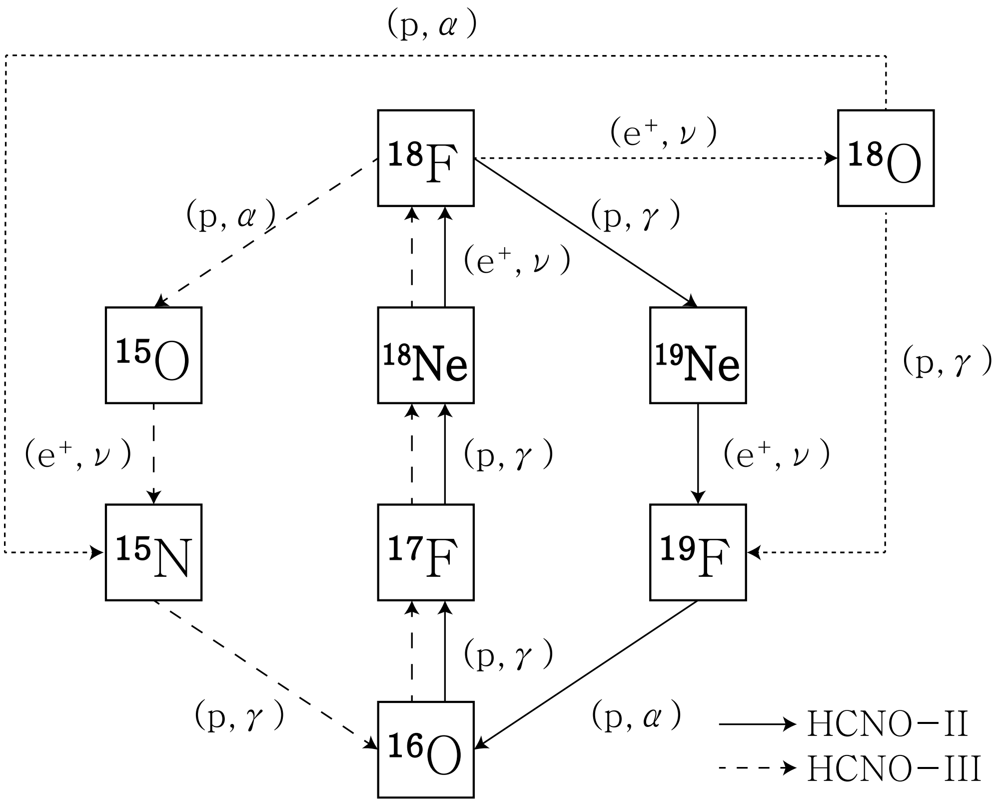
Motivation

❖ ^{18}F nucleosynthesis in classical novae

Large abundance of ^{16}O in classical novae

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

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

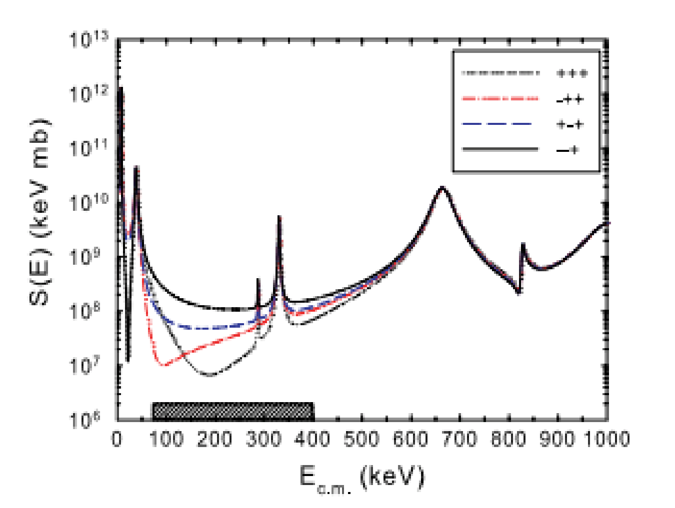


Motivation – ^{19}Ne states near proton threshold

D. Bardayan et al., PRC 70, 015804 (2004)

$E_x(^{19}F)$ (MeV)	$E_x(^{19}Ne)$ (MeV)	$E_{c.m.}$ (keV)	J^π	Γ_γ (eV)	Γ_p (keV)	Γ_α (keV)
6.497	6.419	8(6)	$\frac{3}{2}^+$	0.85(15)	$4.3(9)\times10^{-37}$	0.5(5)
6.429	6.437	26(9)	$\frac{1}{2}^-$	[1(1)]	$(2.8^{+5.6}_{-1.9})\times10^{-20}$	216(19)
6.528	6.449	38(7)	$\frac{3}{2}^+$	1.2(2)	$6.6(6.6)\times10^{-15}$	4.3(3.7)
6.838	6.698	287(6)	$\frac{5}{2}^+$	0.33(6)	$2.5(2.5)\times10^{-5}$	1.2(1.0)
6.787	6.741	330(6)	$\frac{3}{2}^-$	5.50(76)	$2.22(69)\times10^{-3}$	2.7(2.3)
6.927	6.861	450(6)	$\frac{7}{2}^-$	2.40(35)	$1.6(1.6)\times10^{-5}$	3.1(2.7)
7.30	7.076	664.7(1.6)	$\frac{3}{2}^+$	[1(1)]	15.2(1.0)	23.8(1.2)
7.262	7.238	827(6)	$\frac{3}{2}^+$	[1(1)]	0.35(35)	6.0(5.2)
7.364	7.253	842(10)	$\frac{1}{2}^+$	[1(1)]	0.9(9)	23(20)
7.560	7.420	1009(14)	$\frac{7}{2}^+$	[1(1)]	27(4)	71(11)
7.540	7.500	1089(9)	$\frac{5}{2}^+$	5.8(0.9)	1.25(1.25)	0.24(24)
7.590	7.533	1122(11)	$\frac{5}{2}^-$	[1(1)]	10(6)	21(11)

K. Y. Chae et al., PRC 74, 012801(R) (2006)



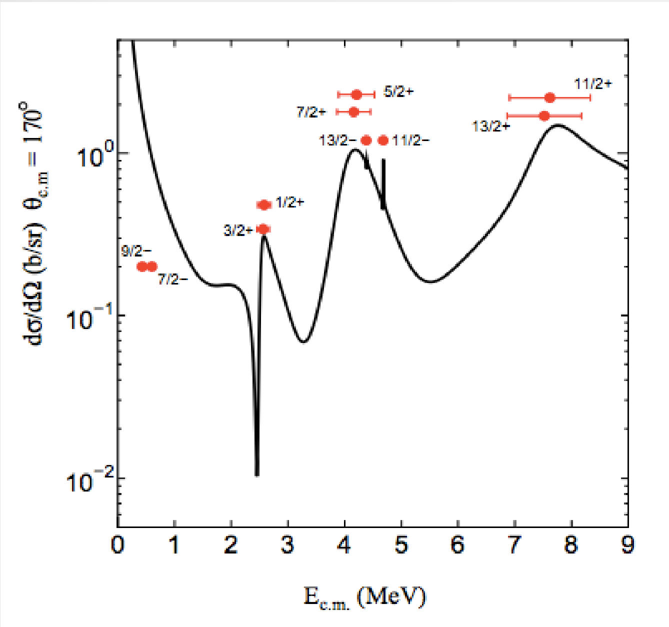
Several resonances near the proton threshold (E_x = 6.411 MeV) mainly affect the $^{18}F(p,\alpha)^{15}O$ reaction rate in T_9 = 0.04 ~ 0.4. These states already were studied but we would like to improve resonance parameters because of its importance.

However, the 3/2+ subthreshold states and near the proton threshold states were interference each other, and it changes the reaction rate between T_9 = 0.04 ~ 0.4.

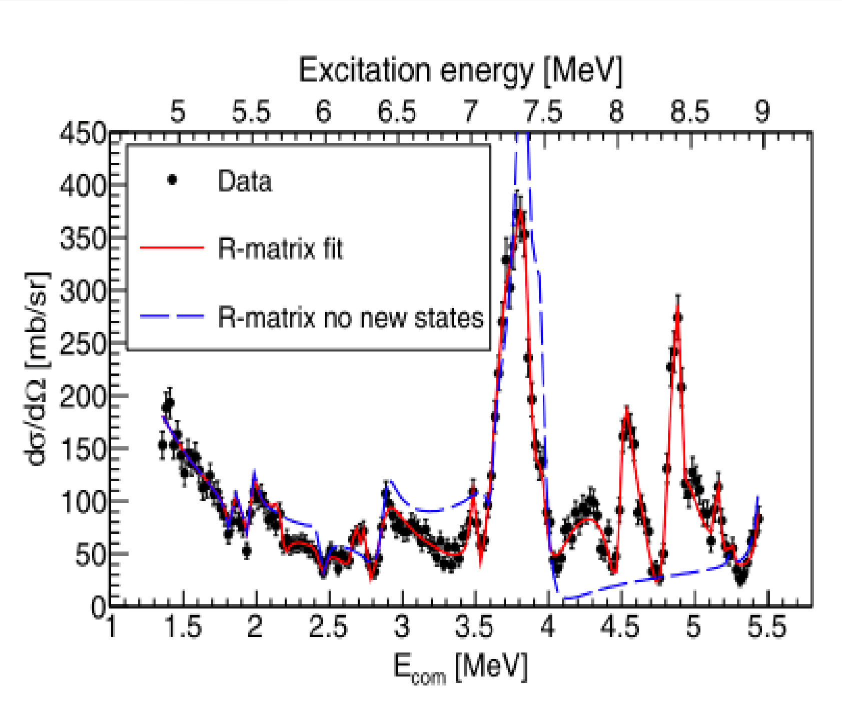
Obtain precise alpha width via alpha elastic scattering experiment!

Motivation – alpha cluster

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



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



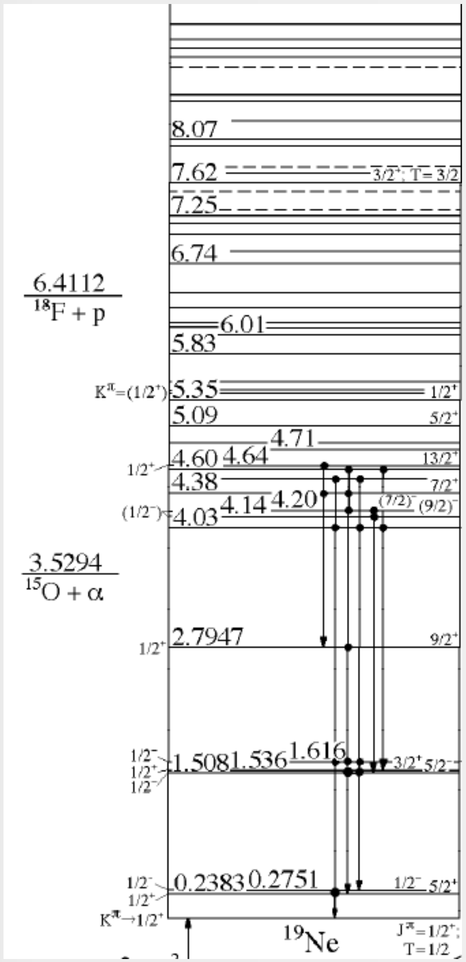
- Theoretical calculation result on the excitation energies of the cluster structure states in ^{19}Ne.

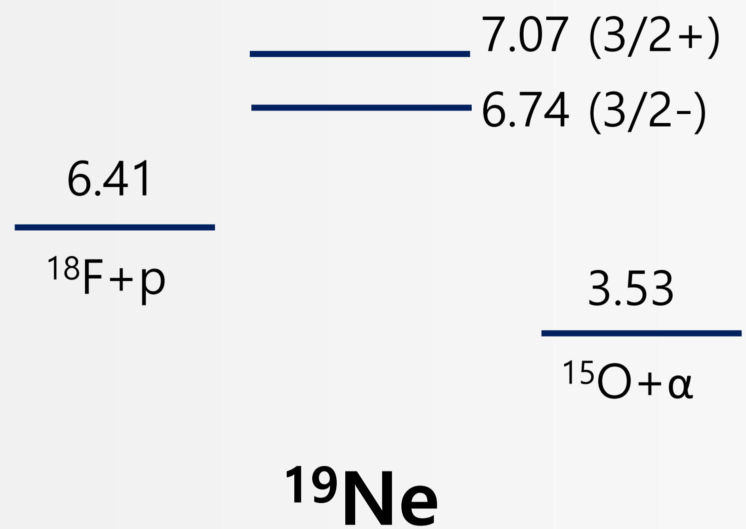
- ^{15}O+α excitation function fitting result. ($\theta_{c.m.}$ = 180°) . The ^{15}O+α elastic scattering was already pe rformed in 2017 but our energy range is more w iden compared with previous result.

Find alpha cluster states!

Motivation

$^{15}O+\alpha$ experiment for ^{19}Ne



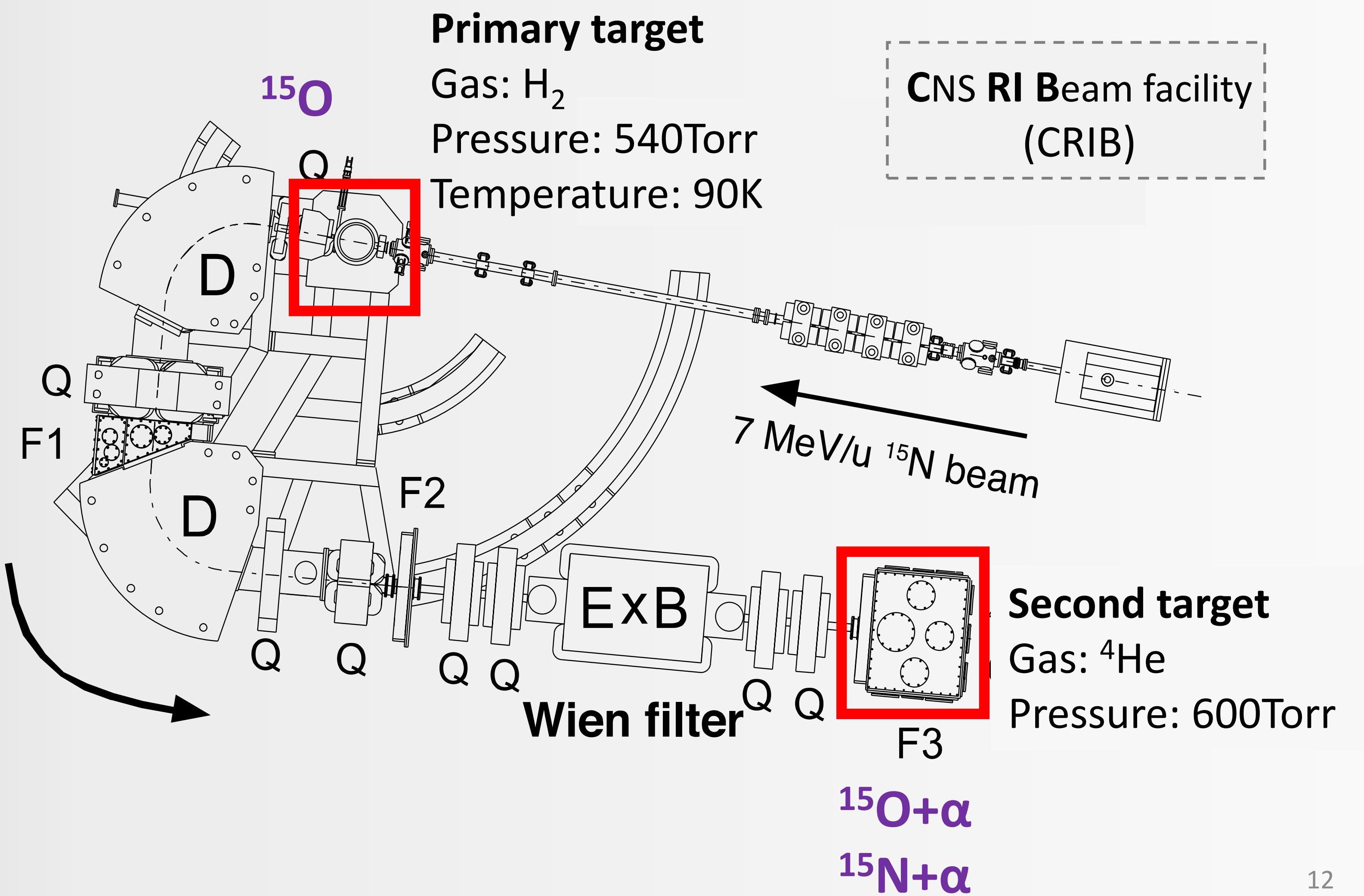


Low alpha threshold energy!

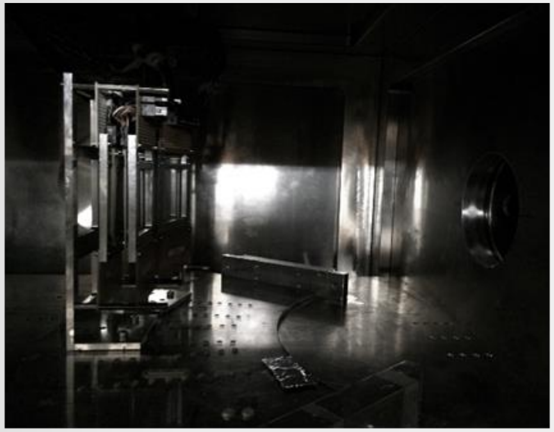
Easy to find the resonances around the proton threshold via $^{15}O + \alpha$.

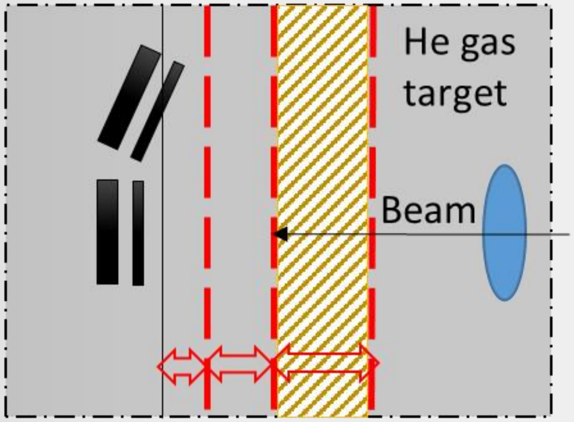
However, half-life of ^{15}O is only ~122 s!

CRIB facility



Experimental set-up



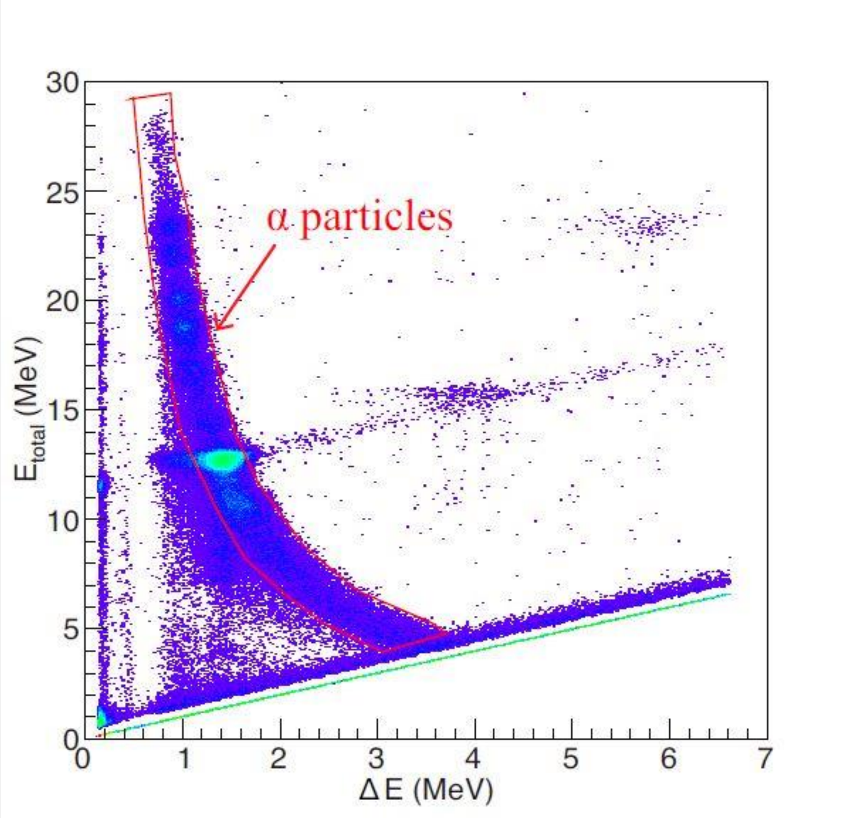


Thickness of the target (Effective thickness)

- Two experiments were conducted.
  - $^{15}O+\alpha$ elastic scattering
  - $^{15}N+\alpha$ elastic scattering

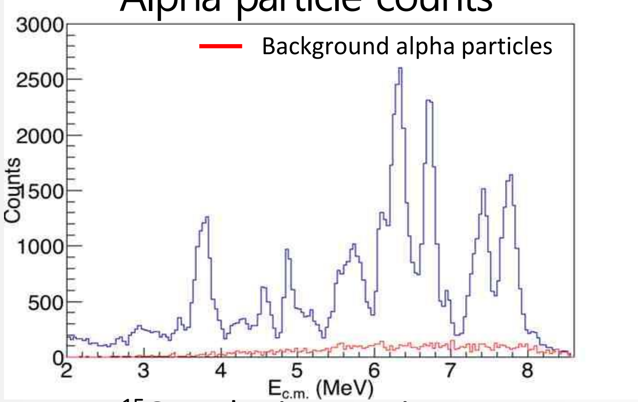
    Purpose: Study of the ^{19}F nuclei (Mirror nuclei of ^{19}Ne), for missing states of ^{19}Ne energy calibration of the $^{15}O+\alpha$ experiment
- Thick Target Inverse Kinematics (TTIK)
- Two ΔE-E telescopes were installed for the particle identification.
  - Type: Silicon detector
  - Thickness: ΔE ~20 μm, E ~480 μm

Analysis

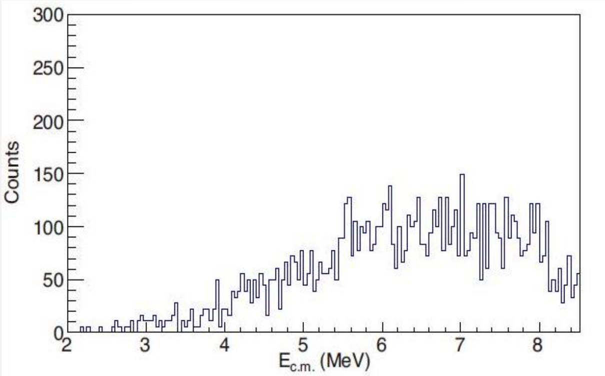


Particle identification using the silicon telescope.

Alpha particle counts



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

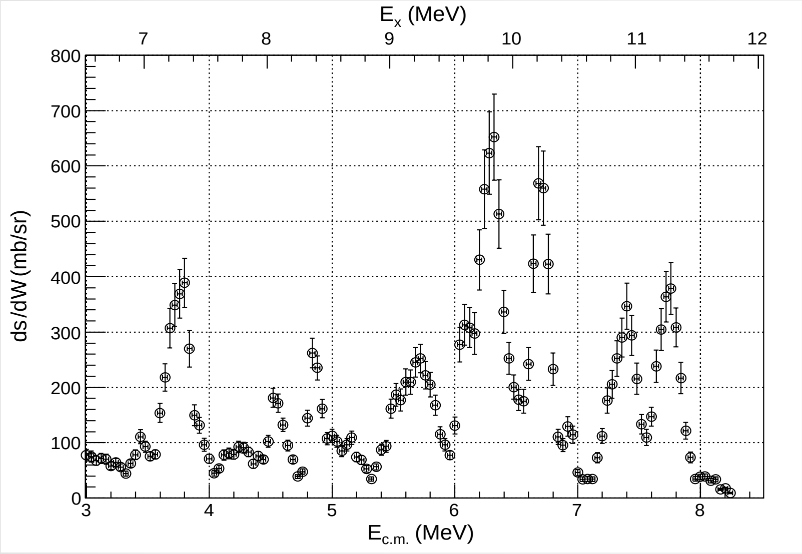


$^{15}O+Ar$ background run

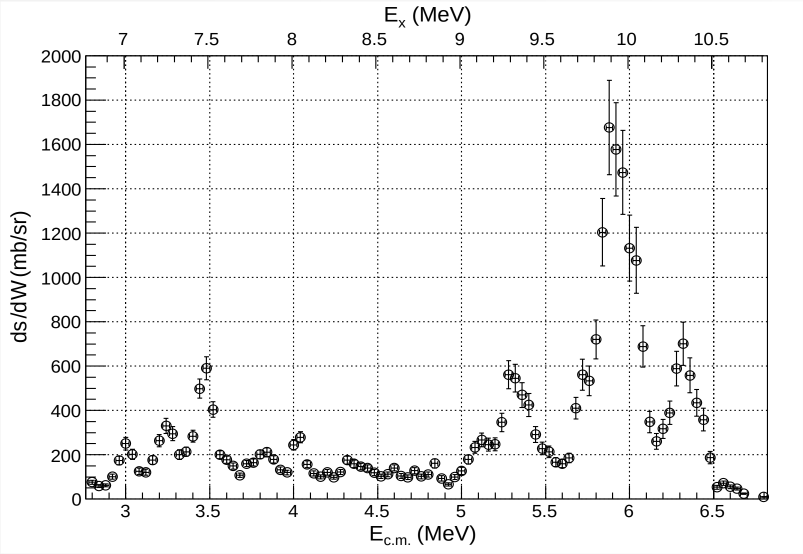
→ Background run is normalized with beam count rate.

Results

^{19}Ne



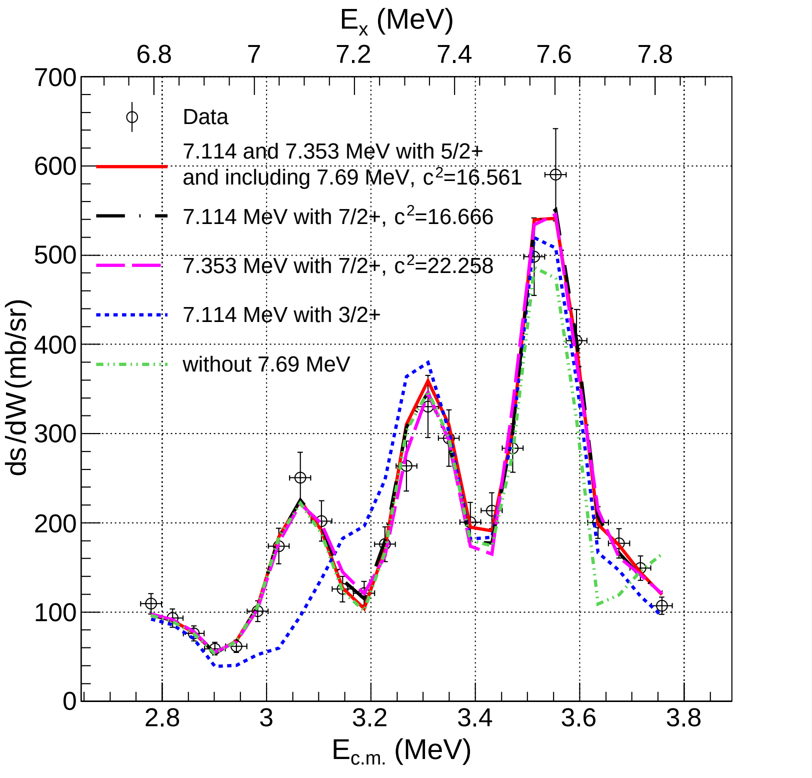
^{19}F

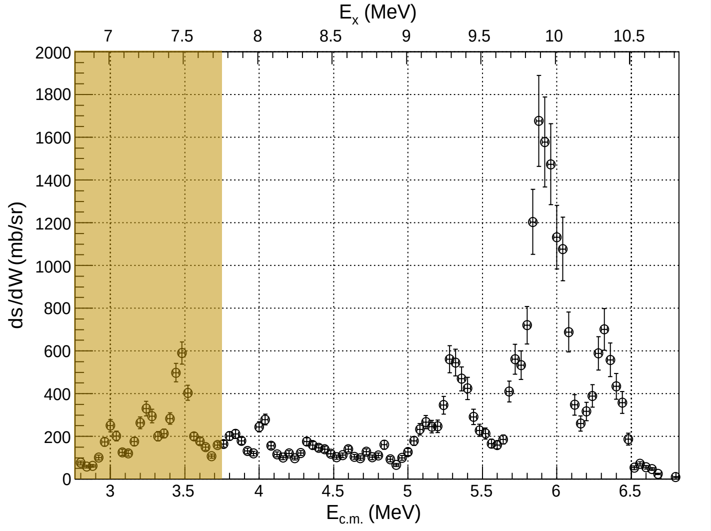


Excitation function for ^{19}Ne and ^{19}F

Results – ^{19}F

- R-matrix fitting result (lower-lying states)





^{19}F

The low-lying states in ^{19}Ne are located in the astrophysically important energy range.

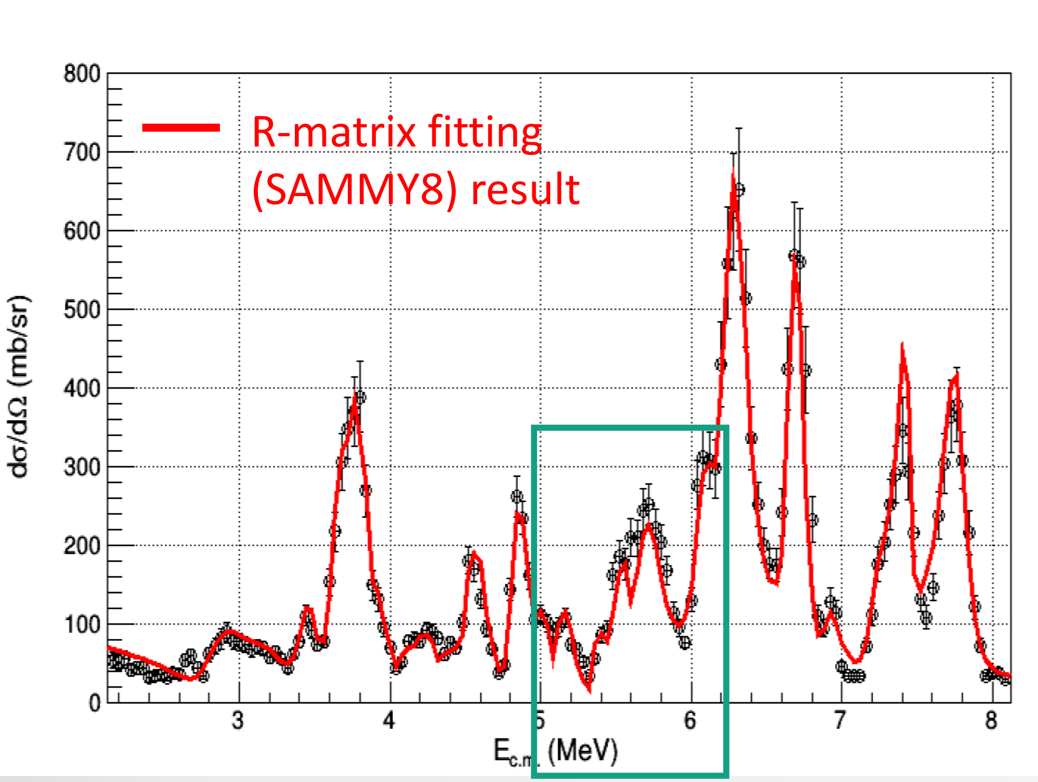
Results – ^{19}F

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

Results – ^{19}Ne



Angle = 174.5°

Spin and parity

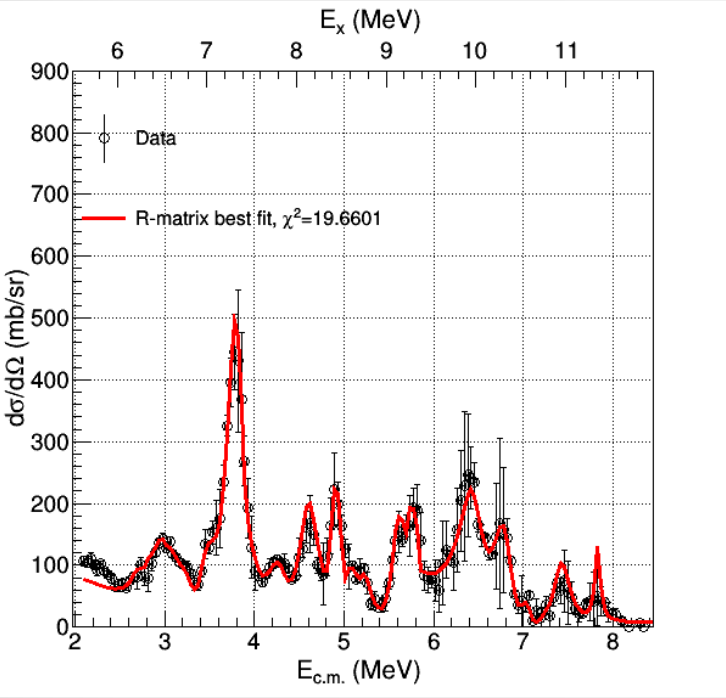
(limitation of R-matrix analysis)

&

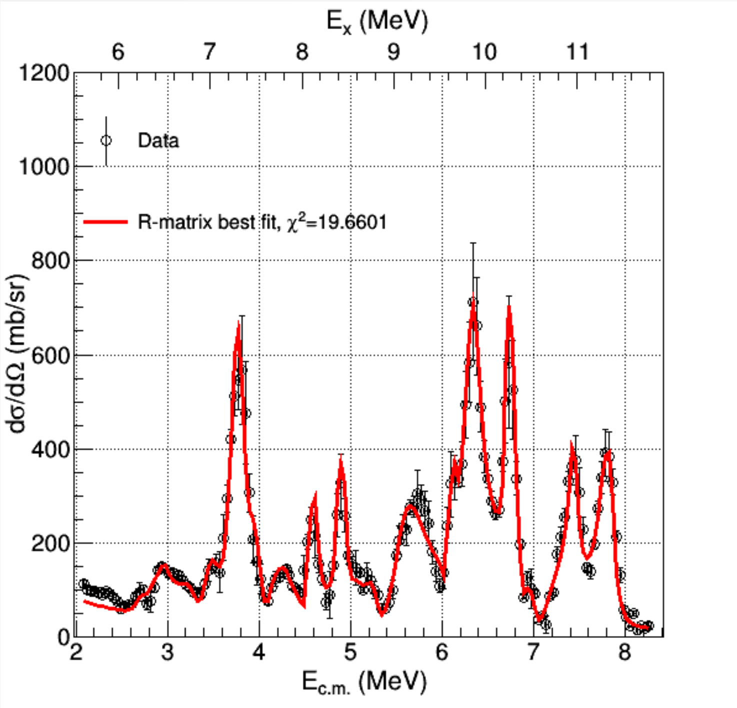
Doublet or triplet

(Energy resolution: ~ 40keV)

Results – ^{19}Ne



Angle = 164.5°



Angle = 170.5°

Results – ^{19}Ne

E_x (MeV)	Γ_α (keV)	J^π	Γ_w (keV)
6.291	71	5/2-	0.0742
6.422	133	3/2+	0.2398
6.437	29	1/2-	0.3708
6.901	137	3/2-	0.2490
7.054	81	7/2+	0.1033
7.076	65	3/2+	0.6259
7.255	234	5/2+	0.1454
7.305	98	7/2+	0.1573
7.531	54	5/2-	0.5626

E_x (MeV)	Γ_α (keV)	J^π	Γ_w (keV)
7.856	471	5/2-	0.7643
8.115	32	11/2+	0.0254
8.430	47	9/2-	0.1935
8.765	243	5/2-	1.3870
8.785	129	5/2+	0.7686
9.200	1039	7/2+	1.0084
9.400	968	5/2-	1.8332
9.620	23	11/2-	0.0349
9.870	175	11/2+	0.2227

Results – ^{19}Ne

E_x (MeV)	Γ_α (keV)	J^π	Γ_w (keV)
10.240	555	7/2-	0.8643
10.260	67	13/2-	0.0723
10.425	227	5/2-	2.5108
11.505	156	9/2-	1.5346
11.010	1354	7/2-	1.2632
11.030	226	7/2+	2.1434
11.340	151	11/2-	0.1933
11.370	66	7/2+	2.3481

- Dimensionless reduced width

$$\theta^2 = \frac{\Gamma_\alpha}{\Gamma_w}$$

- We obtained resonance parameters over 26 states in ^{19}Ne and calculated dimensionless reduced width which indicates the state is alpha-cluster state.

Summary of the ^{15}O+alpha experiment

- 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 26 peaks in ^{19}Ne were shown in silicon telescopes with an 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 affect the reaction rate.
- The alpha-cluster structure evidence was shown in our experimental data between 7.5 MeV < E_x < 8.5 MeV, and the result is consistent with the theoretical calculation.

Collaborators

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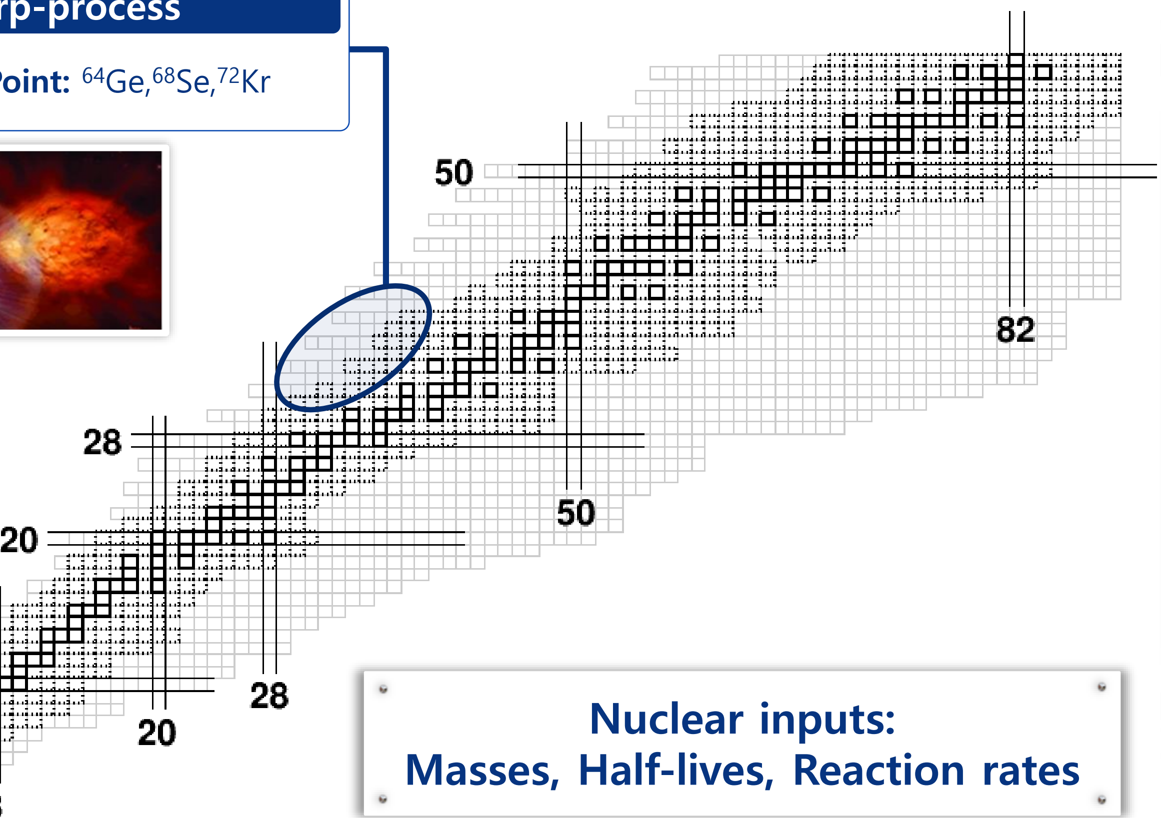
Impact on X-ray burst by nuclear astrophysics experiments

rp-process in X-ray burst

rp-process

Waiting Point: ^{64}Ge, ^{68}Se, ^{72}Kr



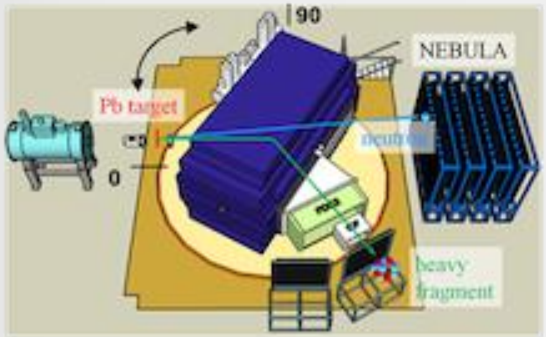
R. Giacconi
2002 Nobel prize

Nuclear inputs:
Masses, Half-lives, Reaction rates

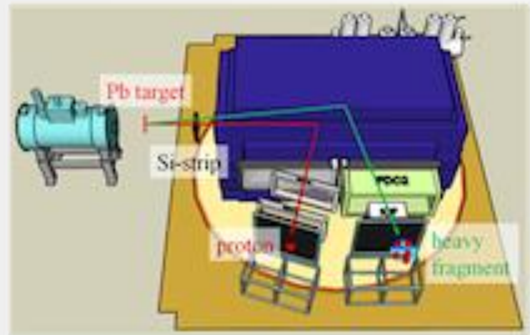
SAMURAI experiment

Different reactions using SAMURAI at RIBF/RIKEN

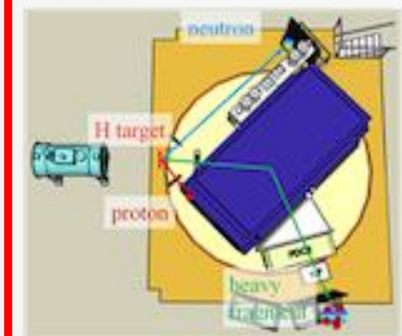
(γ, n) reaction: neutron-rich side



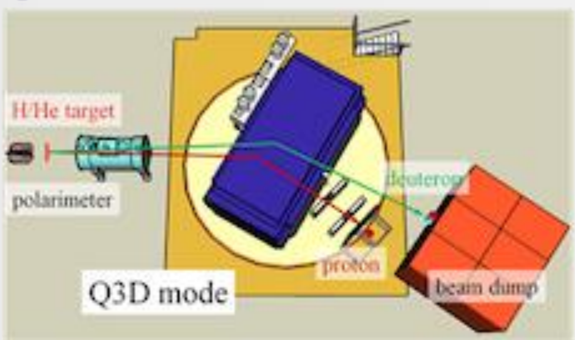
(γ, p) reaction: proton-rich side



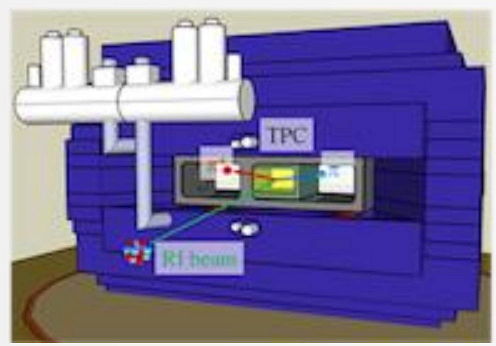
(p,p'), (p,2p), (p,pn), …



pol. d-induced reaction



EOS measurement



- Heavy-ion-Proton (HiP) experiments were performed for investigating rp-process near Waiting Point(WP) in proton drip-line

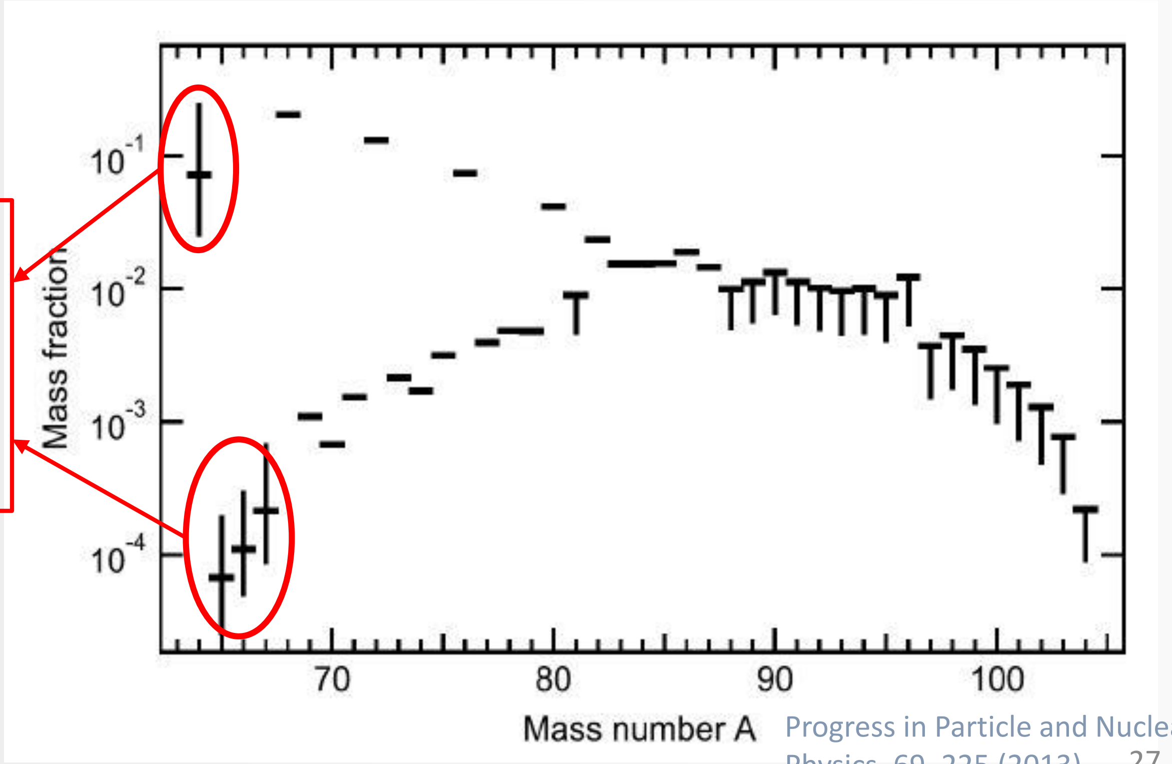
SAMURAI Collaboration experiment

[Subject]:

Investigation of proton-unbound state in neutron-deficient isotopes ^{66}Se and ^{58}Zn

$^{65}As(p,\gamma)^{66}Se$ is the most influential reaction rate in several X-ray burst models

Large uncertainties: factor of 10
Due to the Bridge effect on the Waiting Point nucleus

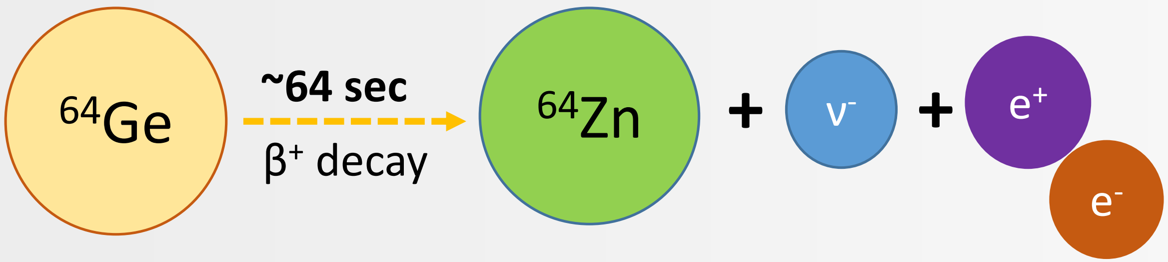


Progress in Particle and Nuclear Physics, 69, 225 (2013)

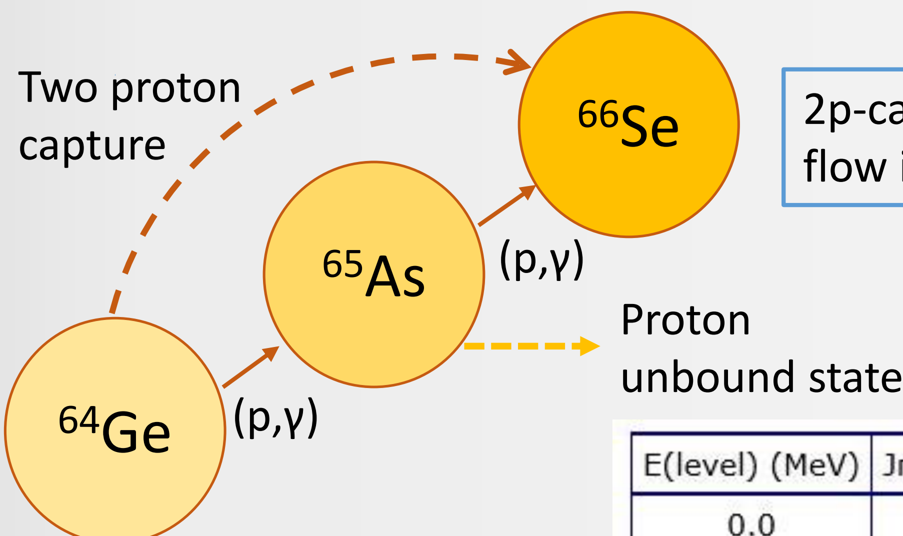
SAMURAI Collaboration experiment

[Subject]:

Investigation of proton-unbound state in neutron-deficient isotopes ^{66}Se and ^{58}Zn



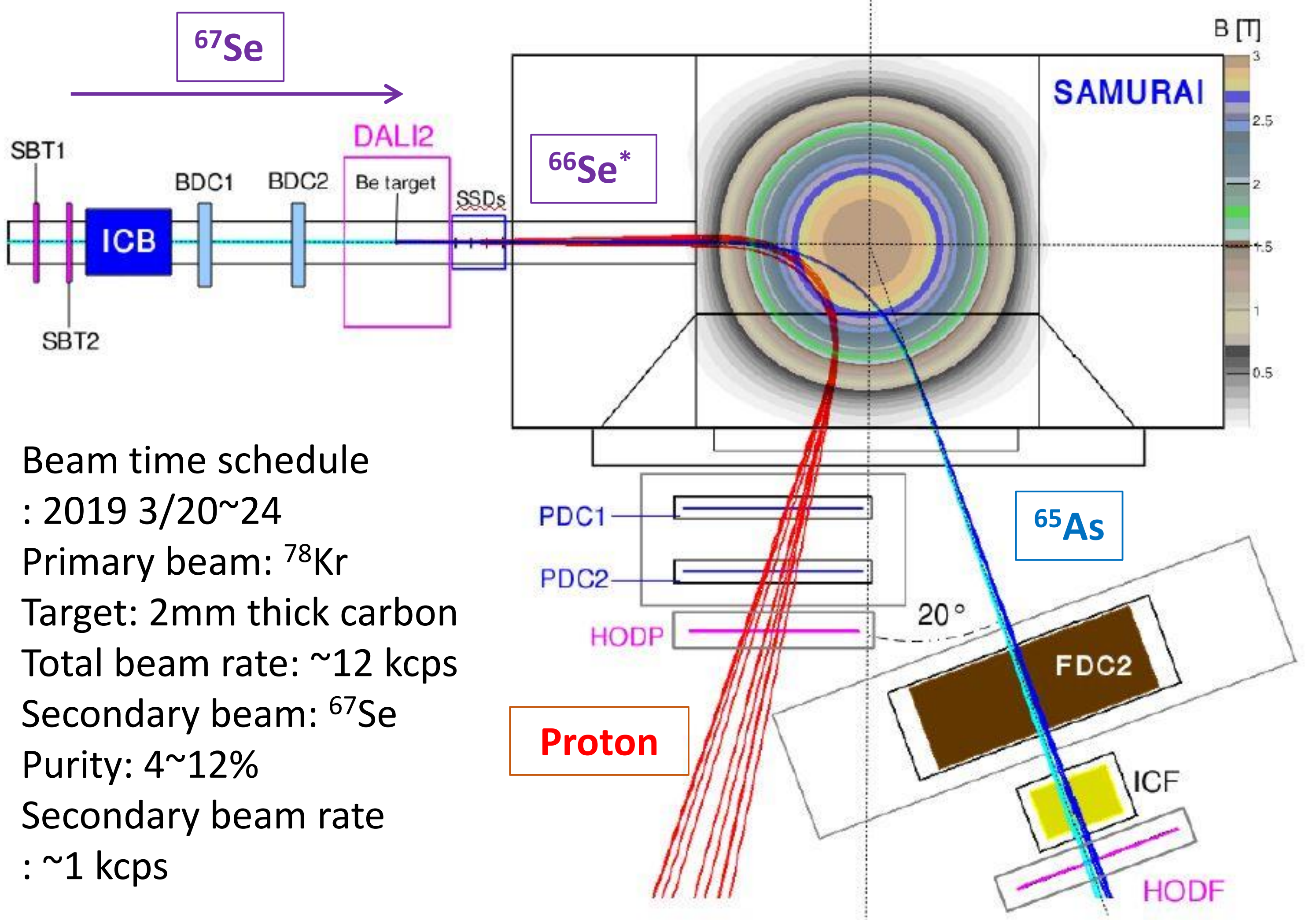
rp-process : β⁺ decay (~1s) and proton capture (Take 100s) Phys. Rev. C 78, 012810 (2008)



2p-capture reactions accelerate the reaction flow into the Z>36 region in X-ray bursts

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes	S_p (keV)
0.0		-46.9370	128 ms *16*	ε : 100.00 %	-9.E+1 *8*

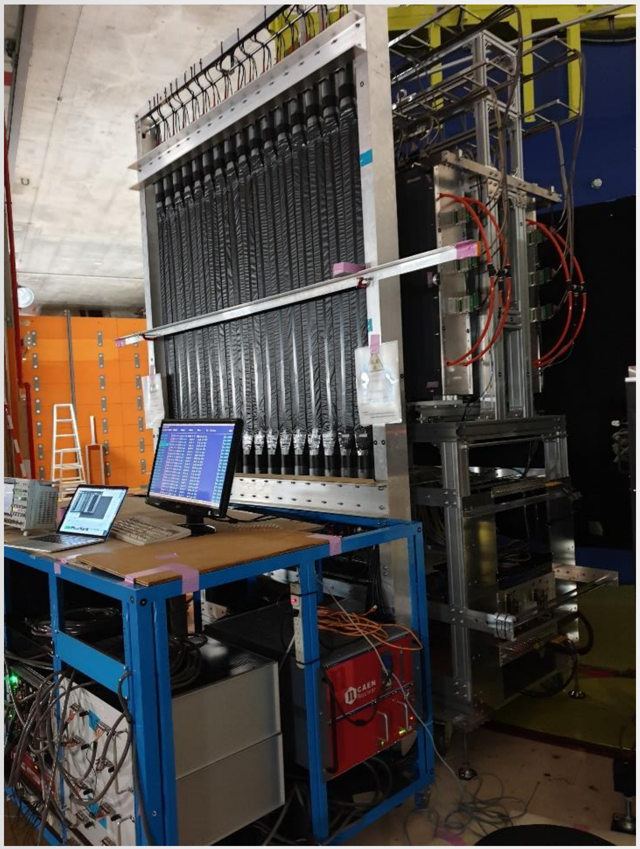
SAMURAI Collaboration experiment



Beam time schedule
: 2019 3/20~24
Primary beam: ^{78}Kr
Target: 2mm thick carbon
Total beam rate: ~12 kcps
Secondary beam: ^{67}Se
Purity: 4~12%
Secondary beam rate
: ~1 kcps

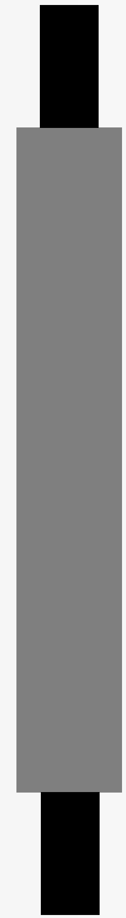
SAMURAI Collaboration experiment

❖ Hodoscope detector



HODP

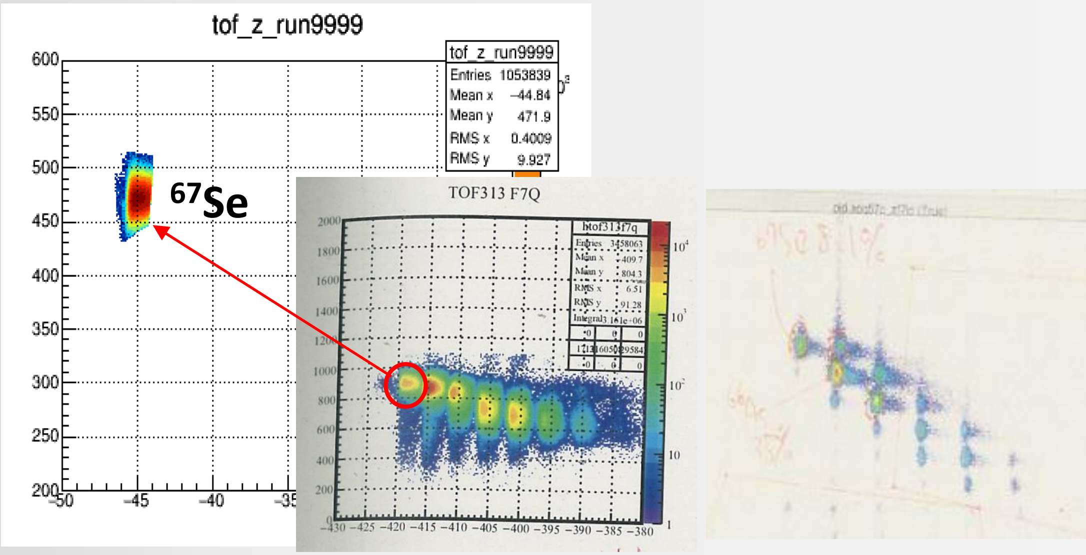
HODS

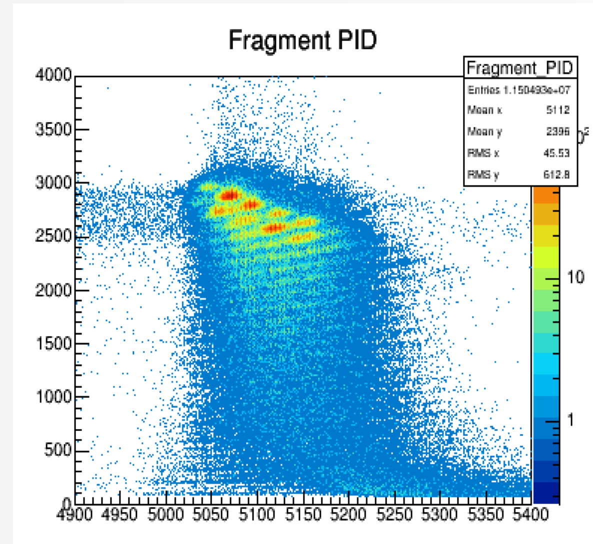


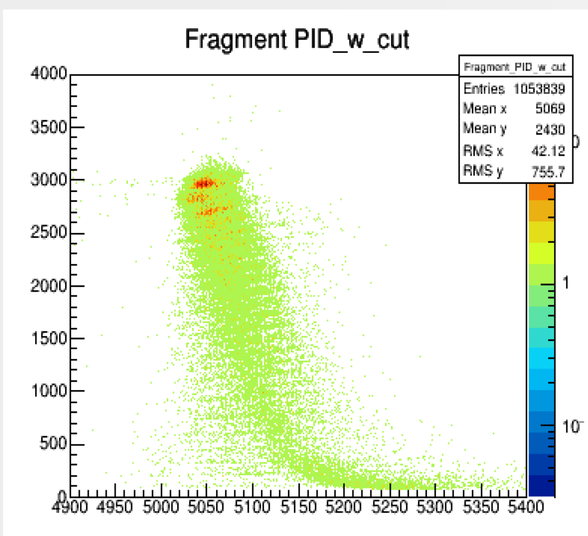
PMT (Photo Multiplier Tube)

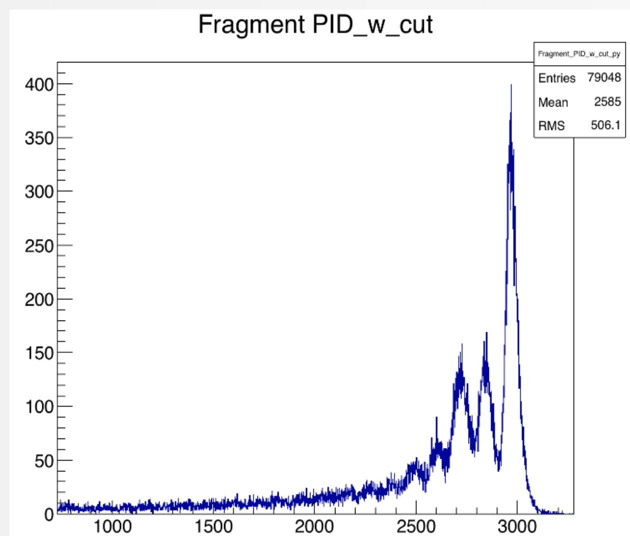
Plastic Scintillator

SAMURAI Collaboration experiment

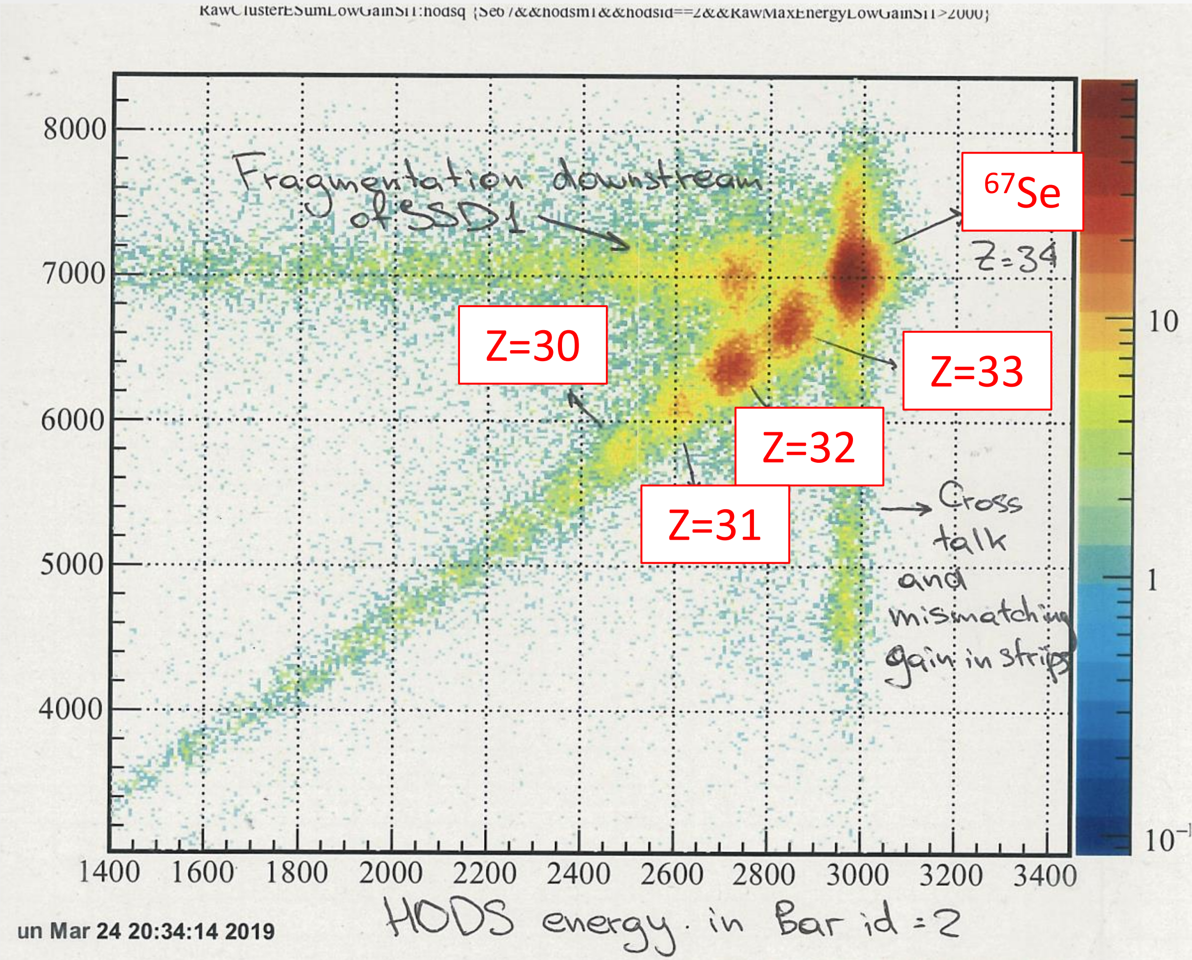








SAMURAI Collaboration experiment



SAMURAI Collaboration experiment

Primary Beam	^{67}Se	^{67}As	^{66}As
One neutron Knockout channel /One proton separation	$^{67}Se^{*} \rightarrow {}^{66}As+p$ $^{66}Se^{*} \rightarrow {}^{65}As+p$ $^{65}Se^{*} \rightarrow {}^{64}As+p$ $^{64}Se^{*} \rightarrow {}^{63}As+p$	$^{67}As^{*} \rightarrow {}^{66}Ge+p$ $^{66}As^{*} \rightarrow {}^{65}Ge+p$ $^{65}As^{*} \rightarrow {}^{64}Ge+p$ $^{64}As^{*} \rightarrow {}^{63}Ge+p$	$^{66}As^{*} \rightarrow {}^{65}Ge+p$ $^{65}As^{*} \rightarrow {}^{64}Ge+p$ $^{64}As^{*} \rightarrow {}^{63}Ge+p$ $^{63}As^{*} \rightarrow {}^{62}Ge+p$
One neutron Knockout channel /Two proton separation	$^{67}Se^{*} \rightarrow {}^{65}As+2p$ $^{66}Se^{*} \rightarrow {}^{64}As+2p$ $^{65}Se^{*} \rightarrow {}^{63}As+2p$ $^{64}Se^{*} \rightarrow {}^{62}As+2p$	$^{67}As^{*} \rightarrow {}^{65}Ge+2p$ $^{66}As^{*} \rightarrow {}^{64}Ge+2p$ $^{65}As^{*} \rightarrow {}^{63}Ge+2p$ $^{64}As^{*} \rightarrow {}^{62}Ge+2p$	$^{66}As^{*} \rightarrow {}^{64}Ge+2p$ $^{65}As^{*} \rightarrow {}^{63}Ge+2p$ $^{64}As^{*} \rightarrow {}^{62}Ge+2p$ $^{63}As^{*} \rightarrow {}^{61}Ge+2p$

Summary of the talk

- The $^{14,15}O$+alpha experiments were performed using CRIB at CNS/RIKEN.

- The $^{65}As(p,g)^{66}Se$ experiment was done using SAMURAI at RIKEN

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Korea is building the RI beam accelerator called RAON. Integration of ISOL and IF will allow us to investigate structure studies of extremely neutron-rich nuclei and nuclear astrophysics experiments.

Thank you for your attention!