2018 DREB Symposium

The structure of ^{19}Ne with a radioactive ^{15}O beam

Ewha Womans University
Dahee Kim

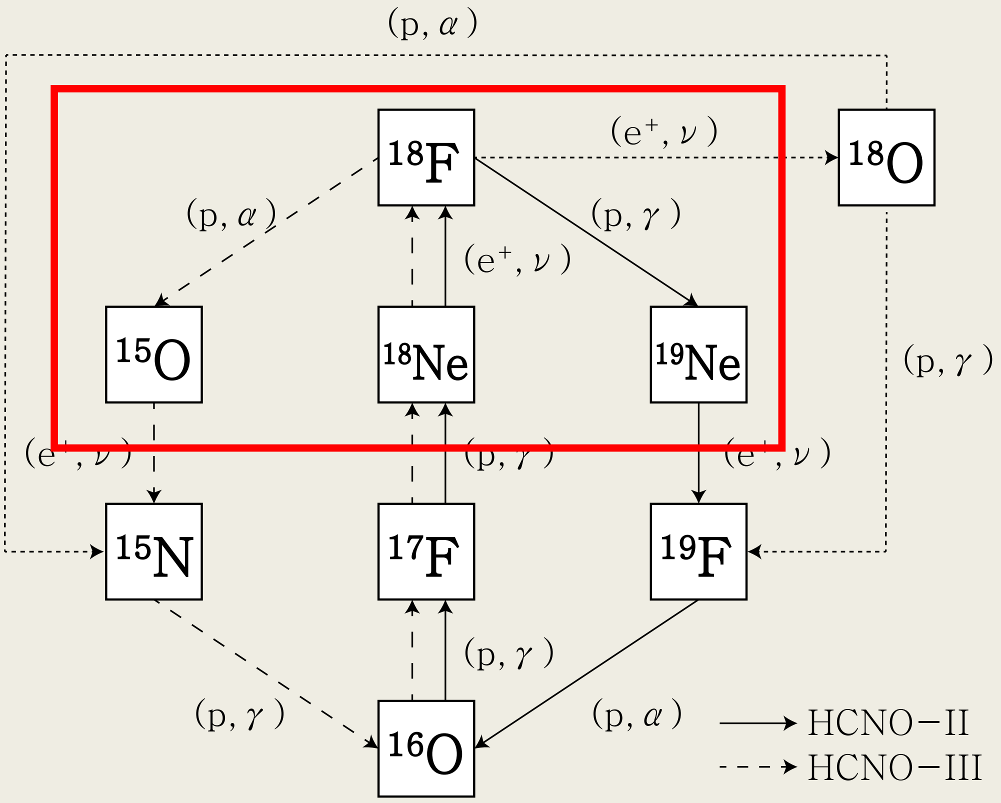
Motivation

- **^{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

K. Y. Chae et al.

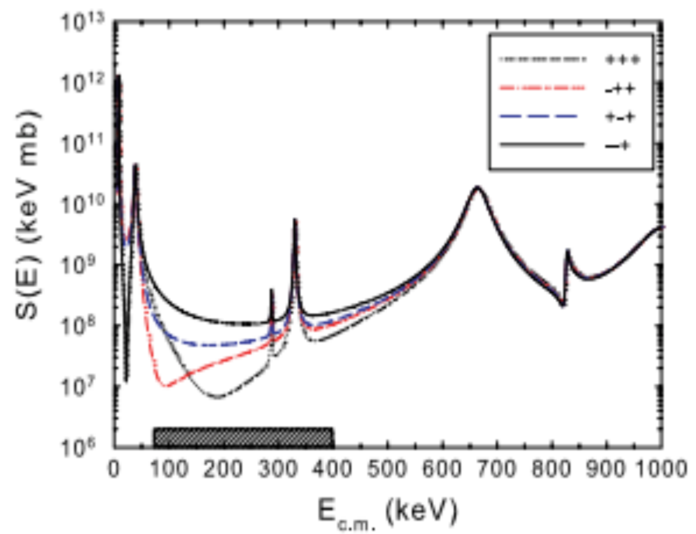
Astrophysical S- factor of the $^{18}F(p,a)^{15}O$ reaction

- **Interference effect**

- 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+ subthreshold states and above the proton threshold states were interference each others, and it 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]



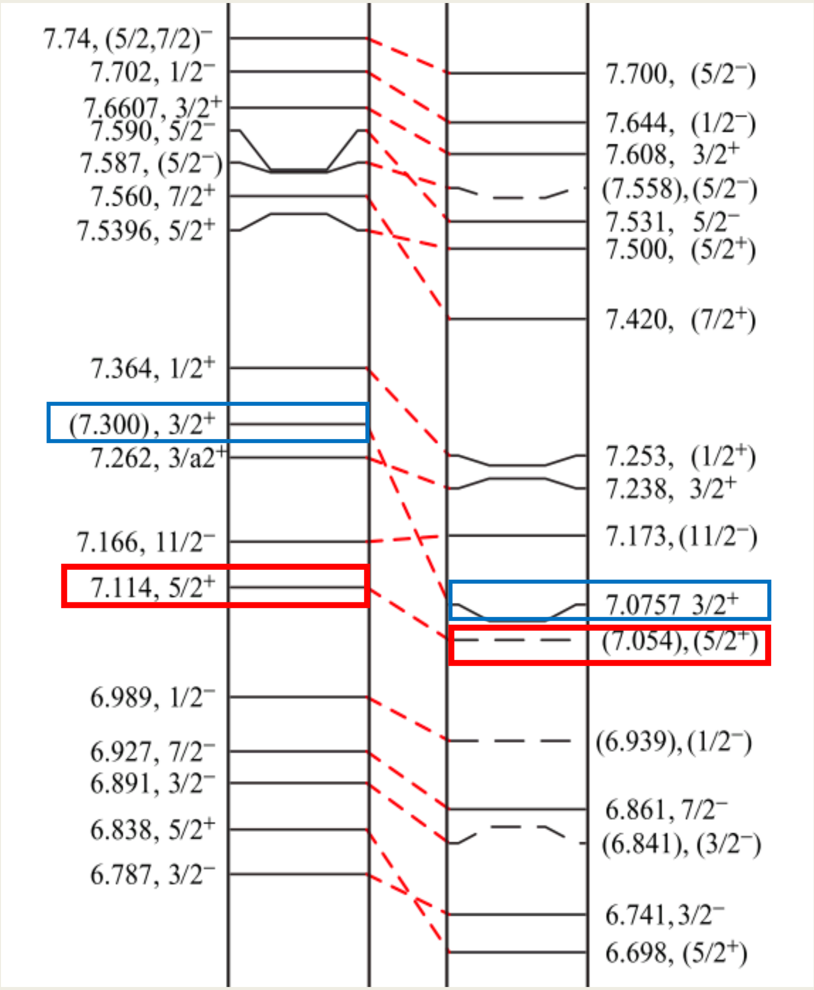
Previous study

- **Missing state**

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

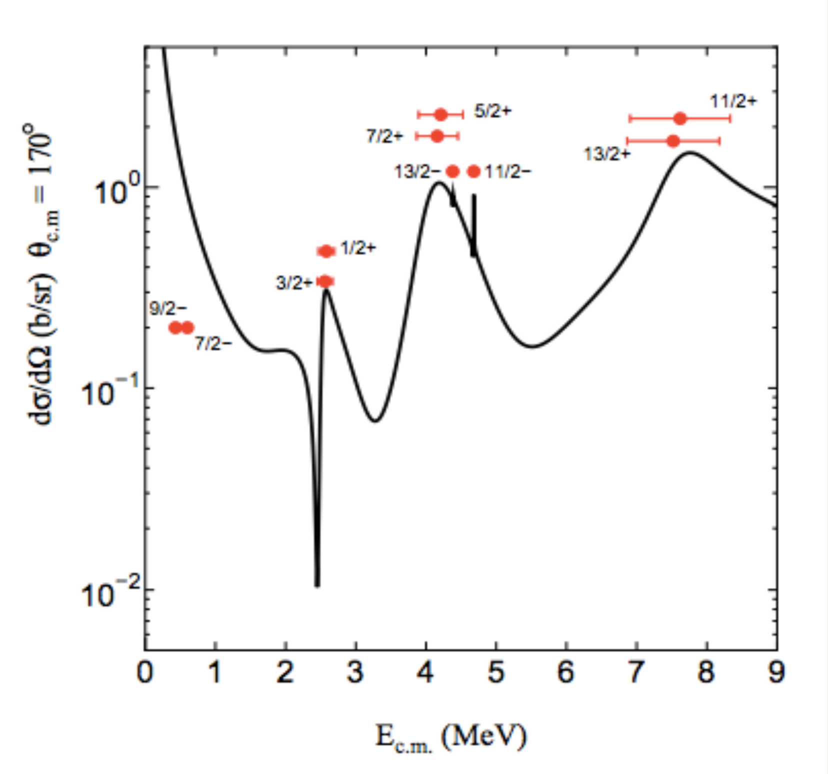
- Due to the insufficient of experimental results in ^{19}Ne, important resonance parameters in ^{19}Ne were extracted from the mirror nuclei ^{19}F.

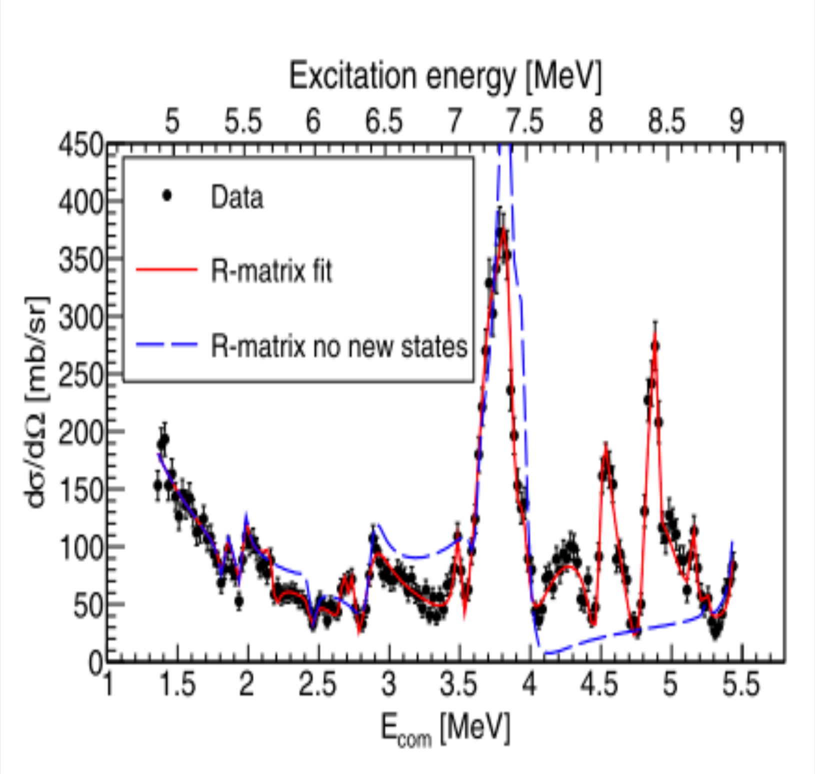
- The E_x = 7.054 MeV state is assumed that it may affect the ^{18}F(p,α)^{15}O reaction rate. However, it has not been measured yet.



Previous study

- **Alpha cluster states**





Otani et al. (2016)
Theorical calculation on excitation energy of ^{19}Ne

D. Torresi et al. (2017)
^{15}O+alpha Excitation function fitting resul t ($\theta_{c.m.}$ = 180°) Fitting result used R-matri x 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

Spin, Parity ?

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

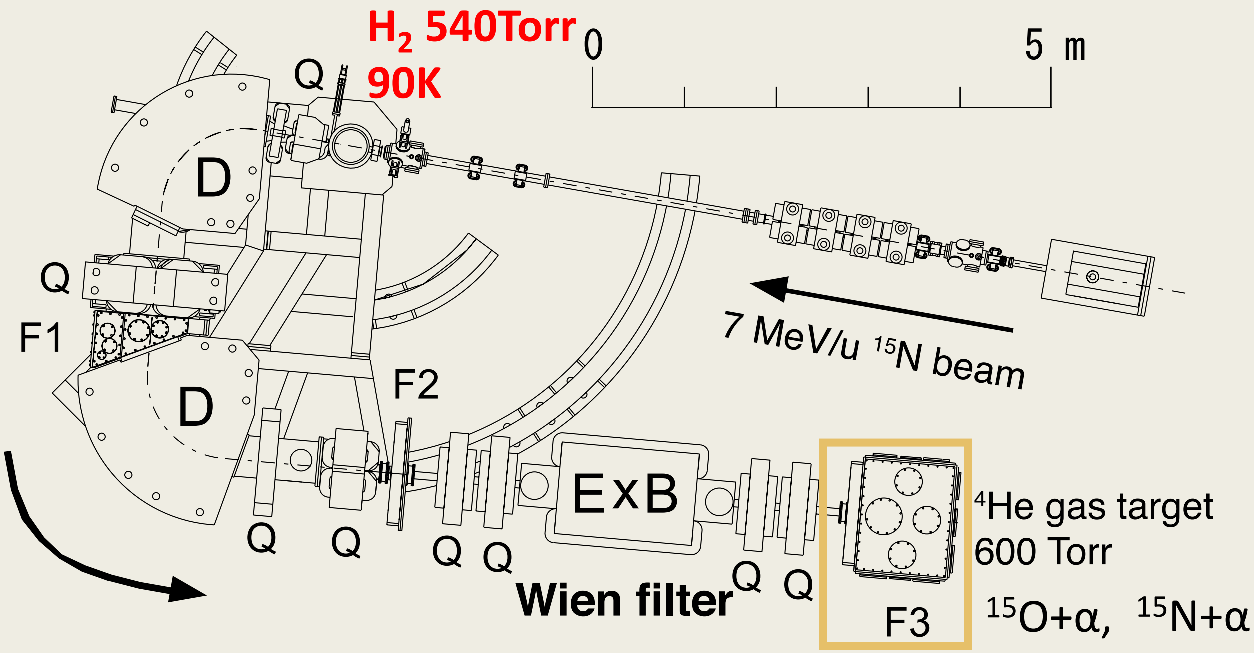
Missing state

…

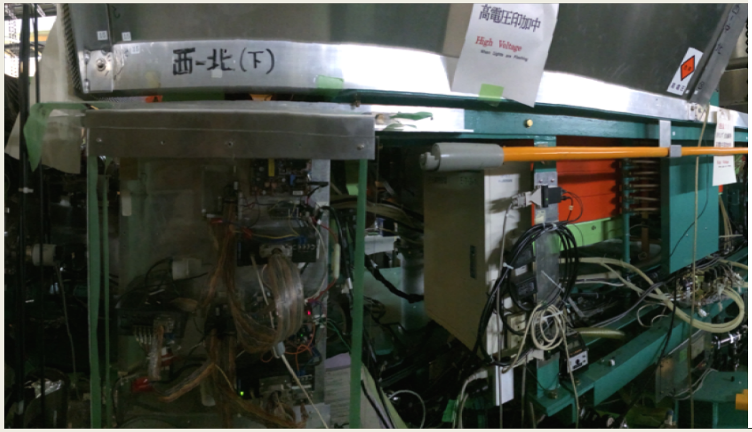
Existence ??

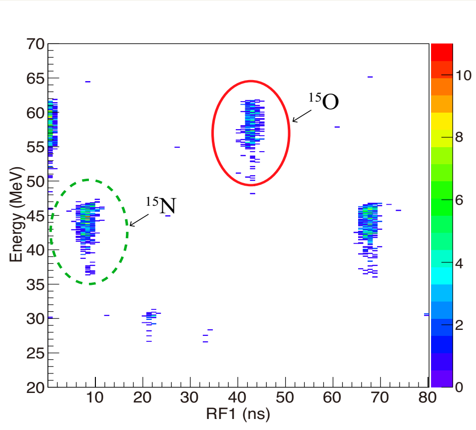
- To investigate the structure of ^{19}Ne & ^{19}F in a wide energy range

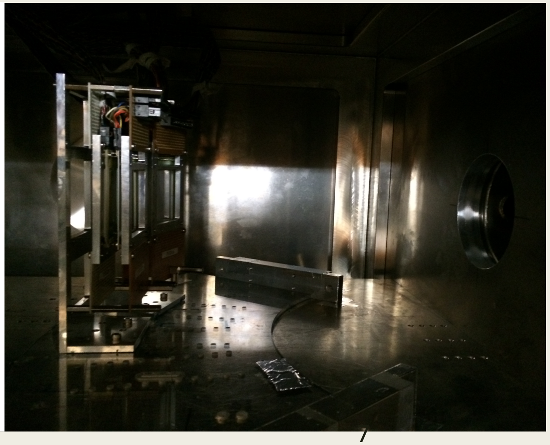
Experimental set-up



Thick target method

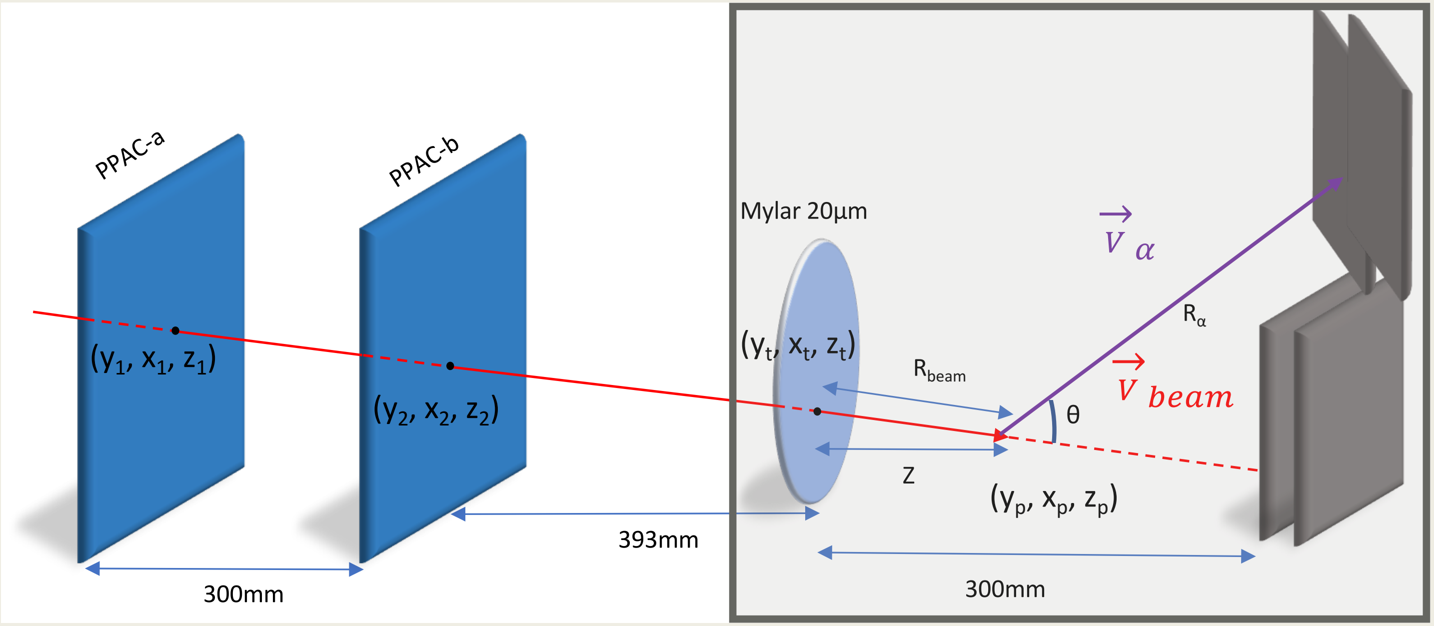






Reaction reconstruction

- ## Reaction reconstruction



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

→ 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**

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

Y : yield (#/s)

$M(^4He)$: 4.003 g/mol

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

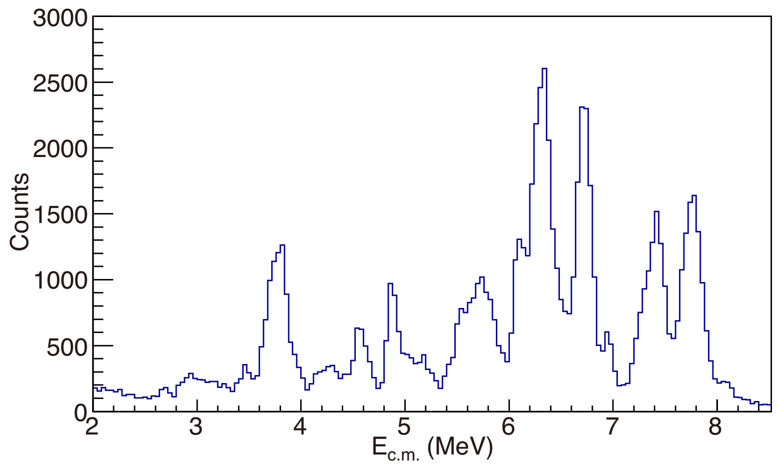
N_A : Avogardro number($6.02*10^{23}$#)

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

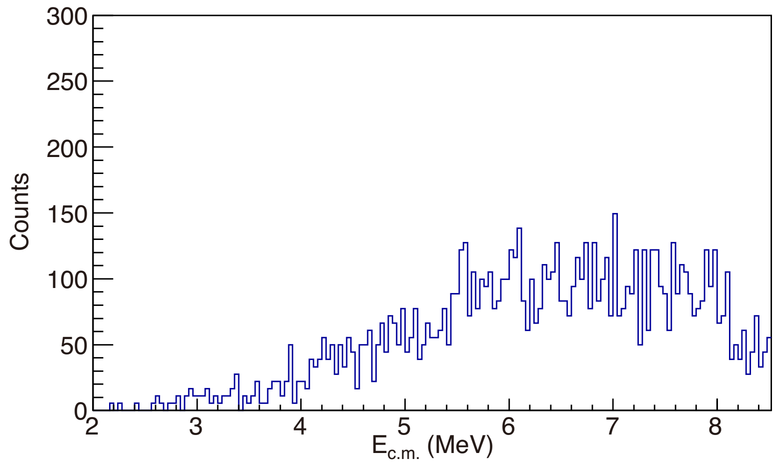
$\Delta\Omega$: solid angle (sr)

Data analysis

- **Background reduction**



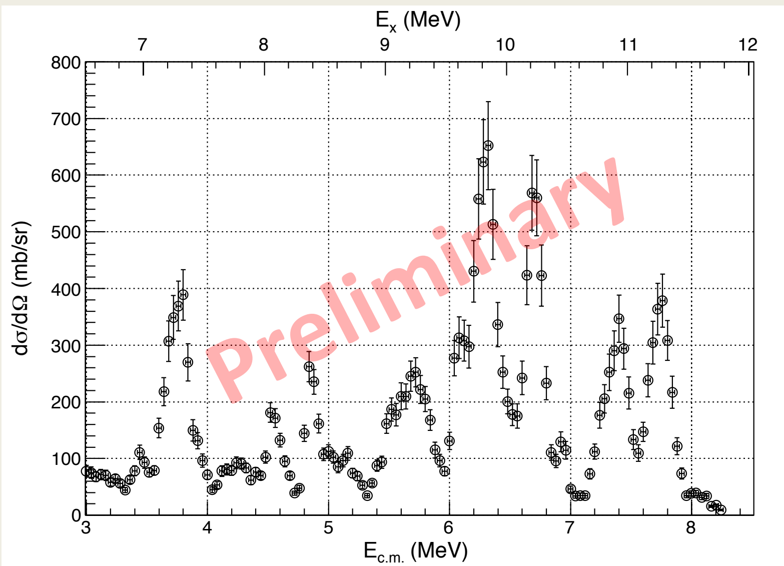
$^{15}O + \alpha$ elastic scattering



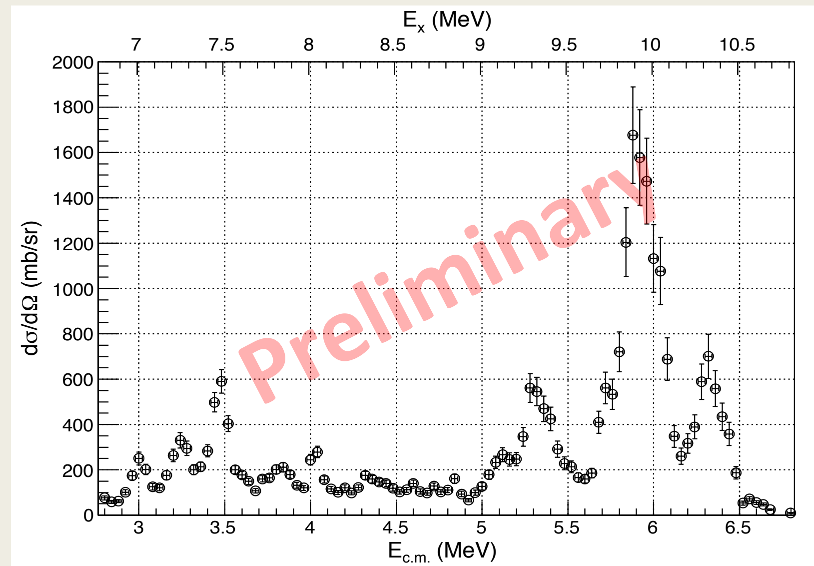
^{15}O + argon run

Result

- **Cross section**



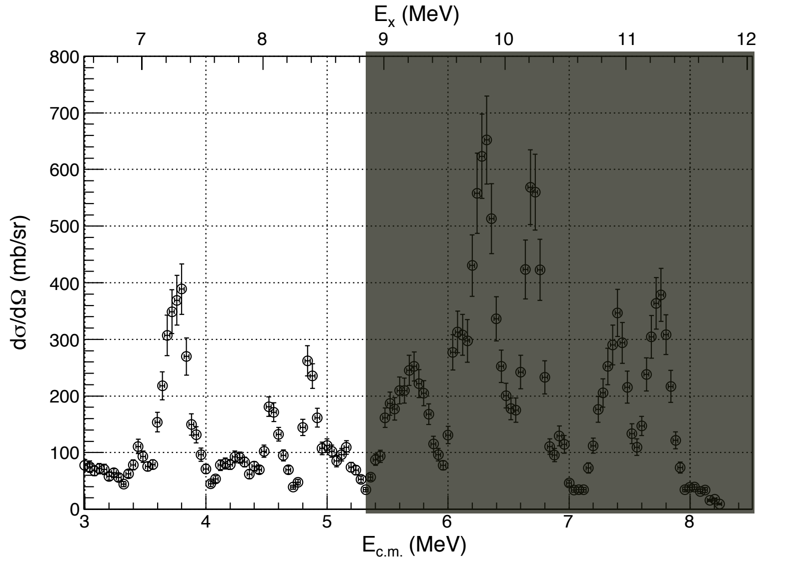
The excitation function for ^{19}Ne



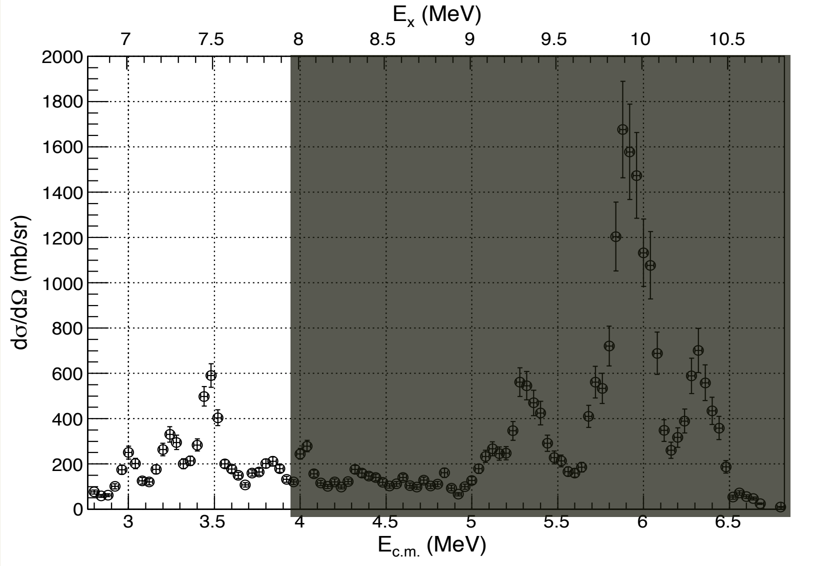
The excitation function for ^{19}F

Result

- **Cross section**



The excitation function for ^{19}Ne



The excitation function for ^{19}F

Result

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

Table 3.2. Summary of ^{19}F resonance parameters compared with previous studies.

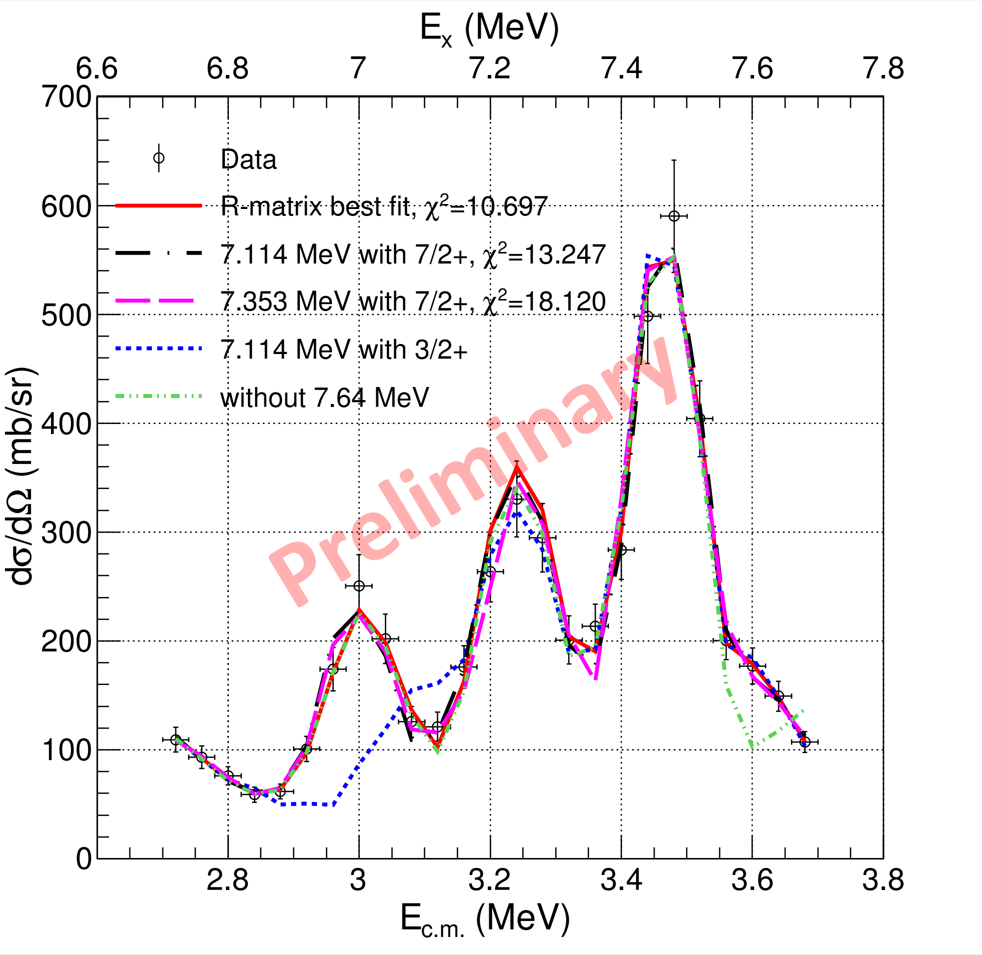
Previous study					This work		
E_x (MeV ± keV)	Γ_α (keV)	Γ (keV)	J^π	Ref.	E_x (MeV)	Γ_α (keV)	J^π
6.536 ± 5^a	245 ± 6	-	$\frac{1}{2}^-$	[24, 25, 46]			
6.838 ± 0.9^b	1.2	-	$\frac{5}{2}^+$	[24, 25]	6.74	0.9 ± 0.4	$\frac{5}{2}^+$
6.989 ± 3^b	96 ± 6	-	$\frac{1}{2}^-$	[24, 25]	6.94	99 ± 26	$\frac{1}{2}^-$
7.114 ± 6^b	25 ± 4	-	$\frac{5}{2}^+$	[15, 24, 25, 43, 45, 46]	7.05	30 ± 4	$(\frac{5}{2}^+, \frac{7}{2}^+)$
7.353^a	65	-	$\frac{7}{2}^+$	[24, 25]	7.26	68 ± 6	$(\frac{5}{2}^+, \frac{7}{2}^+)$
7.56 ± 10^b	-	< 90	$\frac{7}{2}^+$	[24]	7.49	80 ± 6	$\frac{7}{2}^+$
7.587	$\Gamma_{lab} < 50$	-	$(\frac{5}{2}^-)$	[42]	7.52	41 ± 9	$\frac{5}{2}^-$
7.702 ± 5	-	< 30	$\frac{1}{2}^-$	[42]	7.64	57 ± 15	$(\frac{3}{2}^-)$
7.88^c	-	< 260	-	[24]			

[a]from Ref. [25]
[b]from Ref. [42]
[c]from Ref. [24]

Preliminary

Discussion (^{19}F)

- We successfully reproduce the previous result of ^{19}F.
- The Ex = 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 Ex = 7.353 MeV state spin assignment was changed from 7/2+ to 5/2+.
- The Ex = 7.56 and 7.58 MeV states were newly determined the alpha width.
- The Ex = 7.64 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.

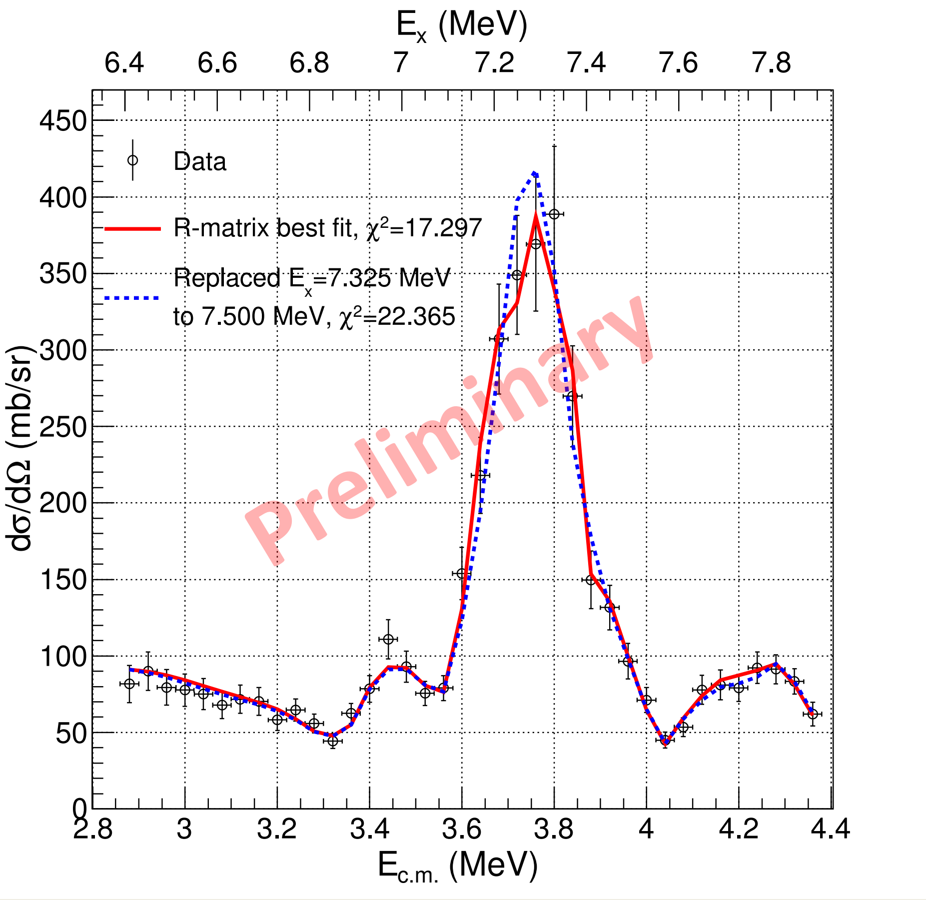
Previous study					This work		
$E_x{}^a$ (MeV ± keV)	$E_\gamma{}^a$ (keV)	Γ_α (keV)	J^π	Ref.	E_x (MeV)	Γ_α (keV)	J^π
6.437	26 ± 9	216 ± 19	$\frac{1}{2}^-$	[26, 49]			
6.939	528 ± 30 9	99 ± 69	$\frac{1}{2}^-$	[51]	6.94	138	$\frac{1}{2}^-$
(7.054)	643 ± 30	29 ± 25	$(\frac{5}{2}^+, \frac{7}{2}^+)$	[15, 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

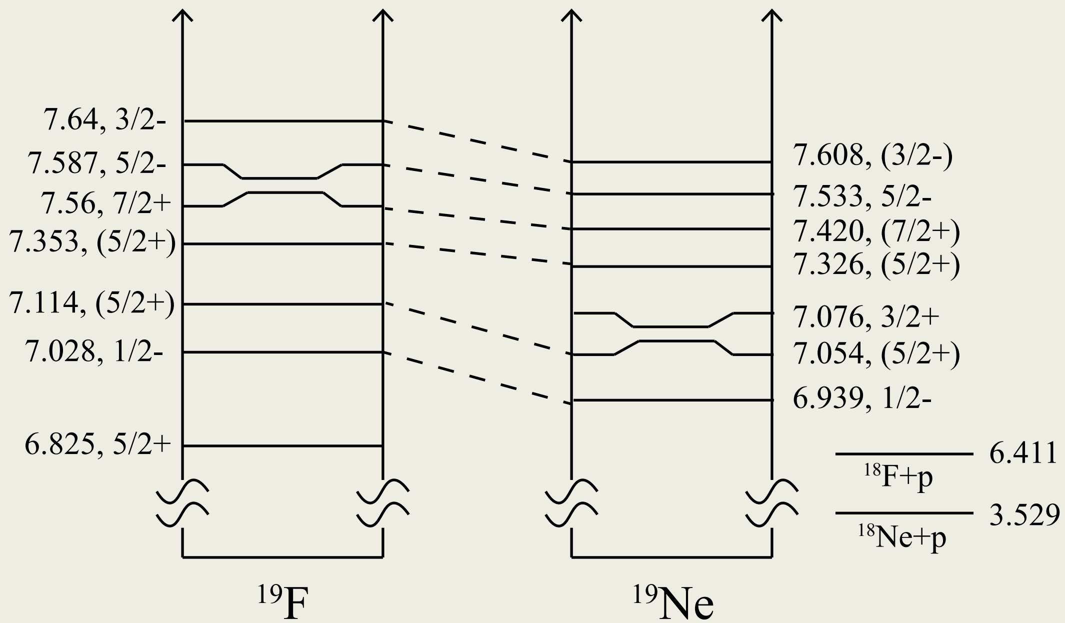
Discussion (^{19}Ne)

- 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 consists with four resonances , Ex = 7.326, 7.420, 7.531, and 7.644 MeV.
- The 7.420 MeV state was ruled out for the ^{18}F(p,α)^{19}Ne reaction rate calculation due to the weak evidence. However, we found with a large alpha width so we suggest the 7.420 MeV state should be considered to the calculation.



Result

- **Mirror states**

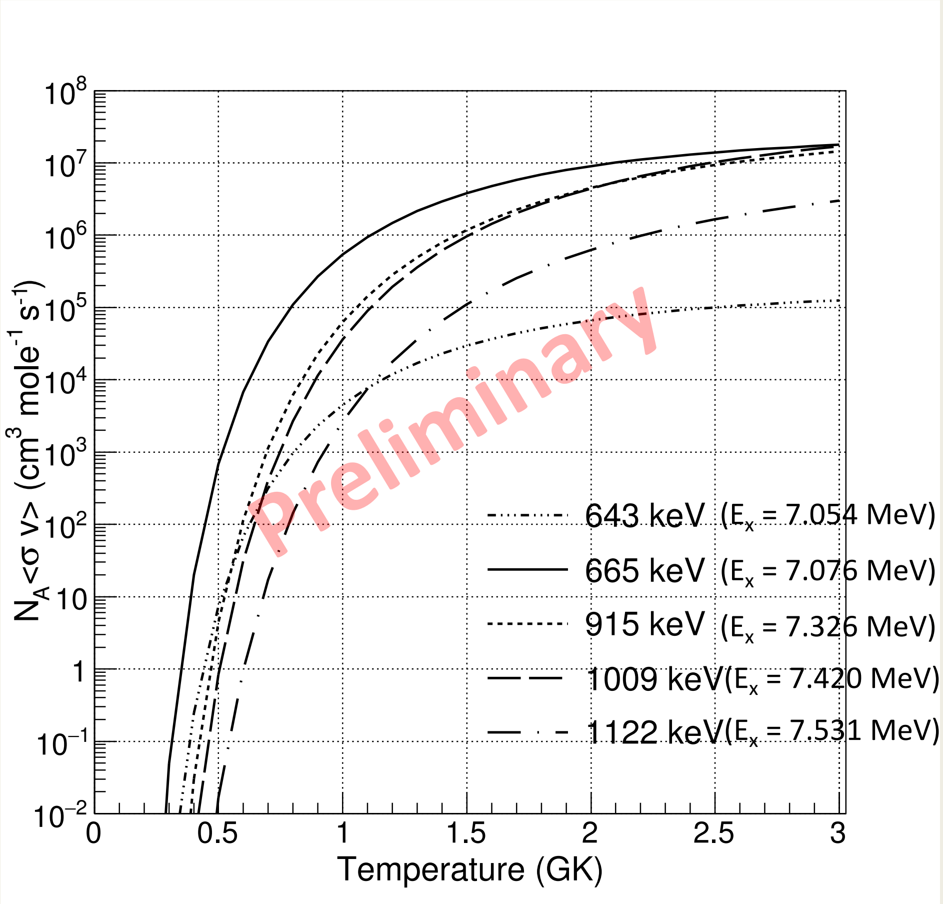


This diagram shows the presumed mirror states using our analysis results.

- The mirror state of 7.076 MeV state in ^{19}Ne is still missing.
- The missing state at Ex = 7.054 MeV was measured in the present experiment. This state can be connected to Ex = 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 are 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 good energy resolution ($E_{c.m.}$ = 40 keV).

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

- Alpha cluster structures were shown in ^{19}Ne and ^{19}F. Further study is going on.

Thank you for your attention

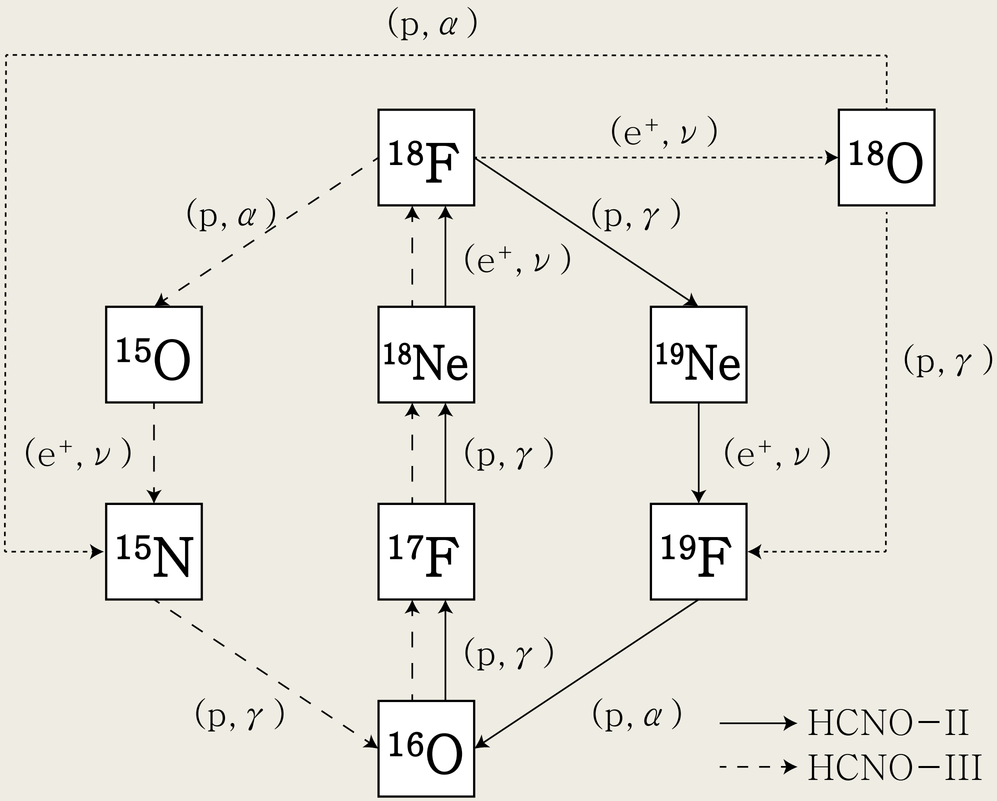
Motivation

- ^{18}F nucleosynthesis in classical novae

1. Large abundance of ^{16}O in the classical nova

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

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



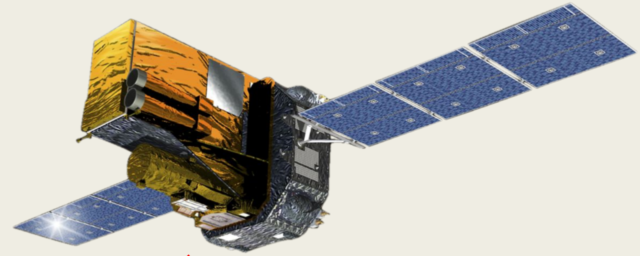
2. HCNO-II : $T_9 > 0.2$

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

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

Motivation

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



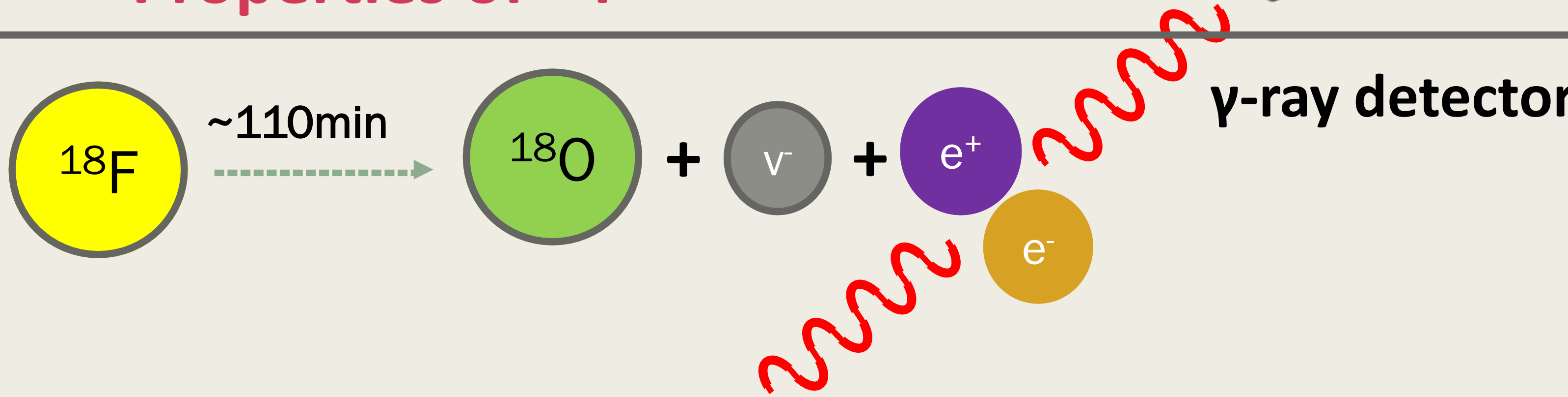


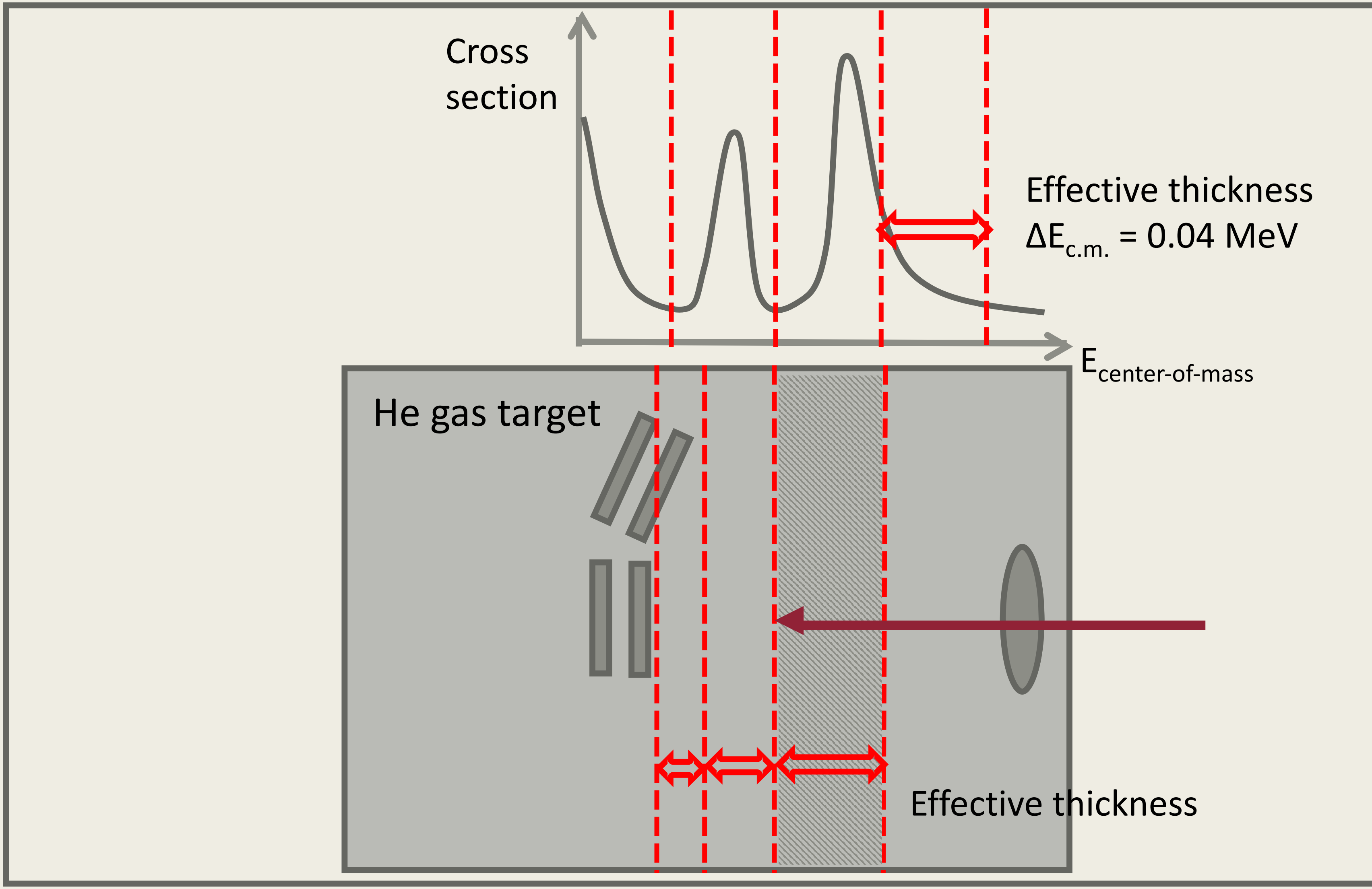
Table 1.1. List of γ-ray emission types for CO and ONe nova [7].

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

Contents

Experiment

- **Thick target method in inverse kinematics (TTIK)**



Uncertainty

- **Error propagation**

$$\delta(\frac{d\sigma}{d\Omega}) = \frac{d\sigma}{d\Omega} \times \sqrt{(\frac{\delta Y}{Y})^2 + (\frac{\delta \Delta\Omega}{\Delta\Omega})^2}$$

Table 2.4. Uncertainties for the ^{15}O+α elastic scattering run.

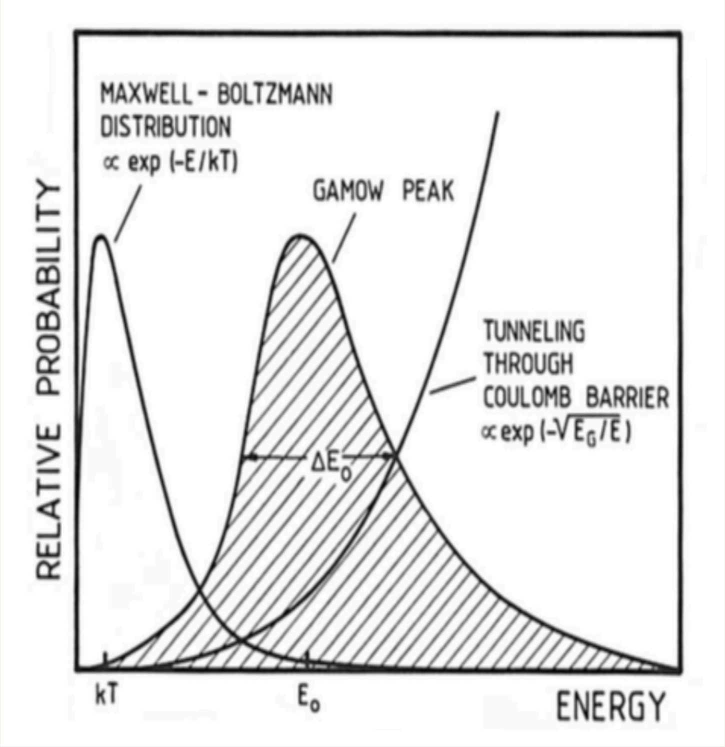
	Factor	Uncertainty	Reference
$E_{c.m.}$ uncertainty	Beam broadening	$\sim$ 55 keV	Section II.E.3
	Detector resolution	30 – 40 keV	Table 2.3
	SRIM calculation	3 – 40 keV	Section II.E.2
	Total	$\sim$ 135 keV	
Cross-section uncertainty	Yield estimation	$\sim < 1\%$	Section II.E.3
	Solid angle calculation	$\sim 10\%$	Section II.E.5

Theoretical overview

- **Reaction rate & Gamow peak**

For the narrow resonance, the stellar reaction rate per particle pair

$$< \sigma v > = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^{\infty} \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE.$$



Gamow peak (E_0)

$$E_0 = \left(\frac{bkT}{2}\right)^{2/3} = 0.1220({Z_1}^2{Z_2}^2\mu{T_9}^2)^{1/3}\mathrm{MeV}$$

Effective range of Gamow peak (E_0)

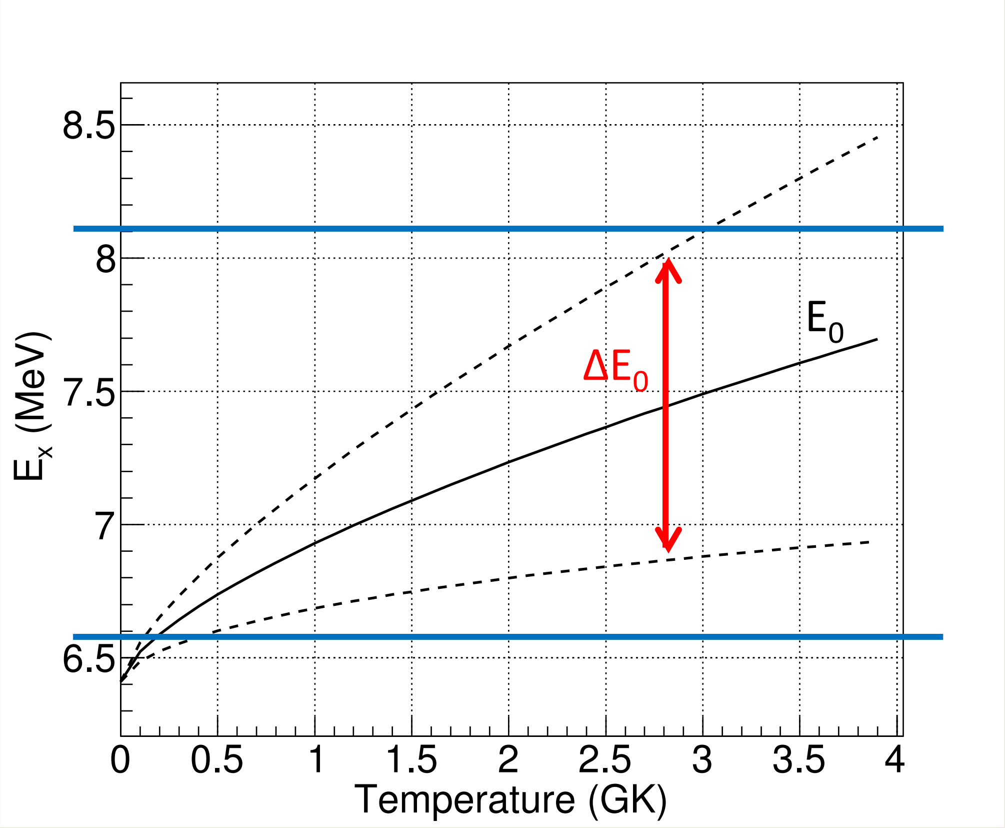
$$\Delta E_0 = \frac{4}{3^{1/2}}(E_0 kT)^{1/2} = 0.2368({Z_1}^2{Z_2}^2\mu{T_9}^5)^{1/6}\mathrm{MeV}$$

→ The energy range of the reaction rate depends on the stellar temperature.

Theoretical overview

- **Reaction rate & Gamow peak**

For the $^{18}F(p,\alpha)^{15}O$ reaction, the Gamow window is



Theoretical overview

- **Narrow resonance**

For the total width (Γ) is smaller than the resonance energy (E_R), the cross section can be changed for an isolated and single narrow resonance (Breit-Wigner formula).

The reaction rate can be expressed as

$$< \sigma v > = \Big(\frac{8}{\pi\mu}\Big)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma_{BW}(E)\mathrm{exp}\Big(-\frac{E}{kT}\Big)dE.$$

For $E \sim E_{R,}$

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

where,

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

→ For this reason, the resonance parameters J^π, Γ_α, and Γ_p are important to estimate the reaction rate

Experiment

- **Error propagation**

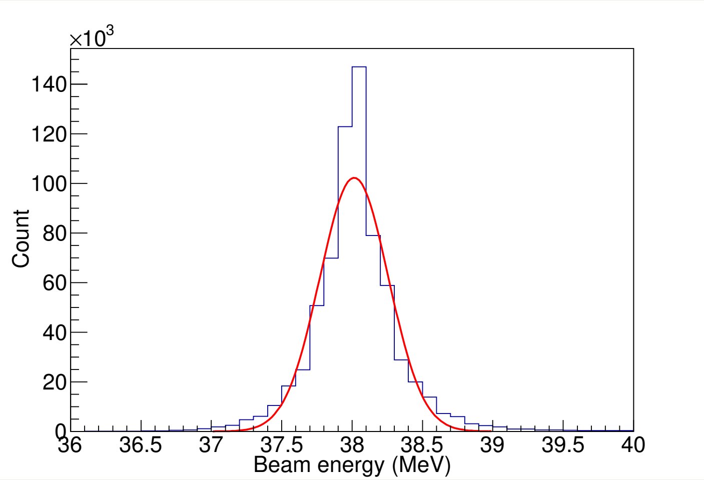


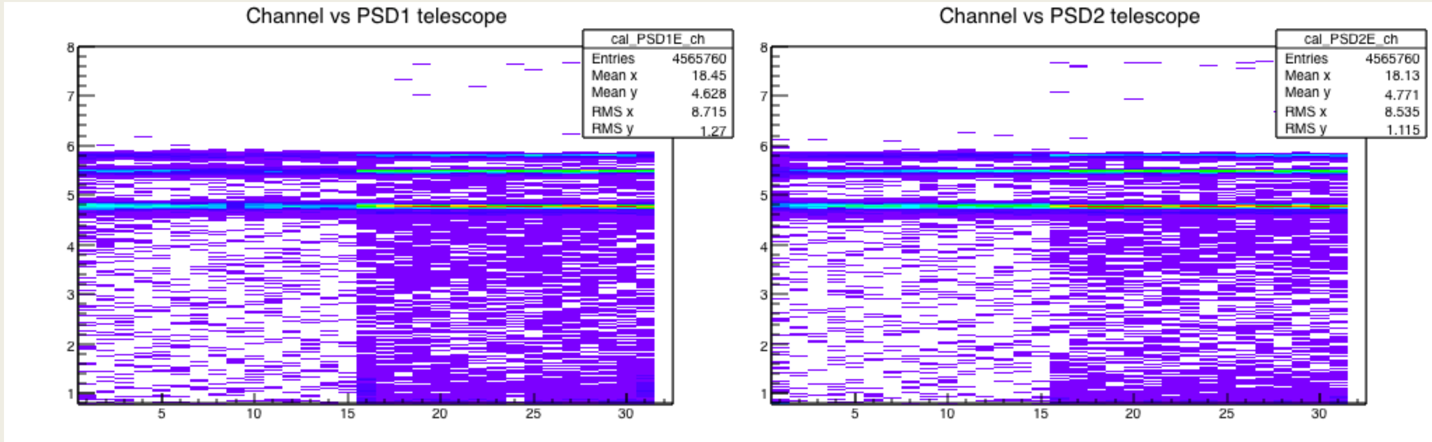
Table 2.3. Energy resolution of Telescopes

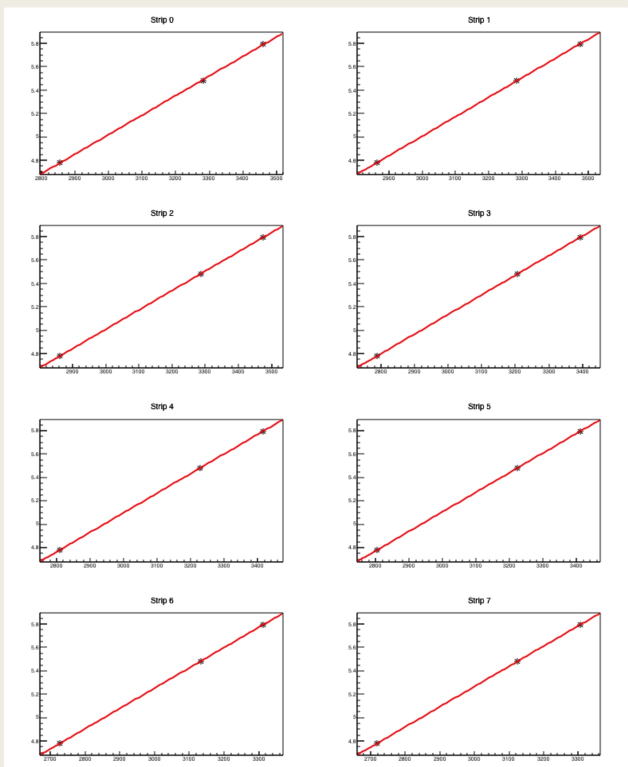
E_α (MeV)	Telescope #1 (keV)	Telescope #2 (keV)
3.148	35	42
5.462	34	33
5.771	34	35
10	90	84
15	74	79
20	116	95

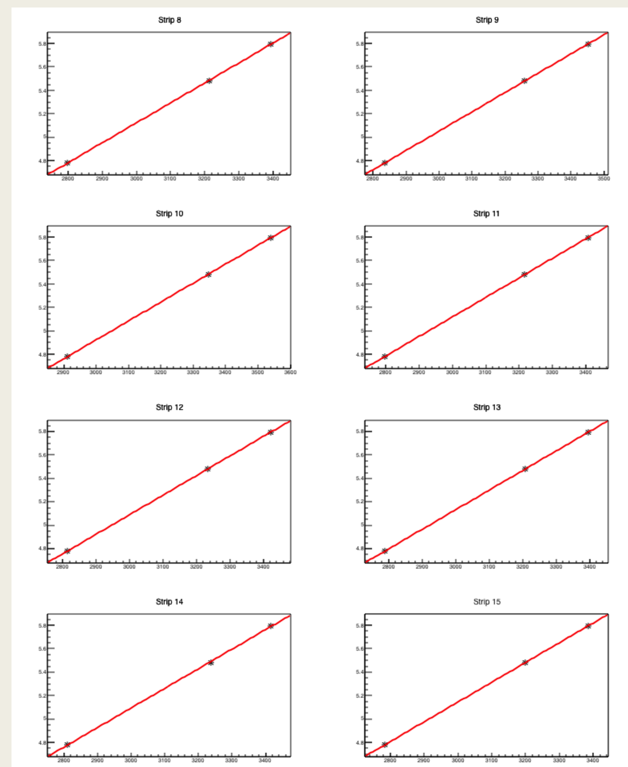
Beam broadening ~300 keV

Silicon telescopes resolution

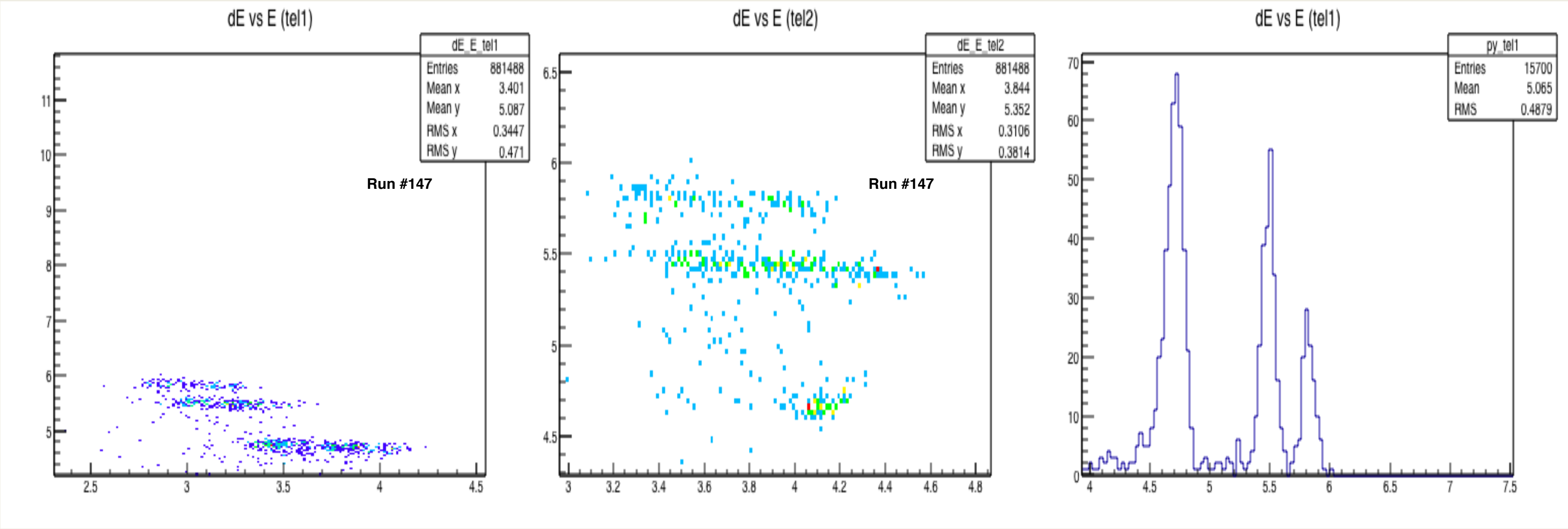
α Calibration using run #148



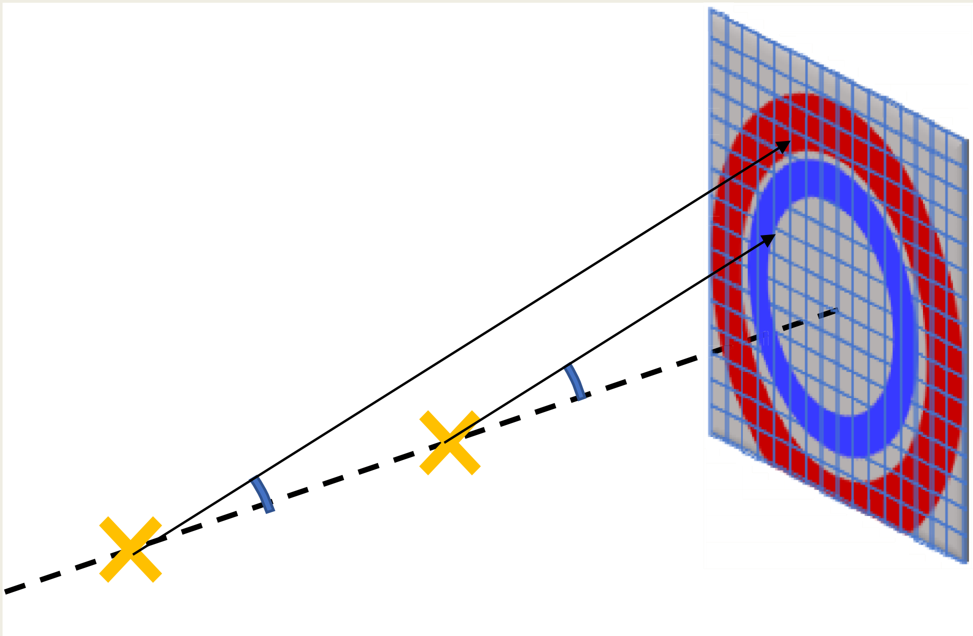




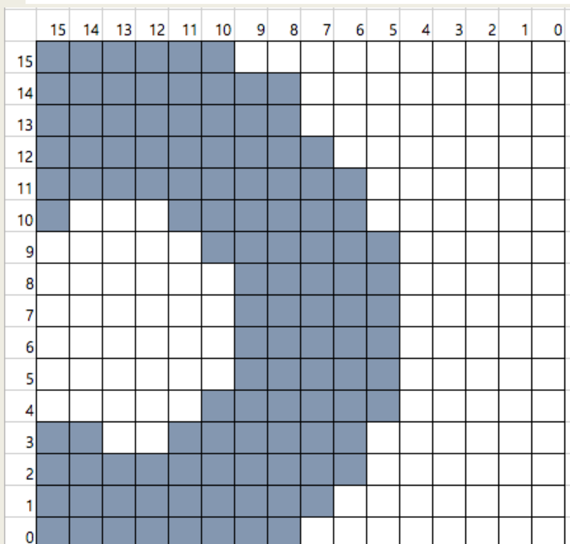
α Calibration with run #147



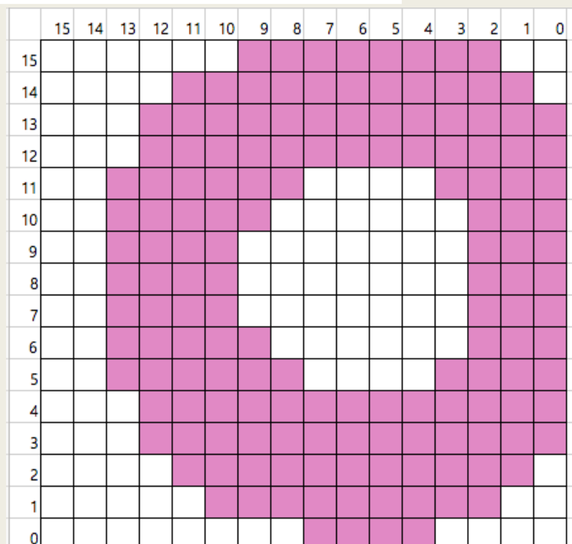
Solid angle concept



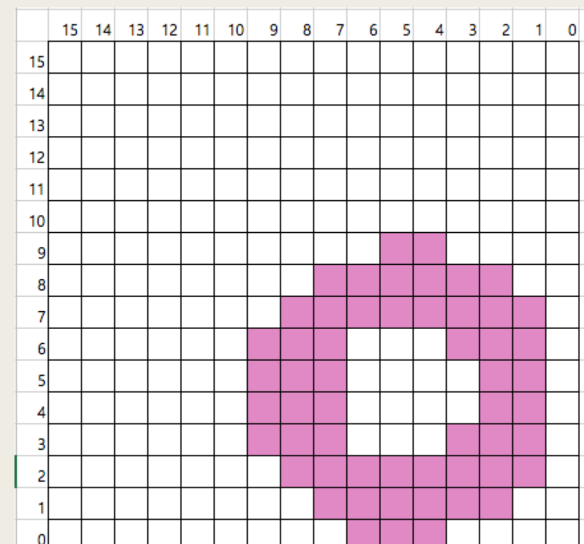
For θc.m. = 165.5 ° ~173.5°



Z = 97.1 mm
0.099959 sr



Z = 98.8 mm
0.14401 sr



Z = 185.5 mm
0.160631 sr

Theoretical overview

- **Stellar reaction rate**

Average of stellar reaction rate per particle pair

$$< \sigma v > = \int_0^\infty \phi(v)\sigma(v) v dv$$

$$= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E)\exp\left(-\frac{E}{kT}\right) dE$$

ϕ(v) = gas velocity which follows Maxwell-Boltzmann distribution

Solving a shorodinger equation for Coulomb potential :

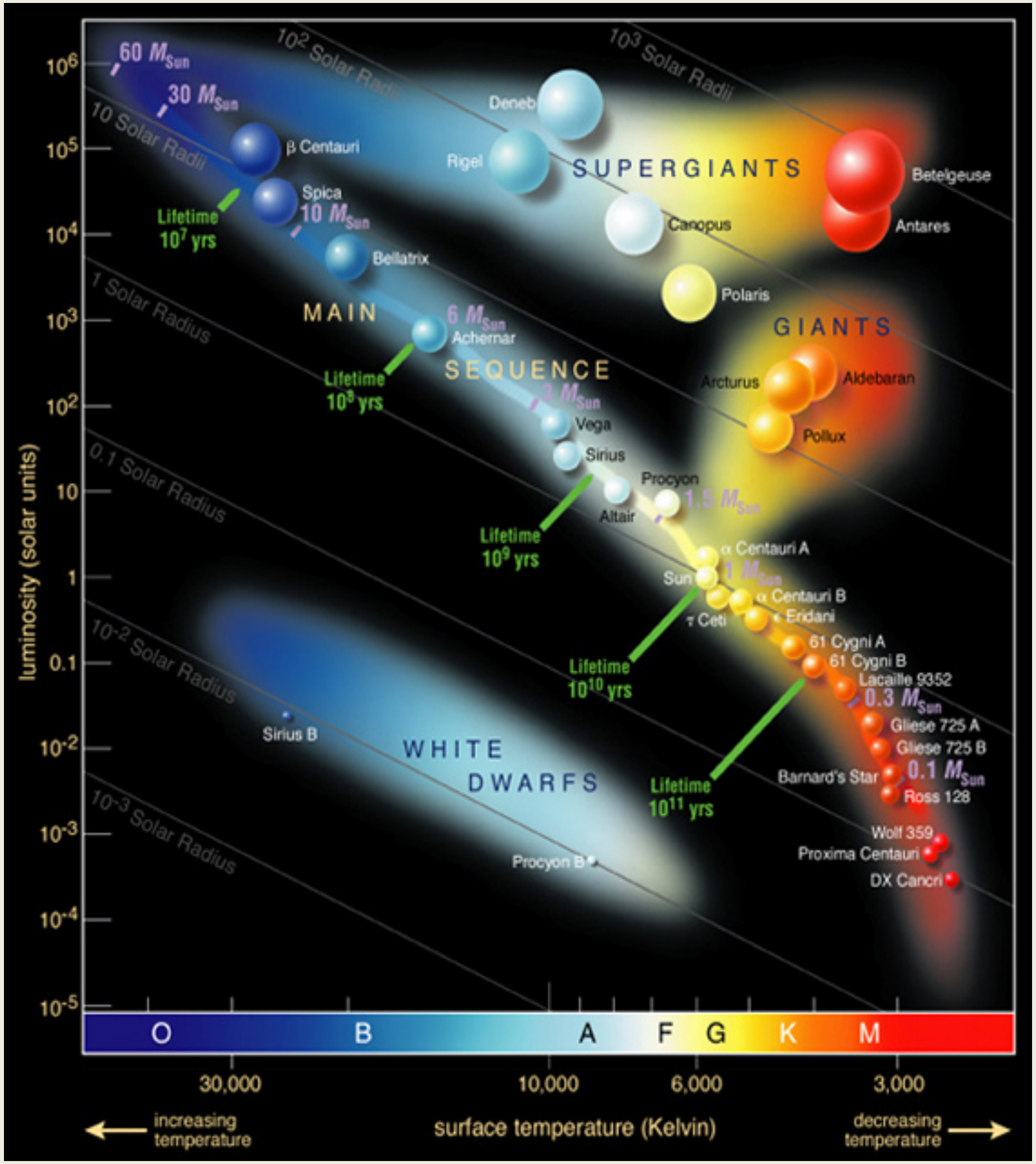
$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta) S(E)$$

S(E) : Astrophysical factor , η : Sommerfeld parameter

Final stellar reaction rate at given temperature T :

$$< \sigma v > = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E)\exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE$$

HR diagram



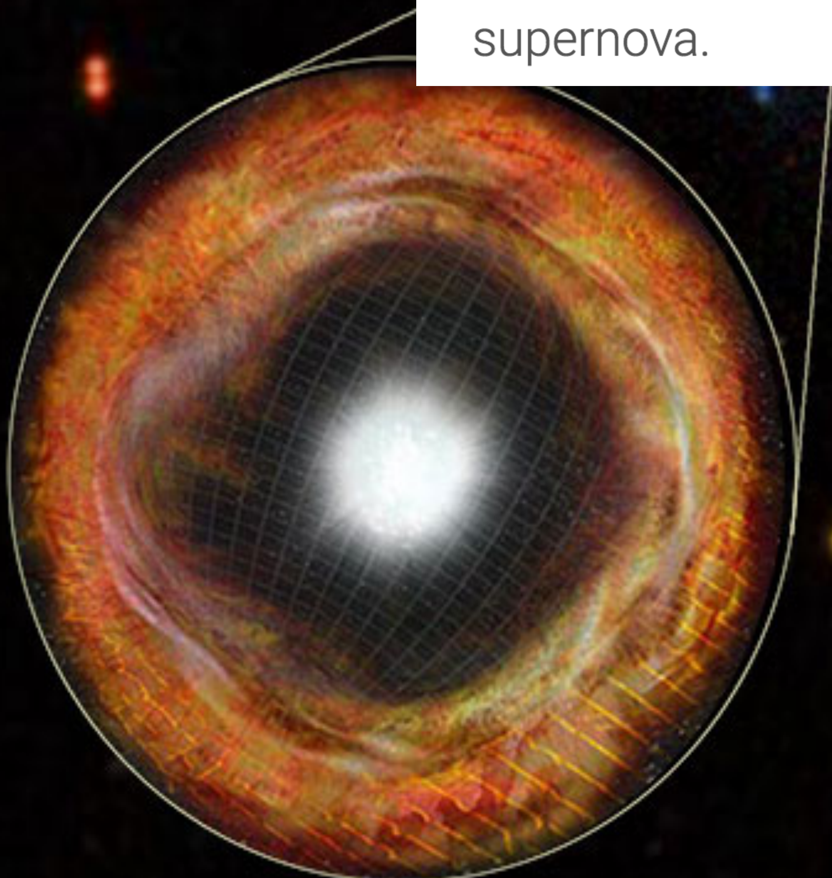
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Deneb
Rigel
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
Sirius B
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Motivation

Supernova observed just after explosion

13th February 2017 by Maarten Rikken

The observation was early enough to determine for the first time what happens in the early stages of a supernova.

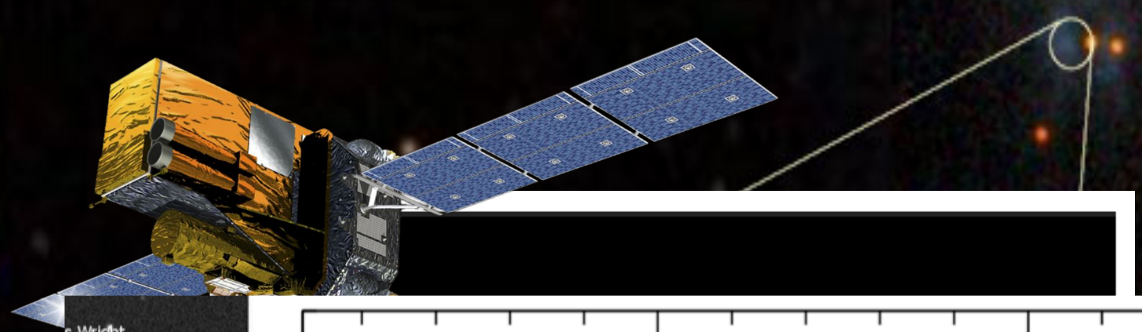


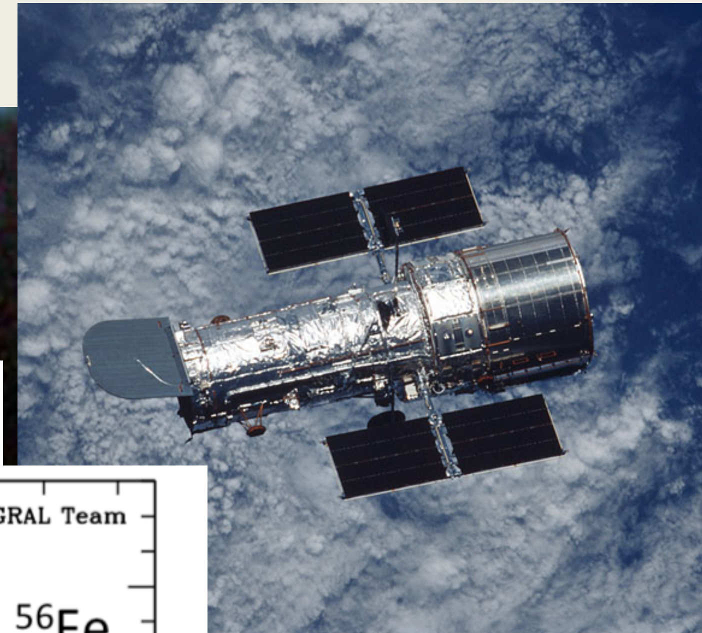
SN2013fs

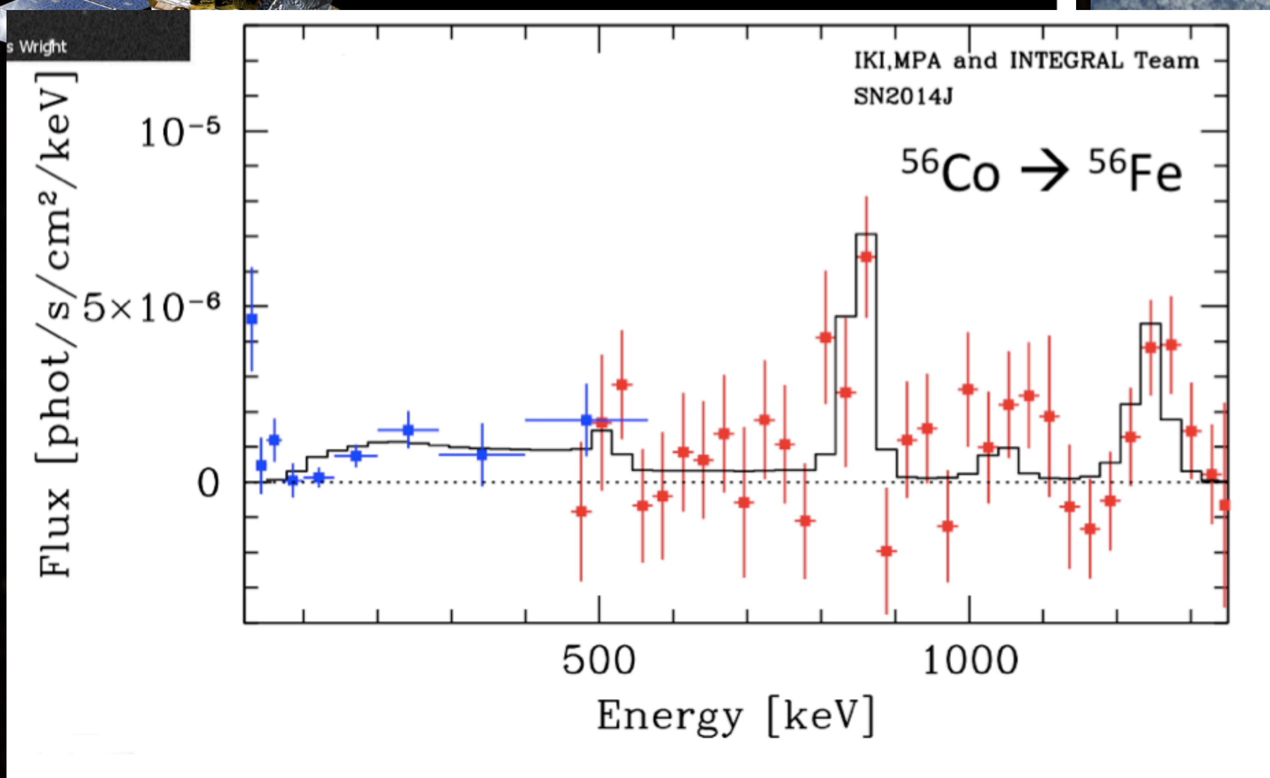
Type-II Supernova

Palomar Transient Factory

Motivation







ni nova

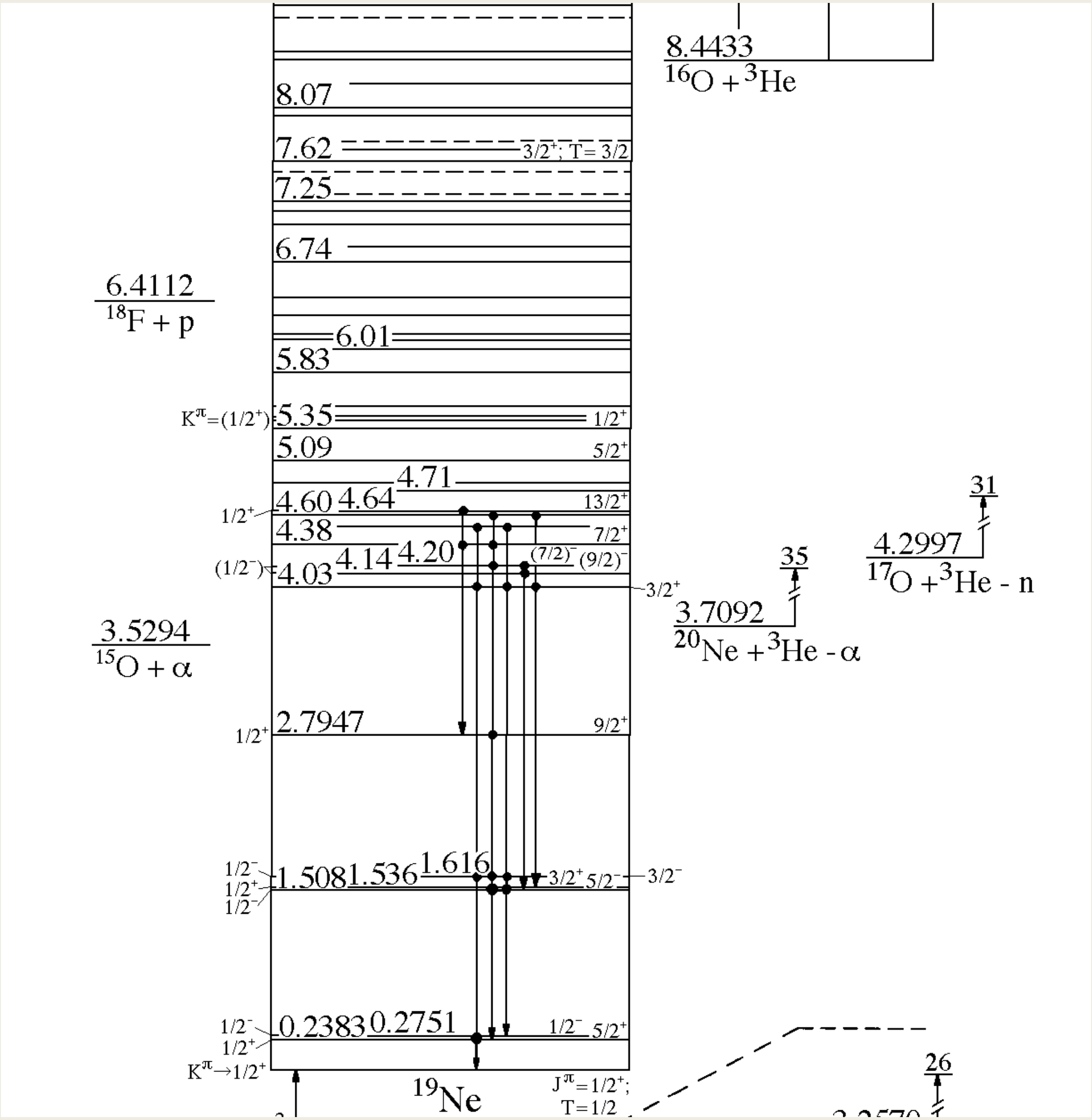
92)

ble space
scope

Motivation

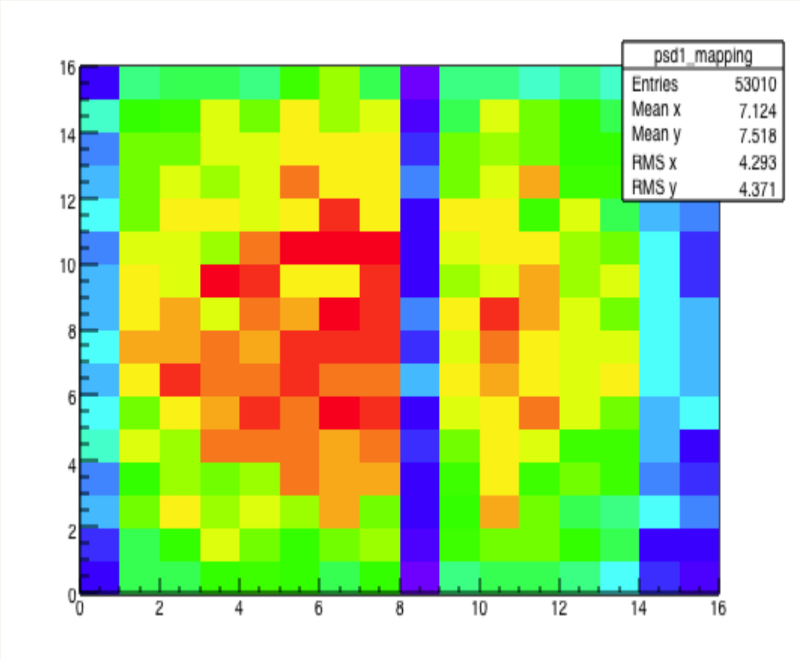
Z			18Na 1.3E-21 S P: 100.00%	19Na <40 NS P	20Na 447.9 MS ε: 100.00% εα: 20.10%	21Na 22.49 S ε: 100.00%	22Na 2.6018 Y ε: 100.00%	23Na STABLE 100%	24Na 14.997 H β-: 100.00%
10		16Ne 9E-21 S 2P: 100.00%	17Ne 109.2 MS εp: 100.00% ε: 100.00%	18Ne 1.6670 S ε: 100.00%	19Ne 17.22 S ε: 100.00%	20Ne STABLE 90.48%	21Ne STABLE 0.27%	22Ne STABLE 9.25%	23Ne 37.24 S β-: 100.00%
9	14F 910 KeV P	15F 660 KeV P: 100.00%	16F 40 KeV P: 100.00%	17F 64.49 S ε: 100.00%	18F 109.77 M ε: 100.00%	19F STABLE 100%	20F 11.07 S β-: 100.00%	21F 4.158 S β-: 100.00%	22F 4230 MS β-: 100.00% β-n < 11.0%
8	13O 8.58 MS ε: 100.00% εp: 11.30%	14O 70.620 S ε: 100.00%	15O 122.24 S ε: 100.00%	16O STABLE 99.757%	17O STABLE 0.038%	18O STABLE 0.205%	19O 26.88 S β-: 100.00%	20O 13.51 S β-: 100.00%	21O 3.42 S β-: 100.00%
7	12N 11.000 MS ε: 100.00%	13N 9.965 M ε: 100.00%	14N STABLE 99.63	15N STABLE 0.364%	16N 7.13 S β-: 100.00% β-α: 1.2E-3%	17N 4171 MS β-: 100.00% β-n: 95.10%	18N 619 MS β-: 100.00% β-α: 12.20%	19N 336 MS β-: 100.00% β-n: 41.80%	20N 136 MS β-: 100.00% β-n: 42.90%
	5	6	7	8	9	10	11	12	N

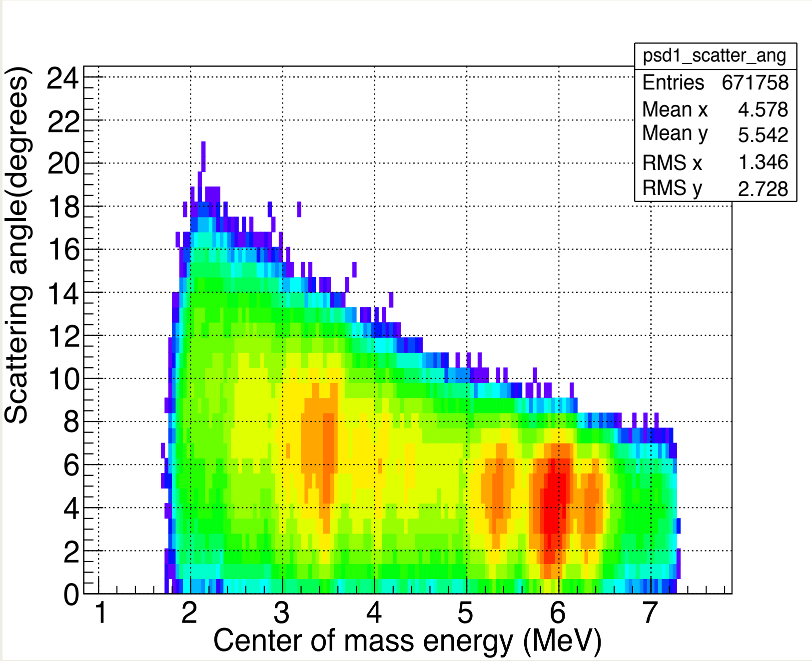
Motivation



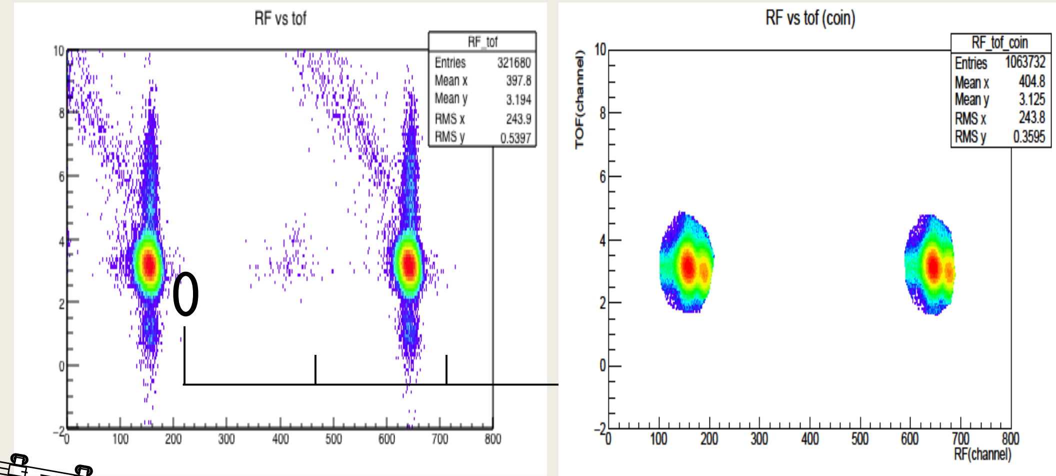
8.4433
^{16}O + ^{3}He
8.07
7.62
3/2^{+}; T= 3/2
7.25
6.74
6.4112
^{18}F + p
6.01
5.83
K$^{\pi}$=(1/2^{+})
5.35
1/2^{+}
5.09
5/2^{+}
4.71
4.60 4.64
13/2^{+}
1/2^{+}
4.38
7/2^{+}
4.14 4.20
(7/2)$^{-}$ (9/2)$^{-}$
(1/2^{-})
4.03
3/2^{+}
31
4.2997
^{17}O + ^{3}He - n
35
3.7092
^{20}Ne + ^{3}He - α
3.5294
^{15}O + α
1/2^{+}
2.7947
9/2^{+}
1/2^{-}
1/2^{+}
1/2^{-}
1.508 1.536 1.616
3/2^{+} 5/2^{-}
3/2^{-}
1/2^{-}
1/2^{+}
0.2383 0.2751
1/2^{-} 5/2^{+}
K$^{\pi}$→1/2^{+}
26
^{19}Ne
J$^{\pi}$=1/2^{+};
T=1/2

Analysis – psd1 mapping

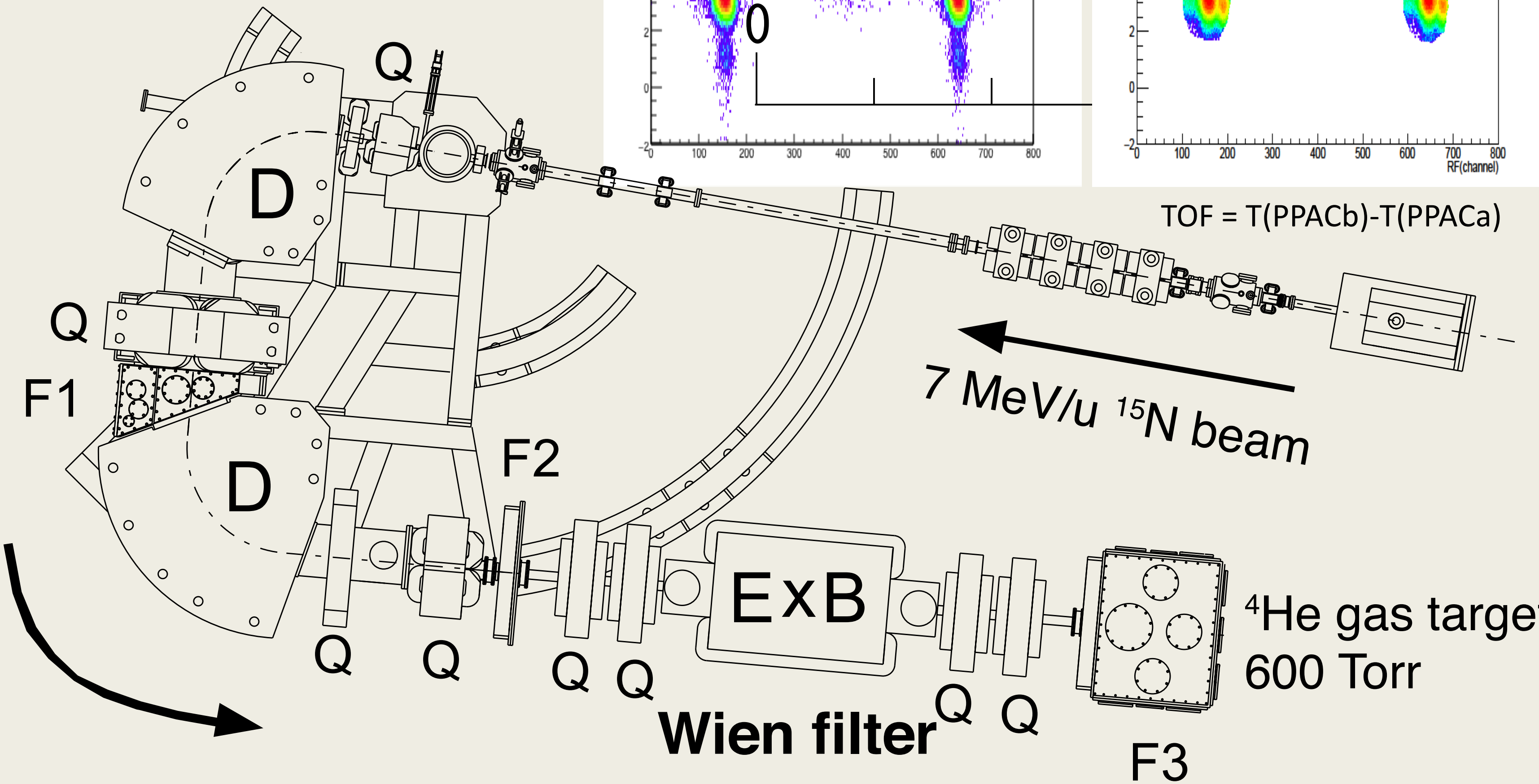




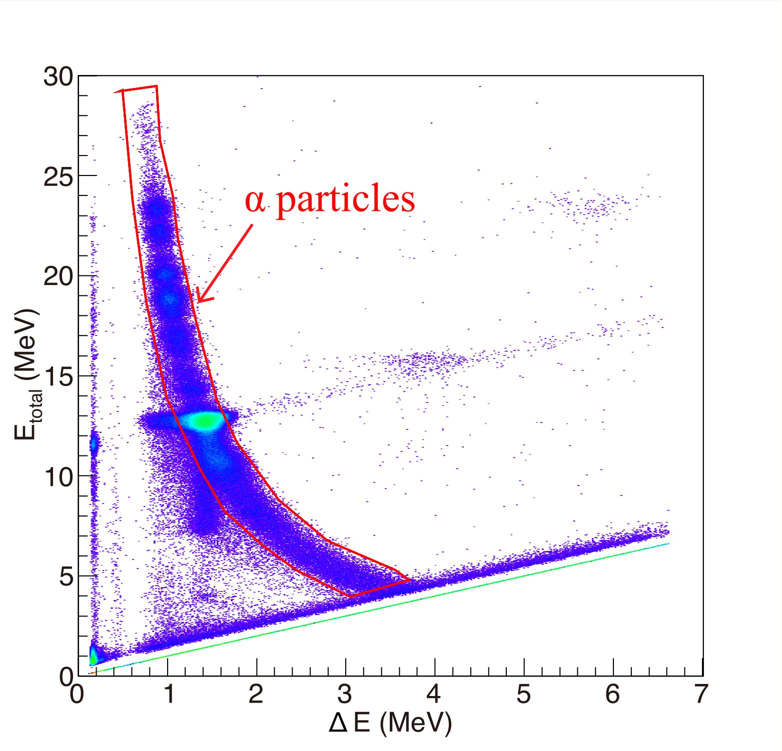
Experiment

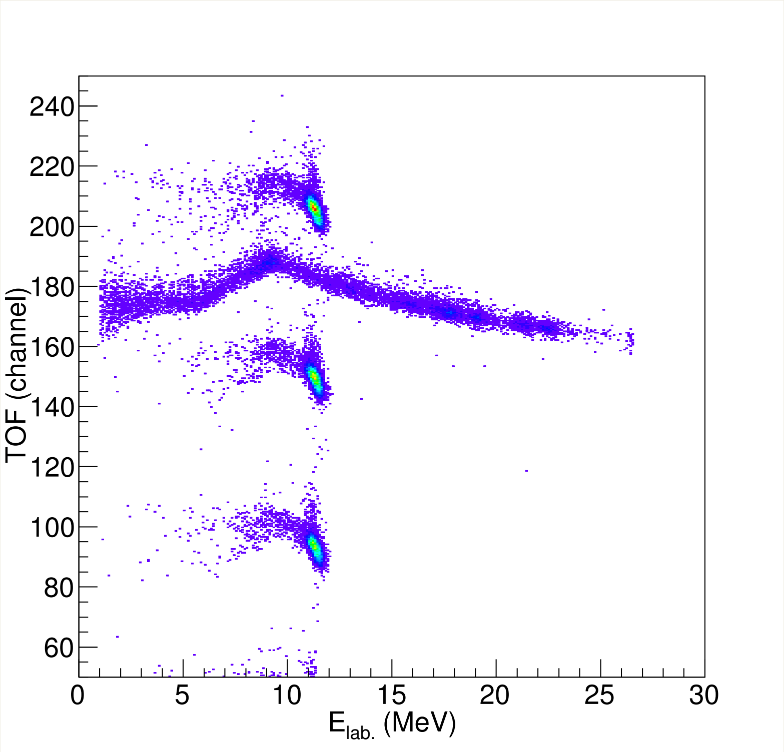


TOF = T(PPACb)-T(PPACa)



Analysis



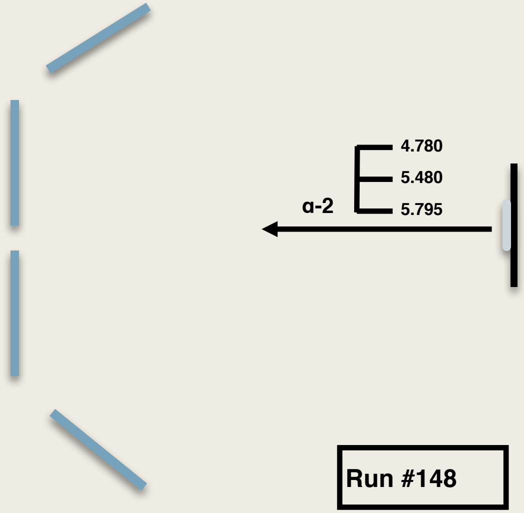


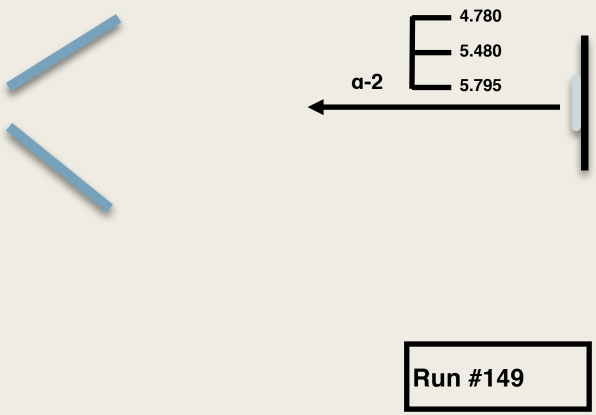
TOF = T(PPACb)-T(PSD1b)

Alpha particle sorting

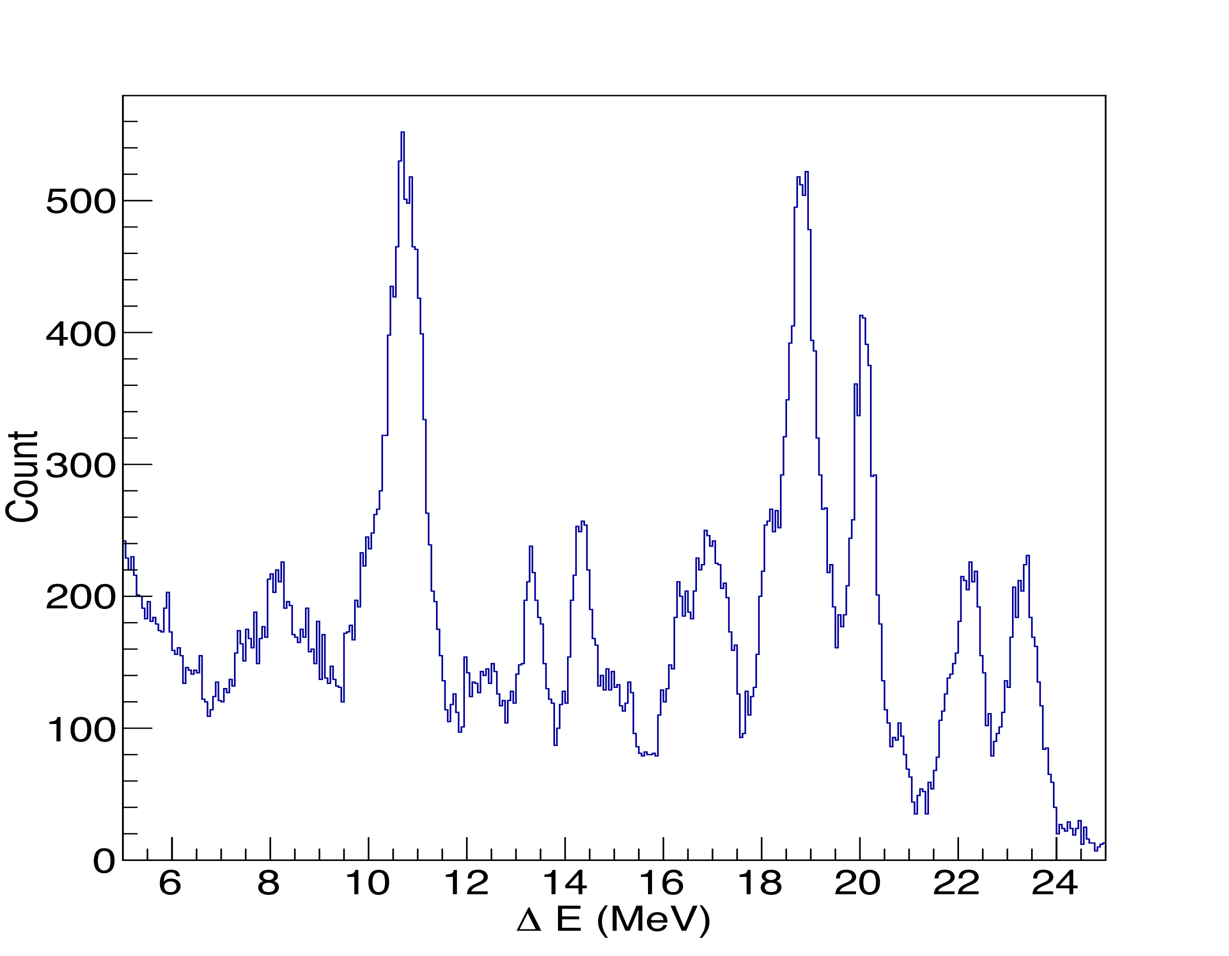
1. Separate ^{15}O beam from produced particles
2. Identify alpha particle from dE-E graph
3. Sort alpha particle from E-TDC graph

α Calibration using run #148 & #149



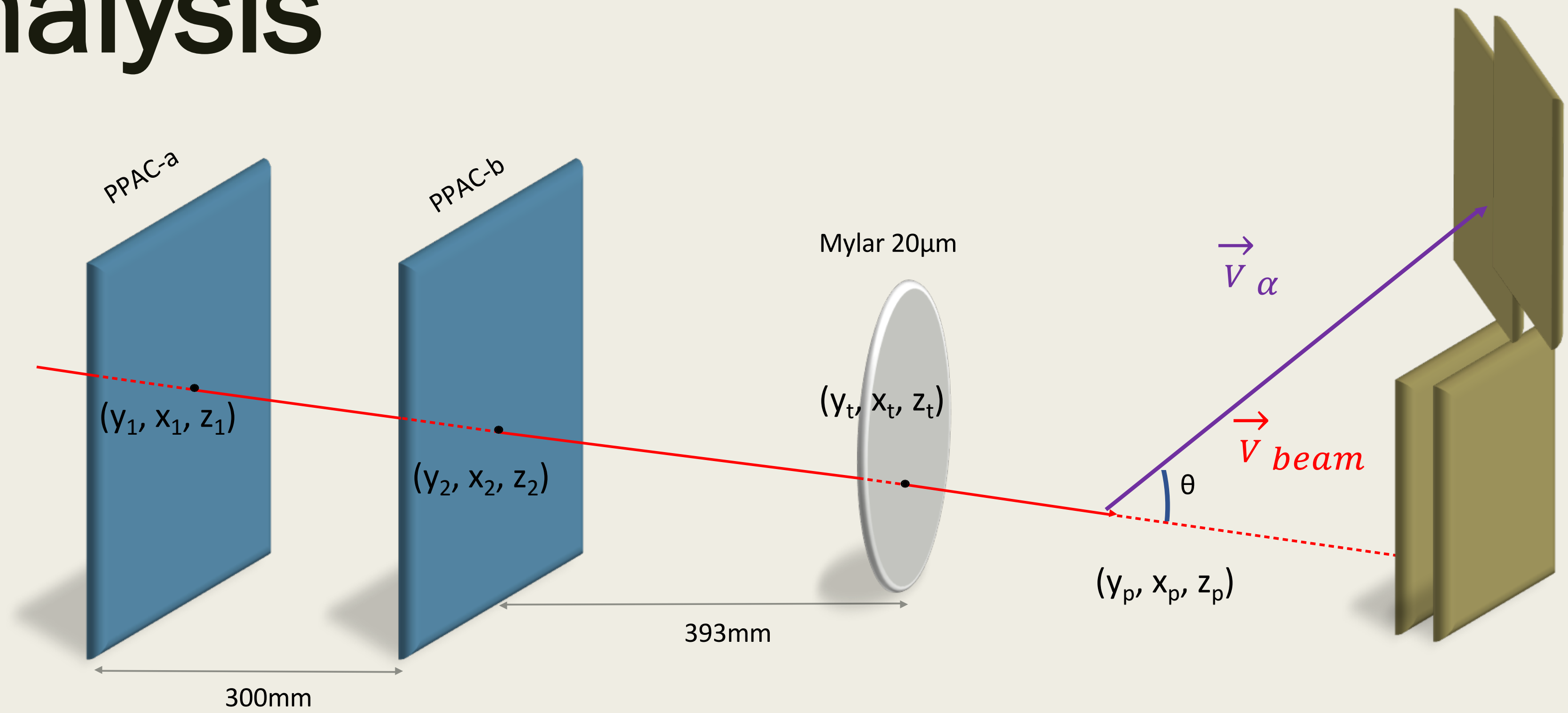


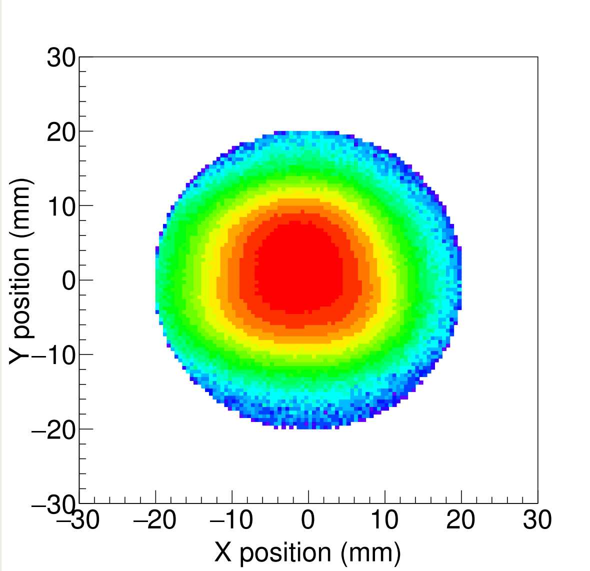
Experiment



$^{15}O + \alpha \rightarrow {}^{15}O + \alpha$

Analysis





$$\cos\theta_{lab} = Ubx \times Uax + U_{by} \times Uay + Ubz + Uaz$$

$$E_{\alpha} = \frac{E_{beam} \times m_{target} \times m_{beam} \times 4\cos^2\theta_{lab}}{(m_{target} + mbeam)^2}$$

$$E_{\alpha f} - Eexp < 10keV$$

R-Matrix(scattering theory)

Cross section :

$$W = P^{1/2}(I - RL)^{-1}(I - RL^{*})P^{-1/2}$$

$$L = (S - B) + iP$$

- S : shift factor
- B : arbitrary boundary constant
- P&S : function of energy (depend orbital angular momentum l and channel radius a_c)

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_{\lambda} - E}\delta_{JJ'}$$

General R-matrix term

Modified with Reich Moore approximation in SAMMY

$$R_{cc'} = \left[\sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_{\lambda} - E - i\overline{\Gamma}_{\lambda\gamma}/2} + R_c^{ext}\delta_{cc'}\right]\delta_{JJ'}$$

R-Matrix(SAMMY code)

```
#prepare parfile
@levels=(
#    Ex   E_width spingroup   #Ex=Ecm+thresholdE
    "7.250  113 2", #select
    "7.449  15  7", #select
    "7.505  64  6", #select
    "7.585  13  14", #select
    "8.244  4   12", #select
```

Orbital momentum	Incidence channel spin	Total angular momentum
0	-1/2	$1/2^-$
1	-1/2	$1/2^+$
	-1/2	$3/2^+$

```
print INP
"Oxygen15-alpha resonance scattering
15O         15.0031     5976500. 30000000.
KEY-WORD PARTICLE-PAir definitions
PRINT ALL INPUT PARAMETERS
chi squared is wanted
differential data are in ascii file
do not suppress any intermediate results
generate odf file automatically
do not solve bayes equations
print debug information
print theoretical values
broadening is not wanted
twenty

Name=15O+a0     Pa=alpha
 Pb=15O         Zb=  8   Mb= 15.00306    Sb= -0.5
Name=18F+p0     Pa=proton
 Pb=18F         Zb=  9   Mb= 18.00090    Sb=  1.0

   5.6750     0.010000
DIFFERENTIAL ELASTIC SCATTERING
    1          180.0
                1.0
  1      1    0 -0.5       1.0
    1  15O+a0      0      -0.5
  2      1    0  0.5       1.0
    1  15O+a0      1      -0.5
  3      1    0  1.5       1.0
    1  15O+a0      1      -0.5
  4      1    0 -1.5       1.0
    1  15O+a0      2      -0.5
```