June 19, 2025
NIC XVIII
Girona

Nuclear Astrophysics Activities at CENS

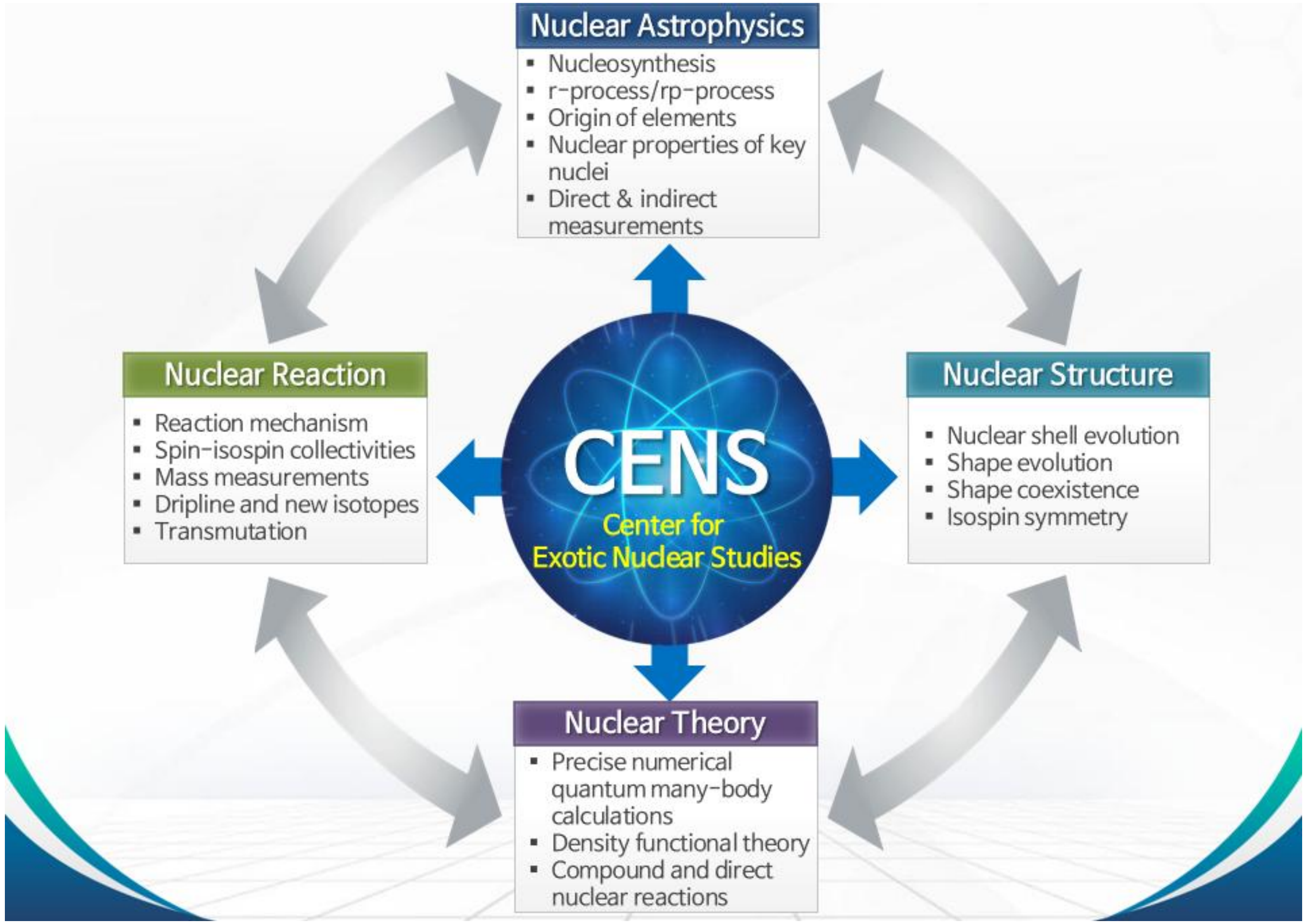
Kevin Insik Hahn / Sunghoon (Tony) Ahn

Center for Exotic Nuclear Studies (CENS), IBS, Korea

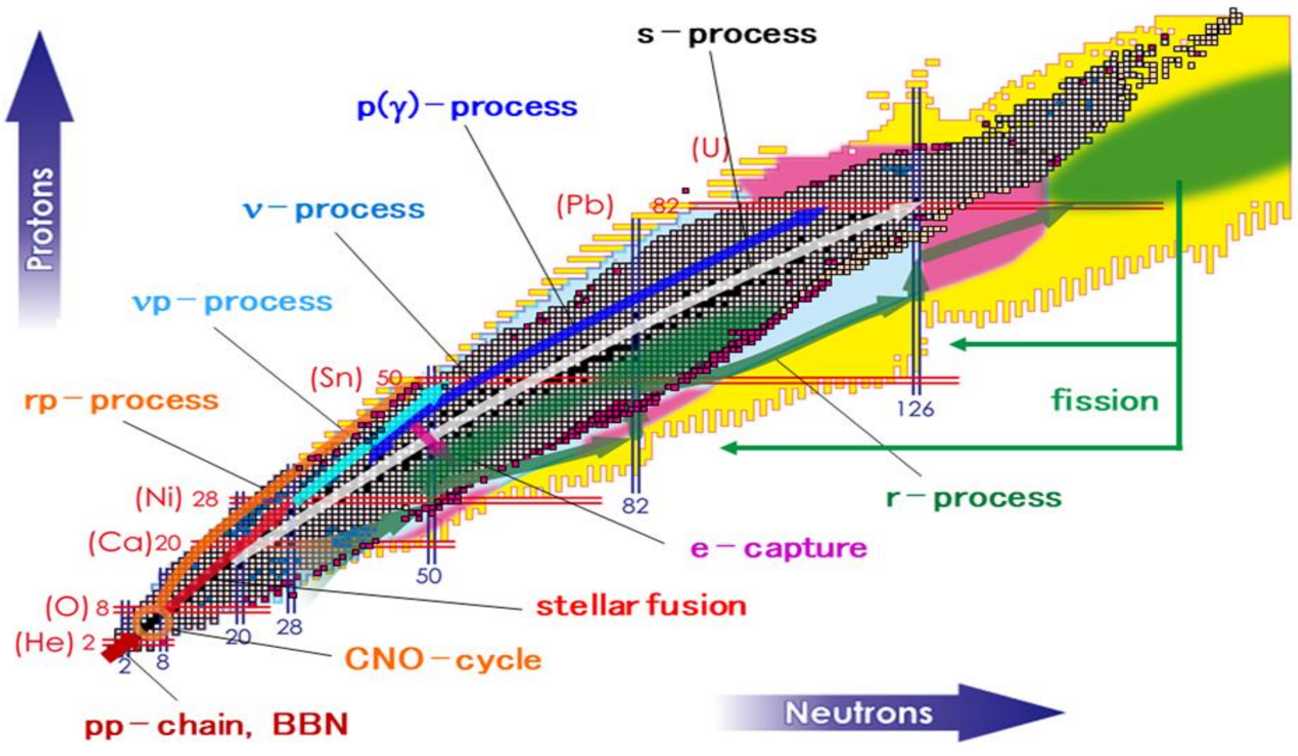
Introduction of CENS(Center for Exotic Nuclear Studies)

- The Center for Exotic Nuclear Studies (CENS) was launched in December 2019.
- We have 28 researchers and 8 Ph.D. students as of today. The Nuclear Astrophysics group is lead by Tony Ahn.

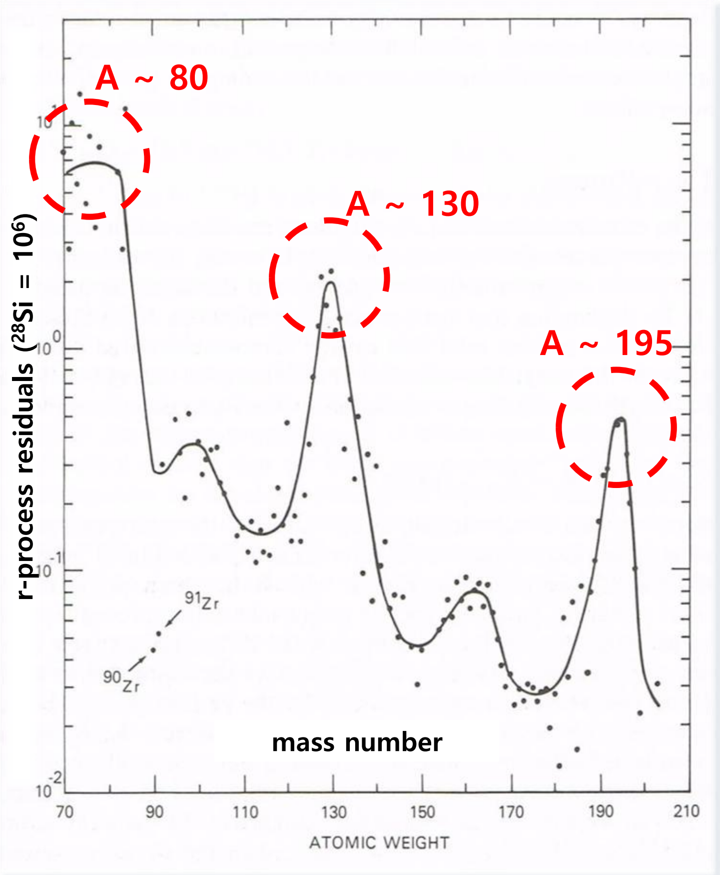
- First approved experiment by RIKEN PAC in Dec. 2020
- 14O(a,p) experiment at CRIB/CNS in Mar. 2023
- CENS organized NIC XVII in September 2023.
- First RAON experiments in Sep. 2024
- CENS co-organized INPC 2025 in May 2025.



Nucleosynthesis processes



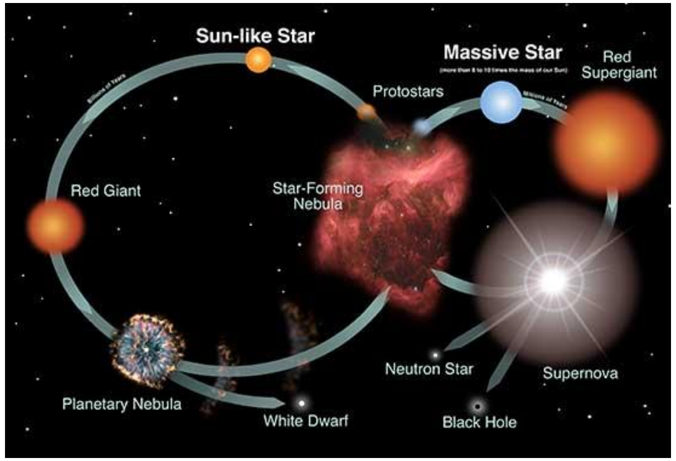
Nuclear chart and the major nucleosynthetic processes in the universe
X. Tang *et al., Association of Asia Pacific Physical Societies* 31, 19 (2021)



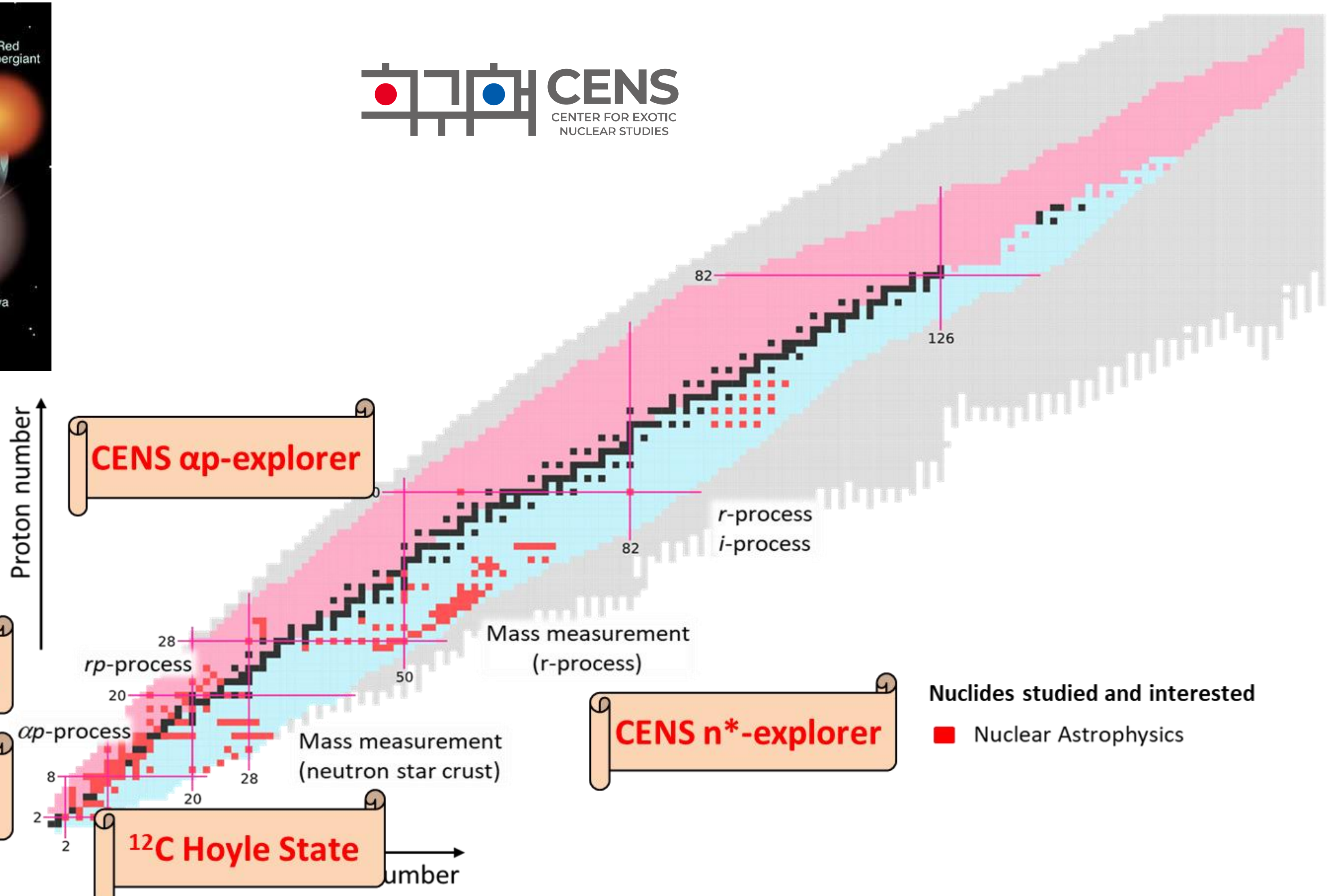
Calculated r-process yields for solar abundance patterns
F. Kappeler *et al. Rep. Prog. Phys.* 52 945 1989

❖ Nucleosynthesis process can explain the observation.
→ **Nuclear Physics plays an important role!**

Astrophysically important nuclei on CENS Nuclear Chart



Credit: NASA and the Night Sky Network

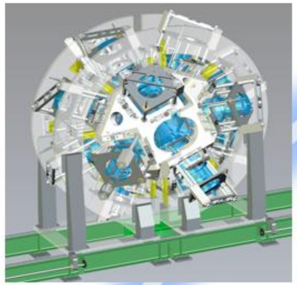


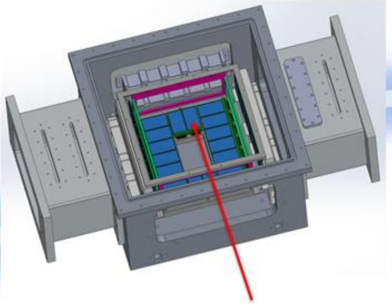
Fusion Reactions

Reactions
In Plasma Env.

CENS detector and device development

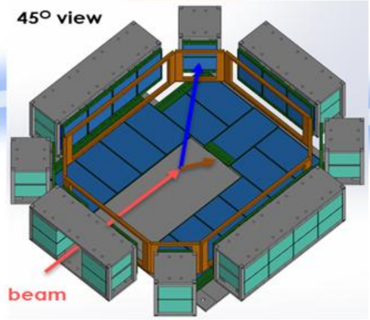
ASGARD



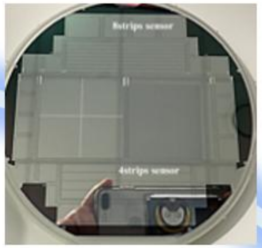


TexAT_v2

AToM-X



Si detectors



GAGG Scintillator

Decay Spectroscopy Station

A New Plunger Device

Detector System for Internal Conversion Electrons

Neutron detector

CENS CENTER FOR EXOTIC NUCLEAR STUDIES

Beam PID

Diagnostics System

DL-MCP

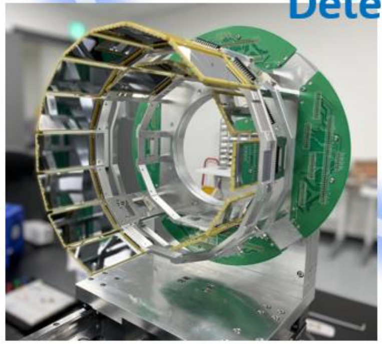
Liquid Organic Scintillator

Gas Jet Target

PPAC

high resolution, high performance, and high efficiency are required.

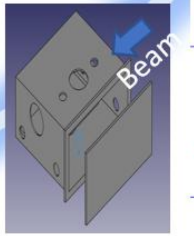
Detector development is required for rare isotope science.

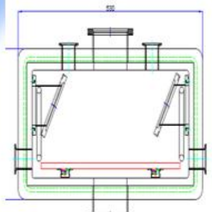


STARK

KWF

CryoSTAR



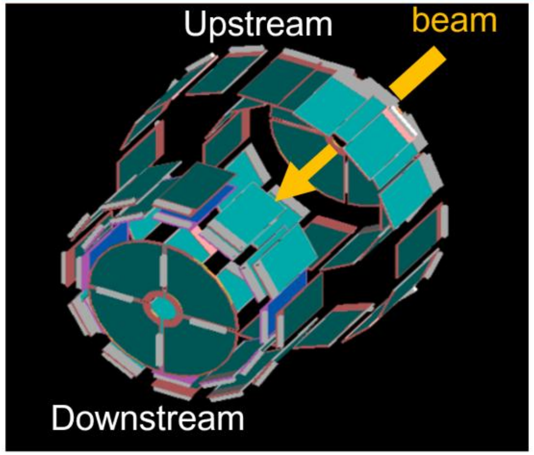


MUSIC/IC

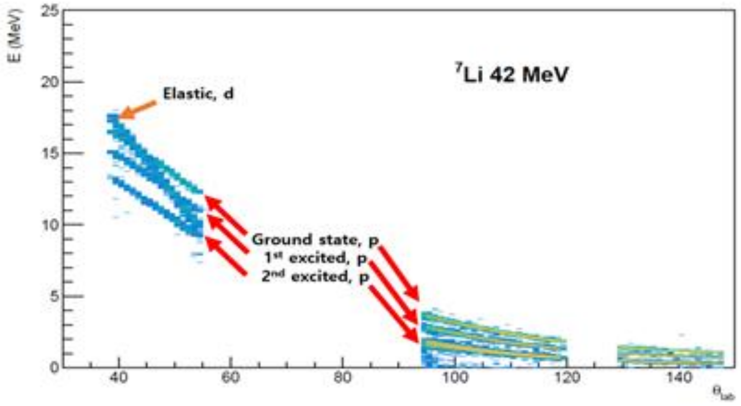
Development of STARK silicon detector array

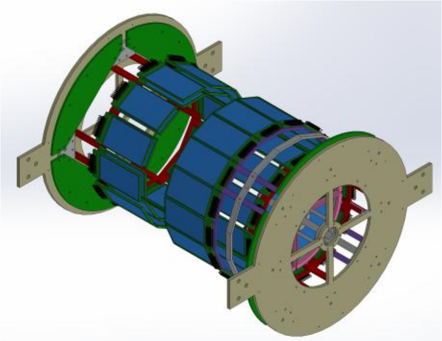
- **STARK: Silicon Telescope Array for Reactions in inverse Kinematics**
- **Three rings with 12-16-12 polygons. 96-116-107 mm from the center of the target**
- **Scattering chamber: 580(X) x 400(Y) x 600(Z) mm3**
- **CryoSTAR (low T. gas cell target) compatible**

→ ***(α,p) reaction studies, transfer reaction studies, OMP studies***

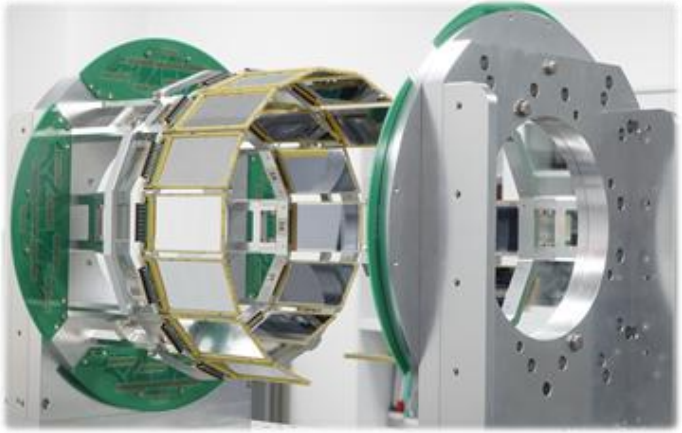


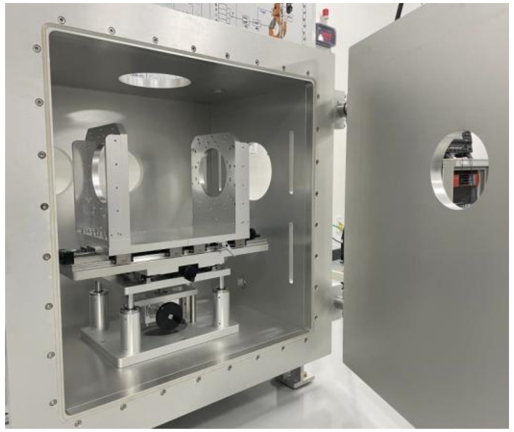
$^{7}Li(d,p)^{8}Li$ reaction simulation with 40 MeV ^{7}Li beam energy

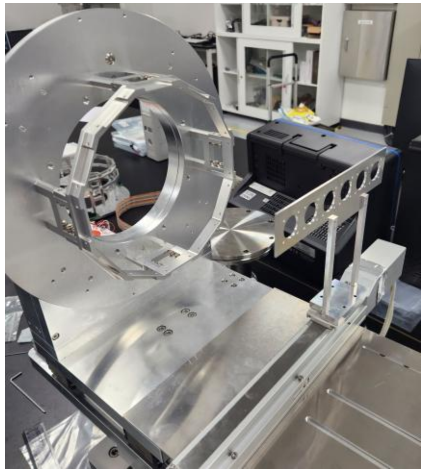


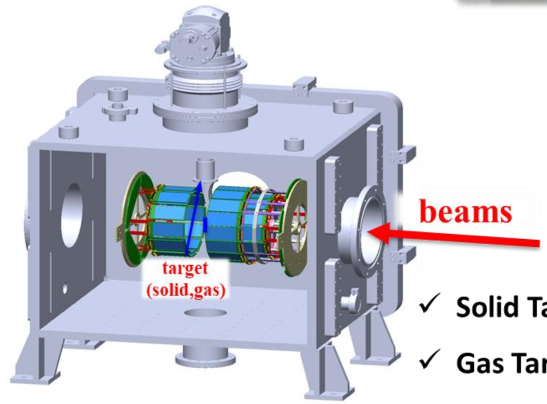


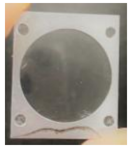
Conceptual Design of STARK











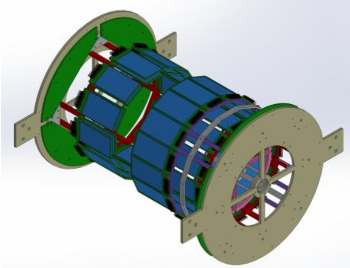
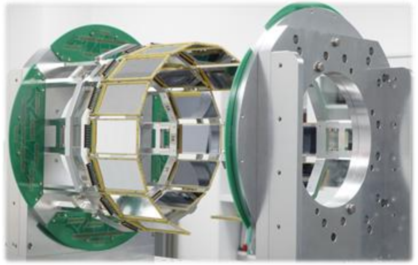
✓ **Solid Targets: CH_2, CD_2**

✓ **Gas Targets: H_2, D_2, ^{4}He, ^{3}He, N_2**

Conceptual Design of STARK chamber

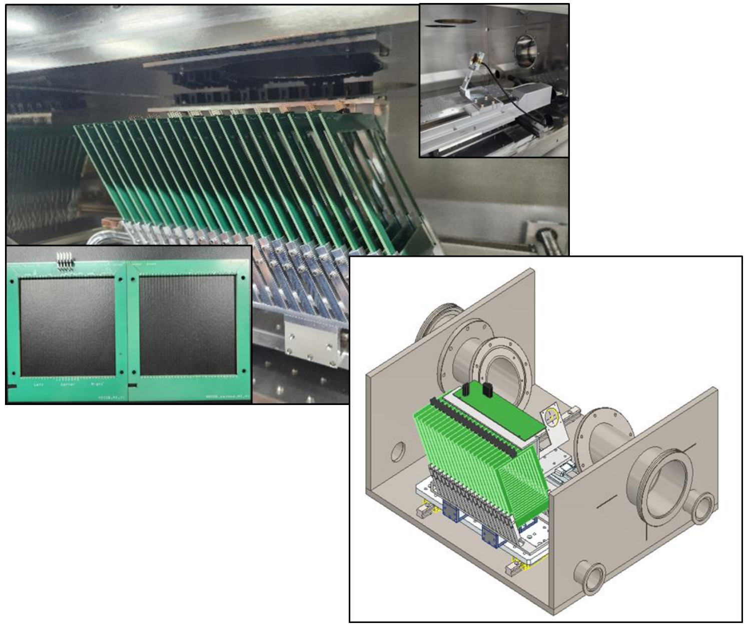
CENS detector and device development (selected)

[STARK]

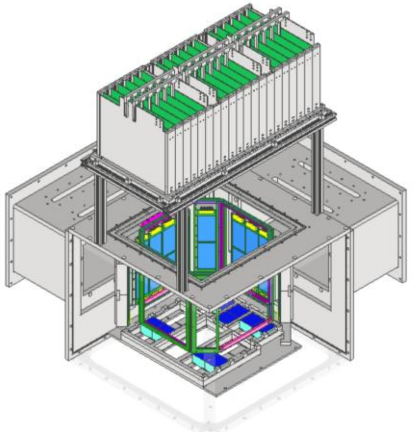
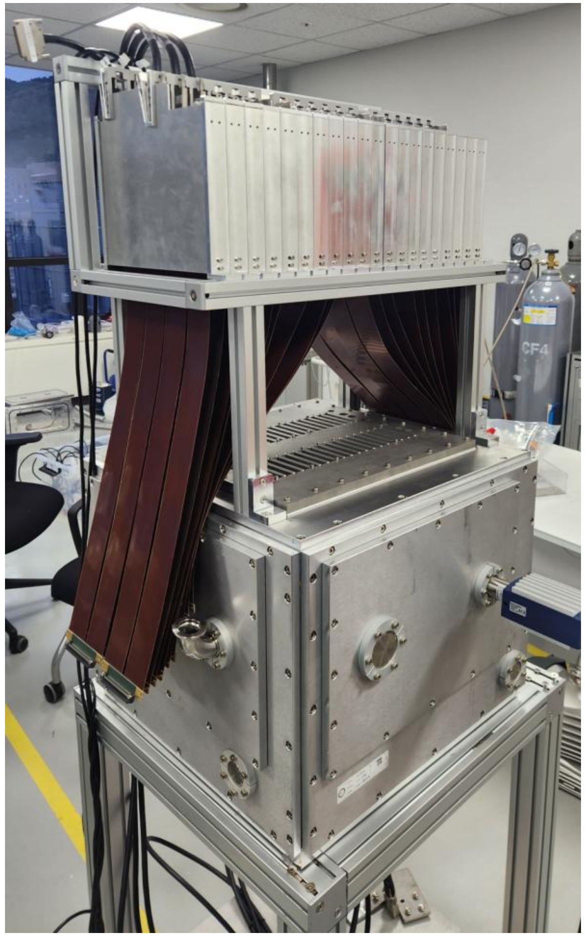
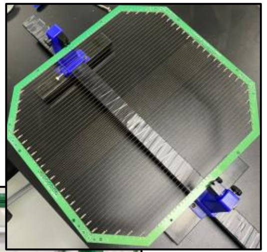
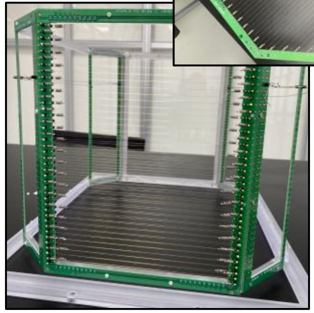
Silicon Telescope Array for Reactions in inverse Kinematics

[VOICE]



[AToM-X]

Active target TPC for Multiple nuclear eXperiments

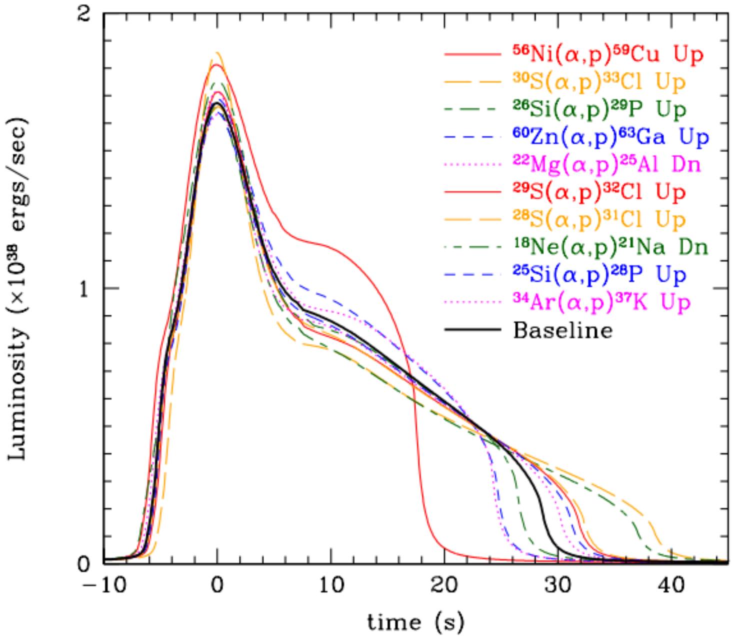





Poster #136 by Soomi Cha
Development of the Active Target TPC for Multiple nuclear physics eXperiments (AToM-X)

[JETTSTAR]

gas JET Target system for nuclear STructure and Astrophysical Research


CENS *αp*-explorer Project



Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{56}Ni(α, p)^{59}Cu	U	12.5	1
2	^{59}Cu(p, γ)^{60}Zn	D	12.1	1
3	^{15}O(α, γ)^{19}Ne	D	7.9	1
4	^{30}S(α, p)^{33}Cl	U	7.8	1
5	^{26}Si(α, p)^{29}P	U	5.3	1
6	^{61}Ga(p, γ)^{62}Ge	D	5.0	1
7	^{23}Al(p, γ)^{24}Si	U	4.8	1
8	^{27}P(p, γ)^{28}S	D	4.4	1
9	^{63}Ga(p, γ)^{64}Ge	D	3.8	1
10	^{60}Zn(α, p)^{63}Ga	U	3.6	1
11	^{22}Mg(α, p)^{25}Al	D	3.5	1
12	^{56}Ni(p, γ)^{57}Cu	D	3.4	1
13	^{29}S(α, p)^{32}Cl	U	2.8	1
14	^{28}S(α, p)^{31}Cl	U	2.7	1
15	^{31}Cl(p, γ)^{32}Ar	U	2.7	1
16	^{35}K(p, γ)^{36}Ca	U	2.5	2
17	^{18}Ne(α, p)^{21}Na	D	2.3	2
18	^{25}Si(α, p)^{28}P	U	1.9	2
19	^{57}Cu(p, γ)^{58}Zn	D	1.7	2
20	^{34}Ar(α, p)^{37}K	U	1.6	3
21	^{24}Si(α, p)^{27}P	U	1.4	3
22	^{22}Mg(p, γ)^{23}Al	D	1.1	3
23	^{65}As(p, γ)^{66}Se	U	1.0	3
24	^{14}O(α, p)^{17}F	U	1.0	3
25	^{40}Sc(p, γ)^{41}Ti	D	0.9	3
26	^{34}Ar(p, γ)^{35}K	D	0.8	3
27	^{47}Mn(p, γ)^{48}Fe	D	0.8	3
28	^{39}Ca(p, γ)^{40}Sc	D	0.8	3

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 830:55 (2016)

- **Key Research Question:**
  Direct measurements of key (*α,p*) reaction cross sections which important for *αp*-process *and p*-process.

- **Methods:**
  1. Thick Target in Inverse Kinematics (TTIK) using TexAT_v2, AToM-X or VOICE
  2. (*α,p*) Reaction in Inverse Kinematics using JENSA, CryoSTAR or JETTSTAR with STARK

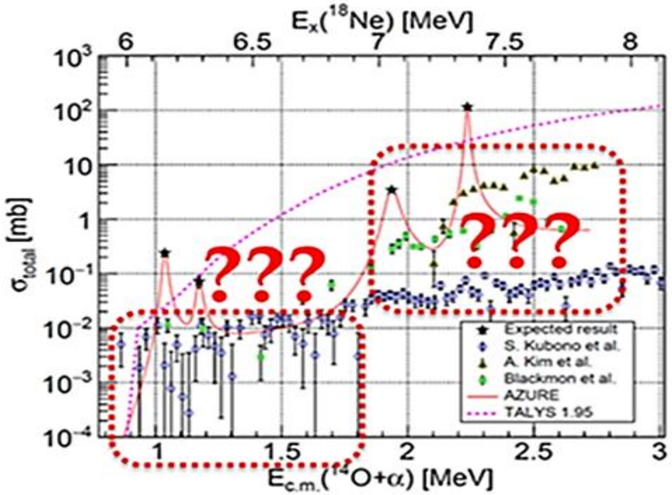
Direct measurement of $^{14}O(\alpha,p)^{17}F$ cross section at CRIB

- "A direct measurement of the $^{14}O(\alpha,p)^{17}F$ reaction with the Texas Active Target detector" approved by RIKEN PAC (2020)
- Beam time was very hard to get due to the Covid-19. We performed the experiment in Mar. 2023.

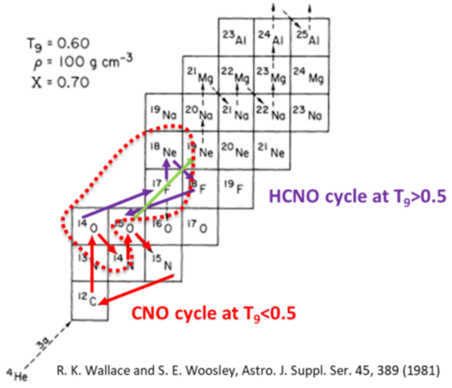
R. H. Cyburt *et al.* 2016

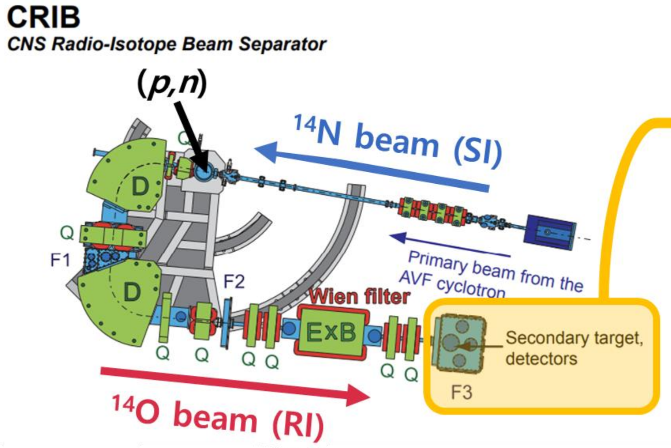
Rank	Reaction	Type	Sensitivity
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3
6	**$^{14}O(\alpha,p)^{17}F$**	D	5.8
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4
10	$^{19}F(p,\alpha)^{16}O$	U	1.3

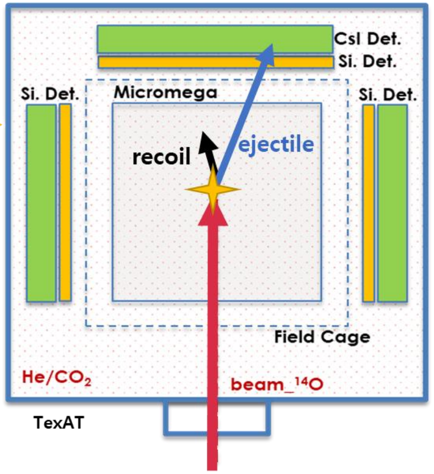
Reactions that impact the burst light curve in the multi-zone X-ray burst model



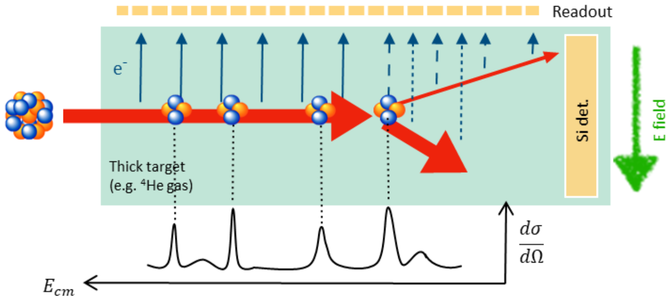
Previous measured data and calculated total cross sections of $^{14}O(\alpha,p)$ reaction

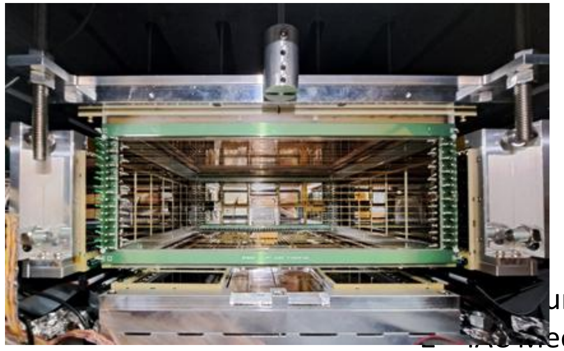


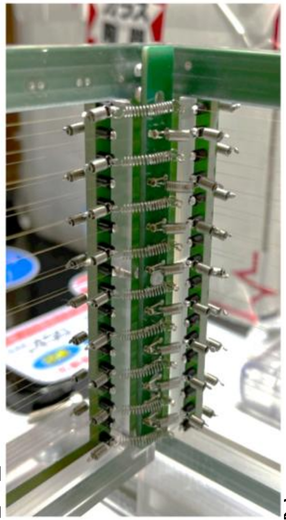




more than 40 participants!

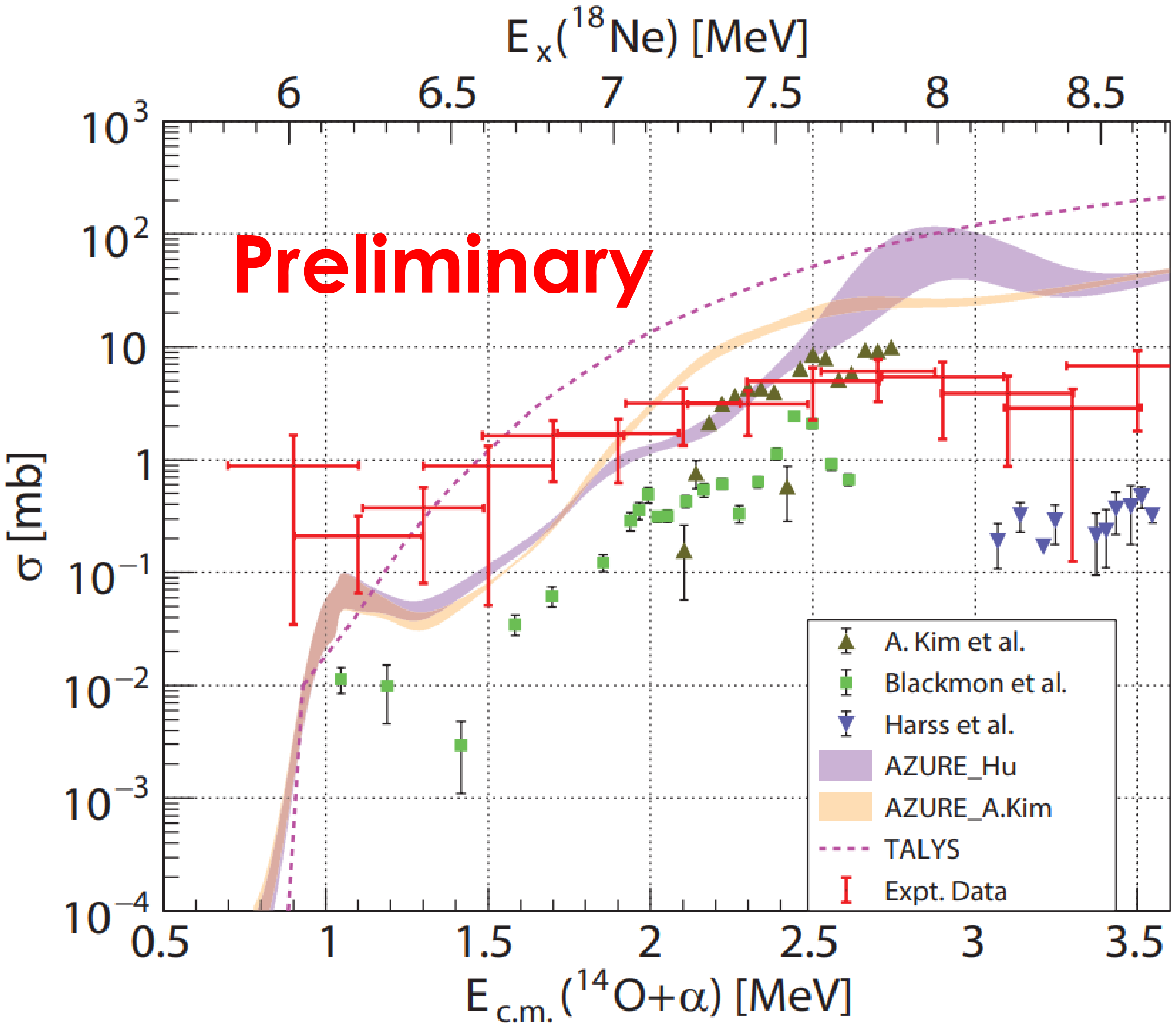






Proposed by S. Ahn & Data analysis by C. Park

Data Analysis Results - Preliminary

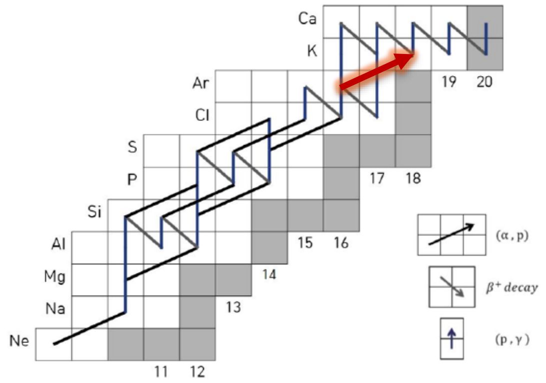


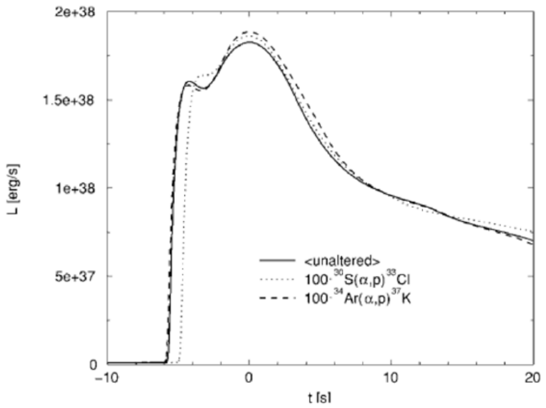
- Cross sections of the (a,p0) & (a,p1) reactions
- 2 - 2.8 MeV
  Shows good agreement
- 1 - 1.5 MeV
  Higher cross sections
  → contributions from new resonances or the restricted resolution at low energies
- 2.8 MeV -
  No resonance features
  → limited E_{cm} resolution
  Lower cross sections than AZURE calculation

Direct measurement of $^{34}Ar(\alpha,p)^{37}K$ cross section at CRIB/CNS

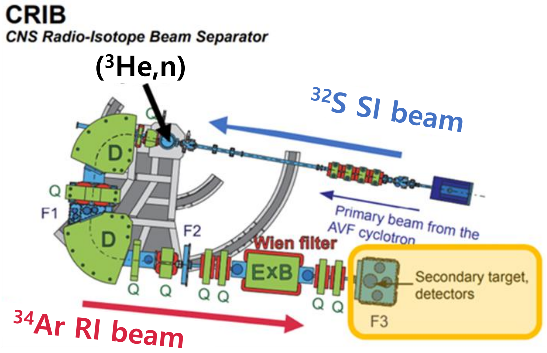
Motivation: a key reaction for understanding the luminosity curve of the double peak and nucleosynthesis mechanism in X ray bursts.

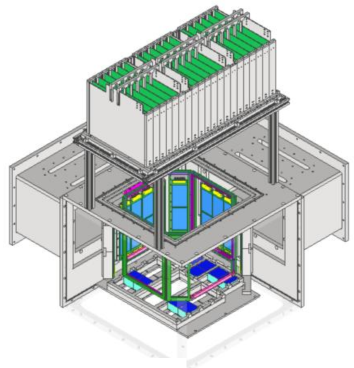
$^{18}Ne(\alpha,p)^{21}Na(p,\gamma)^{22}Mg(\alpha,p)^{25}Al(p,\gamma)^{26}Si,(\alpha,p)^{29}P(p,\gamma)^{30}S(\alpha,p)^{33}Cl(p,\gamma)\boxed{^{34}Ar(\alpha,p)^{37}}K(p,\gamma)^{38}Ca(\alpha,p)^{41}Sc$

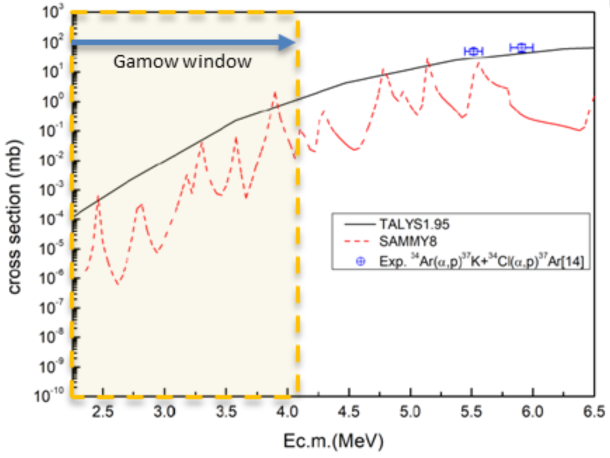


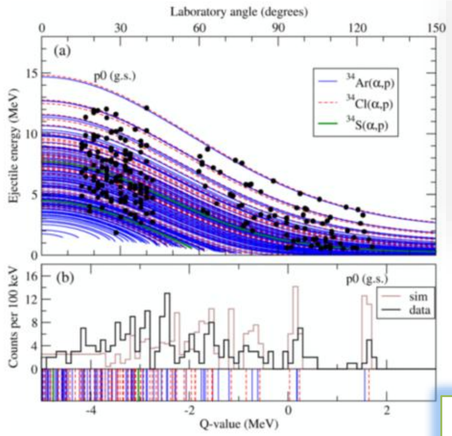


(Left) Nuclear flow chart from ^{18}Ne to ^{40}Ca
(Middle) Computed luminosity curves of double peak structure observed during X-ray burst

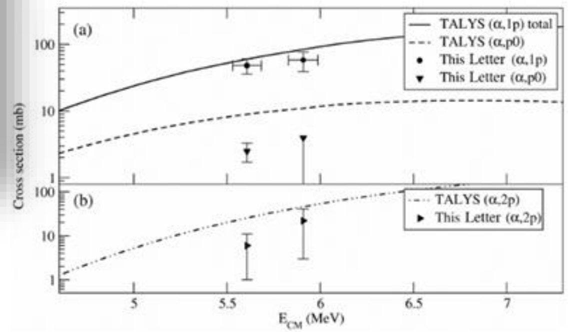








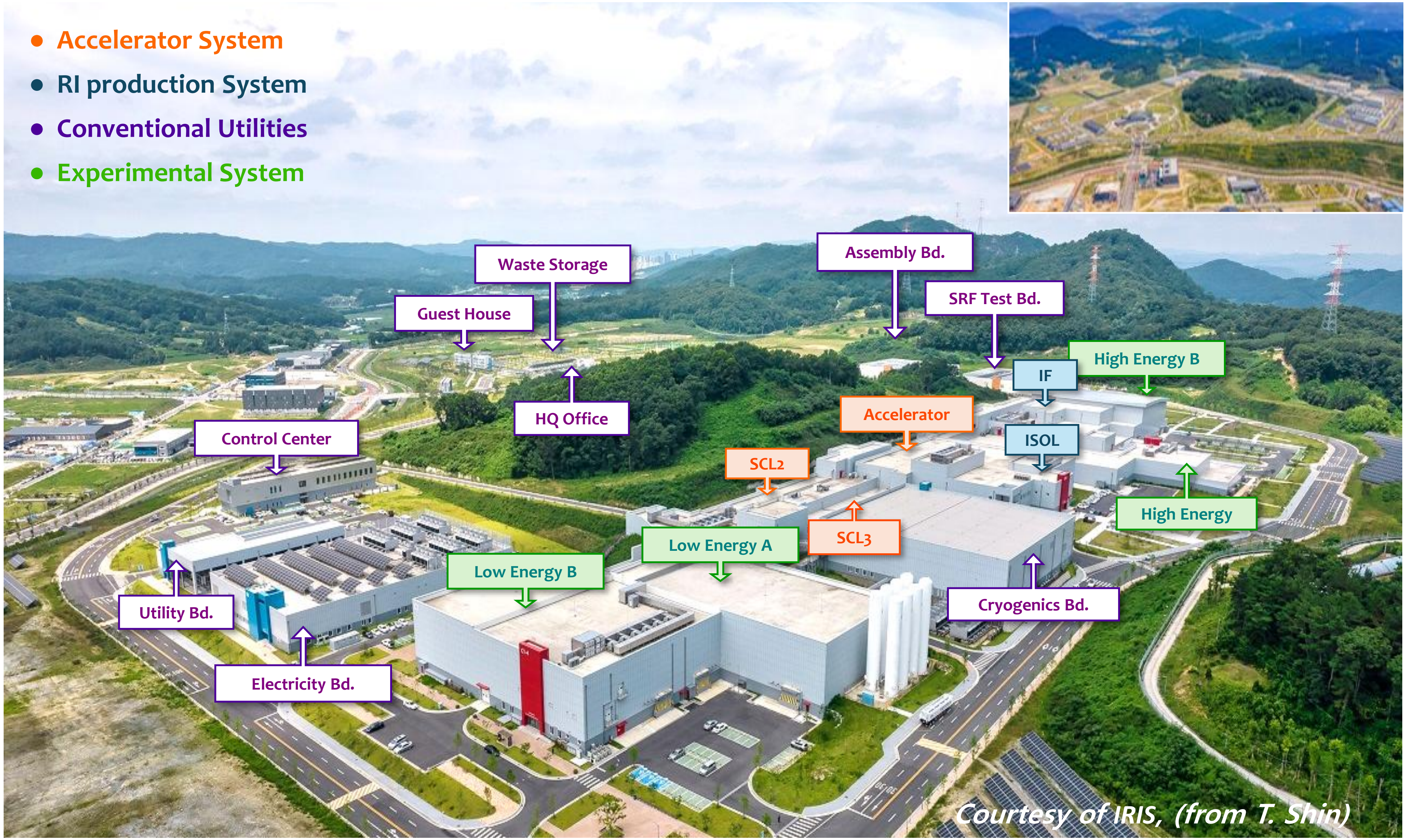
J. Browne *et al.*, PRL 130, 212701 (2023)



Proposed by A. Kim at Korea Univ

Poster #238 by Aram Kim – Measurement of the $^{34}Ar(a,p)^{37}k$ reaction using ^{34}Ar beam and an active target TPC

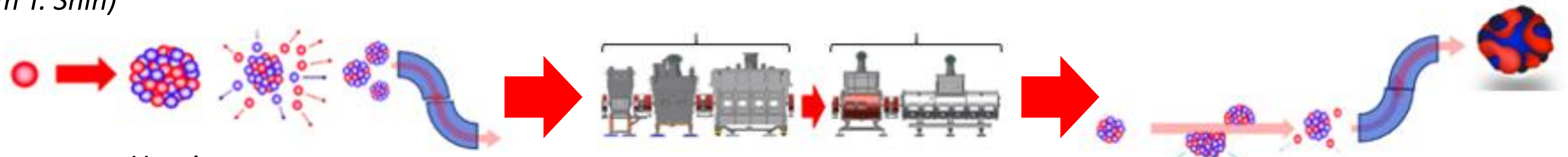
Bird's eye-view of RAON



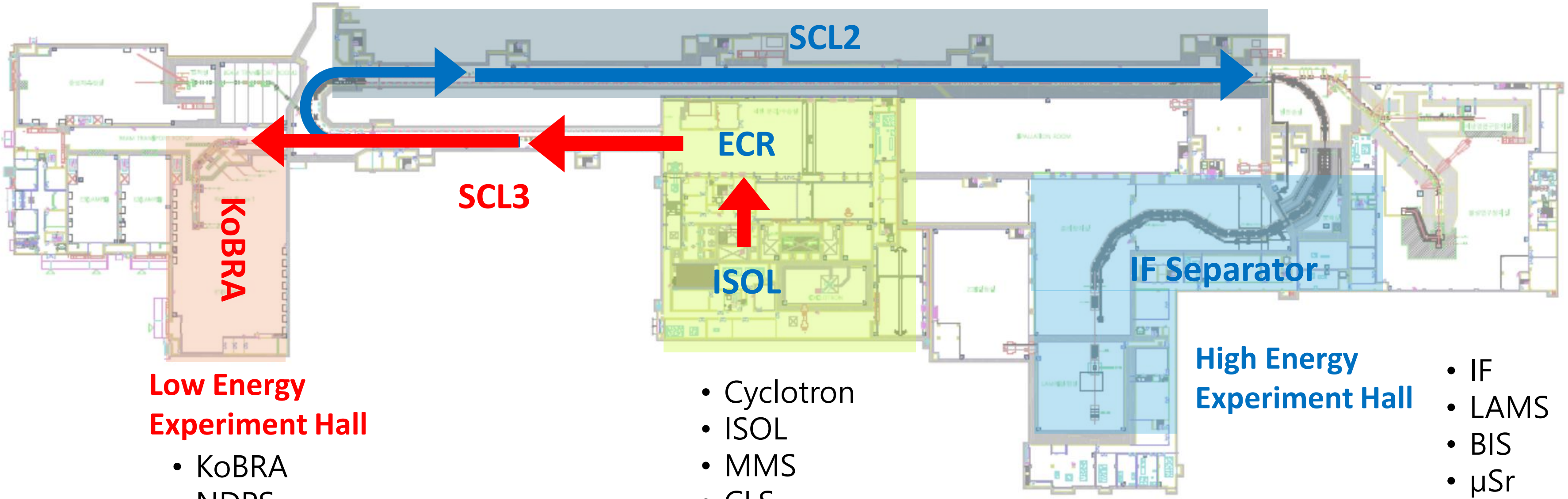
RAON

ISOL(Isotope Separation On-Line) | **Accelerator** | **IF(In-flight Fragmentation)**

Courtesy of IRIS (from T. Shin)



The RAON at the IRIS has a potential for the unique feature of combining the ISOL and In-Flight for the production of very rare isotopes.



Low Energy Experiment Hall

- KoBRA
- NDPS

- Cyclotron
- ISOL
- MMS
- CLS

High Energy Experiment Hall

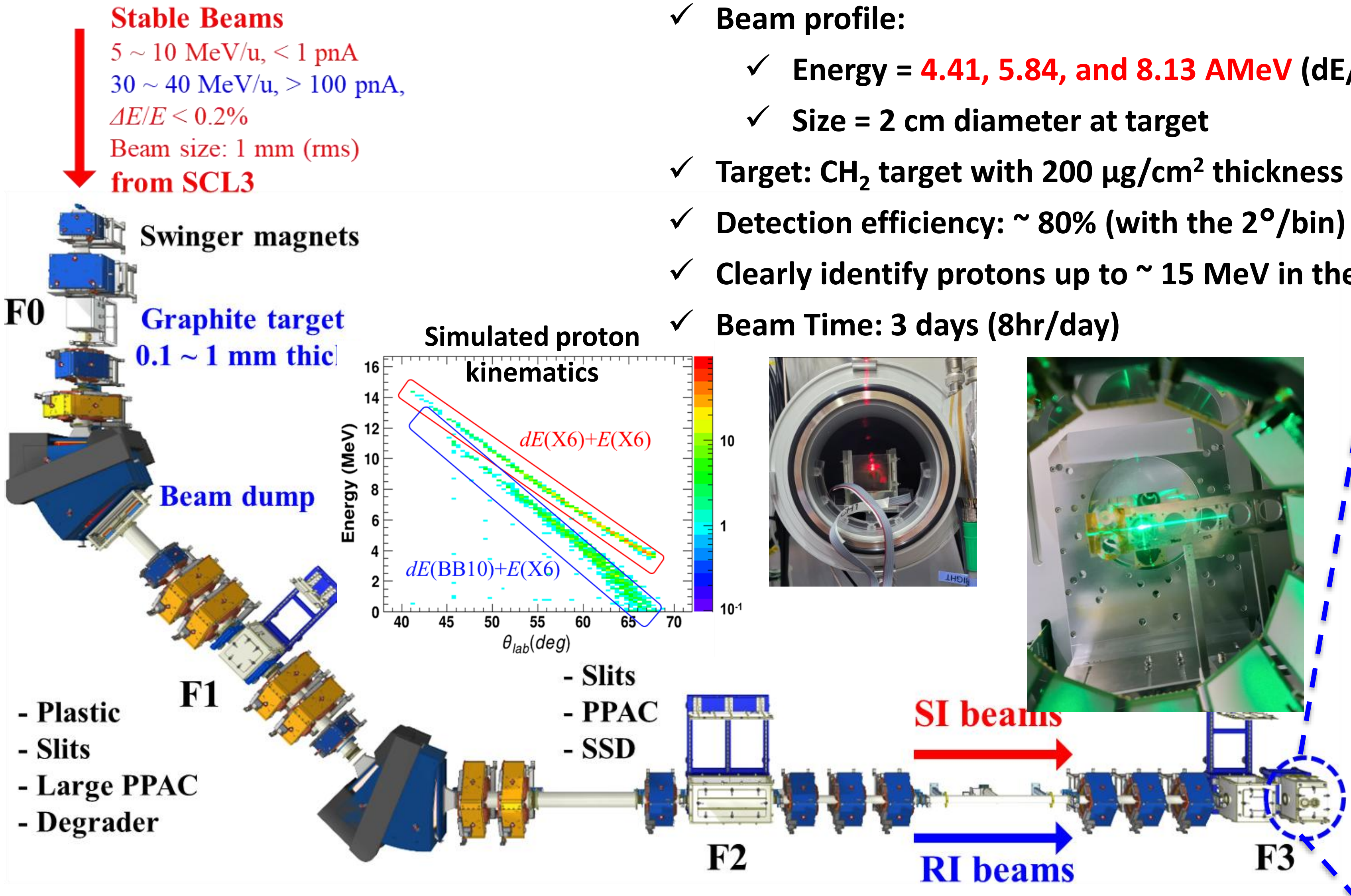
- IF
- LAMS
- BIS
- μSr

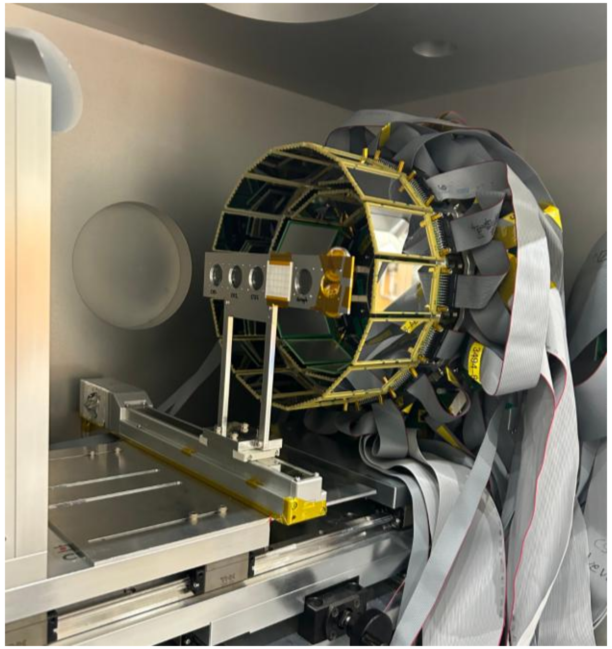
KoBRA : Korea Board acceptance Recoil spectrometer & Apparatus **ISOL** : Isotope-Separator On-Line

IF : In-flight Fragmentation separator **SCL 3**: (Low-energy) Super Conduction Linac 3 **SCL2** : (High-energy) SCL2

Experimental Setup of ^{40}Ar+p elastic scattering

- ✓ Beam profile:
  - ✓ Energy = 4.41, 5.84, and 8.13 AMeV (dE/E = 0.5% FWHM at F0)
  - ✓ Size = 2 cm diameter at target
- ✓ Target: CH_2 target with 200 μg/cm^2 thickness (plus Phosphor, Carbon and blank)
- ✓ Detection efficiency: ~ 80% (with the 2°/bin)
- ✓ Clearly identify protons up to ~ 15 MeV in the range of 40° < θ_{lab} < 70°
- ✓ Beam Time: 3 days (8hr/day)

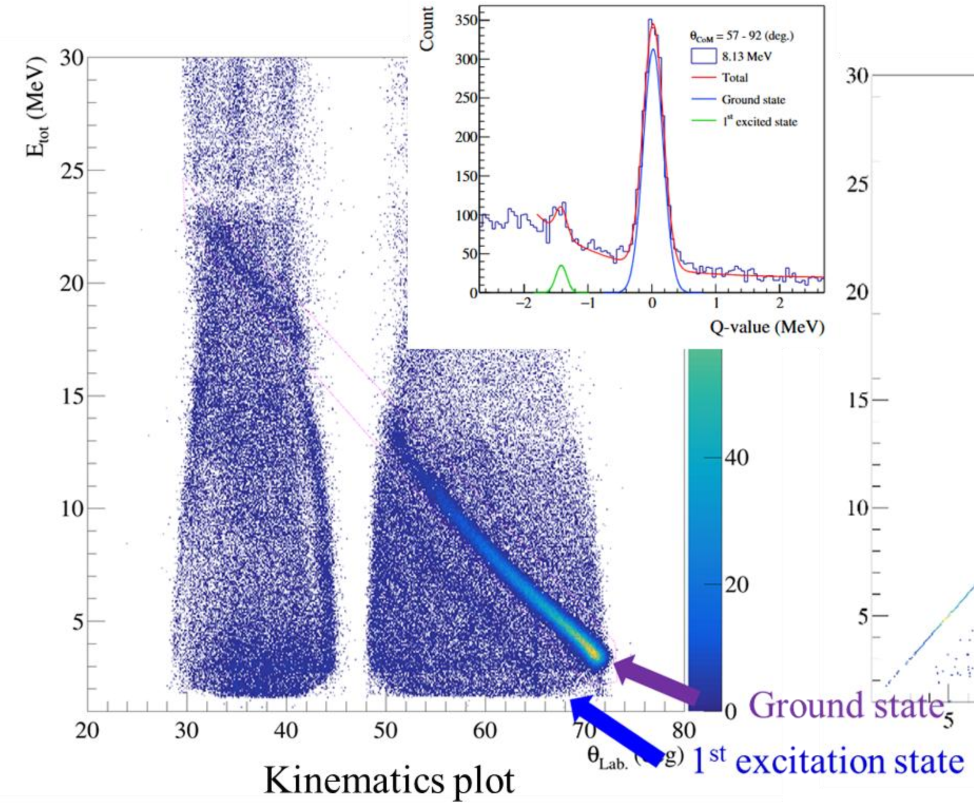


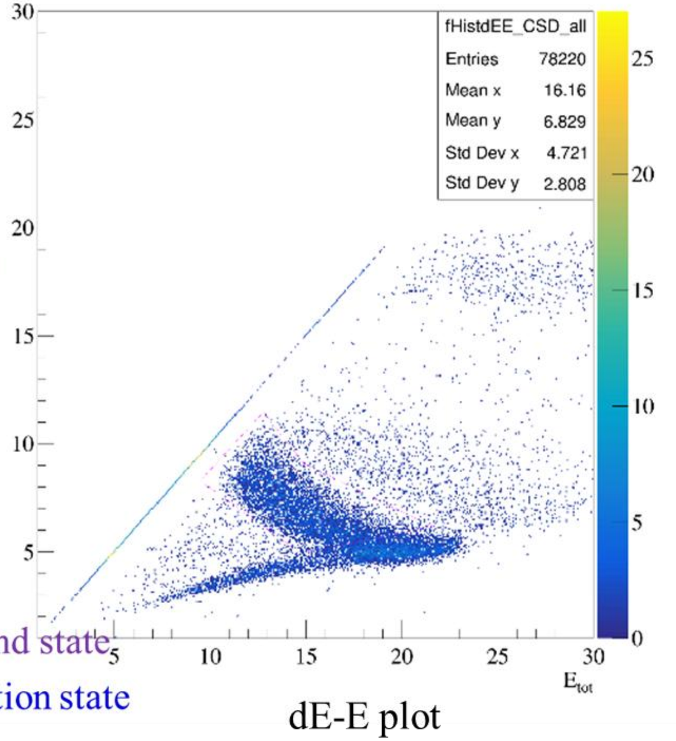


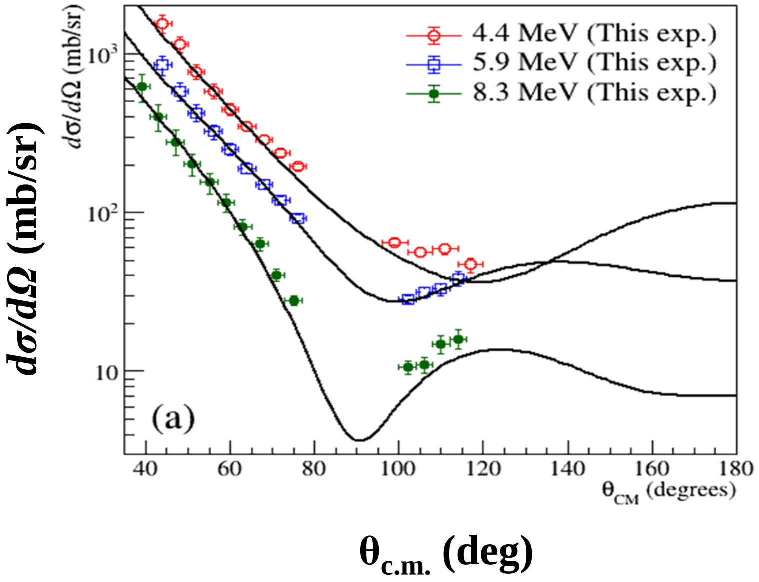
STARK

M. Kwag, CENS-KoBRA Collaboration Meeting (2019)

Analysis results of the ^{40}Ar+p scattering data







Energy (MeV)	V (MeV)	r_v (fm)	a_v (fm)	W_d (MeV)	r_d (fm)	a_d (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
4.4	58.1	1.19	0.672	0.050	1.29	0.540	5.75	0.996	0.590
5.9	43.2	1.39	0.430	5.97	1.87	0.368	5.75	0.996	0.590
7.77 [13]	55.8	1.19	0.672	6.35	1.29	0.540	5.75	0.996	0.590
8.3	57.5	1.19	0.672	8.02	1.29	0.540	5.75	0.996	0.590
9.36 [13]	55.1	1.19	0.672	8.21	1.29	0.540	5.75	0.996	0.590
10.5 [13]	56.0	1.19	0.672	8.63	1.29	0.540	5.75	0.996	0.590
14.1 [13]	52.0	1.19	0.672	8.96	1.29	0.540	5.75	0.996	0.590

Extracted new optical model parameters using SFRESCO.

D. Kim, S. Ahn *et al.*, submitted for publication

Summary

❖ The objectives of **CENS** are to conduct theoretical studies and perform experiments using RI and stable beams at accelerator facilities around the world including RAON in Korea. Our **nuclear astrophysics group** investigates key nuclear reactions relevant to various stellar environments.

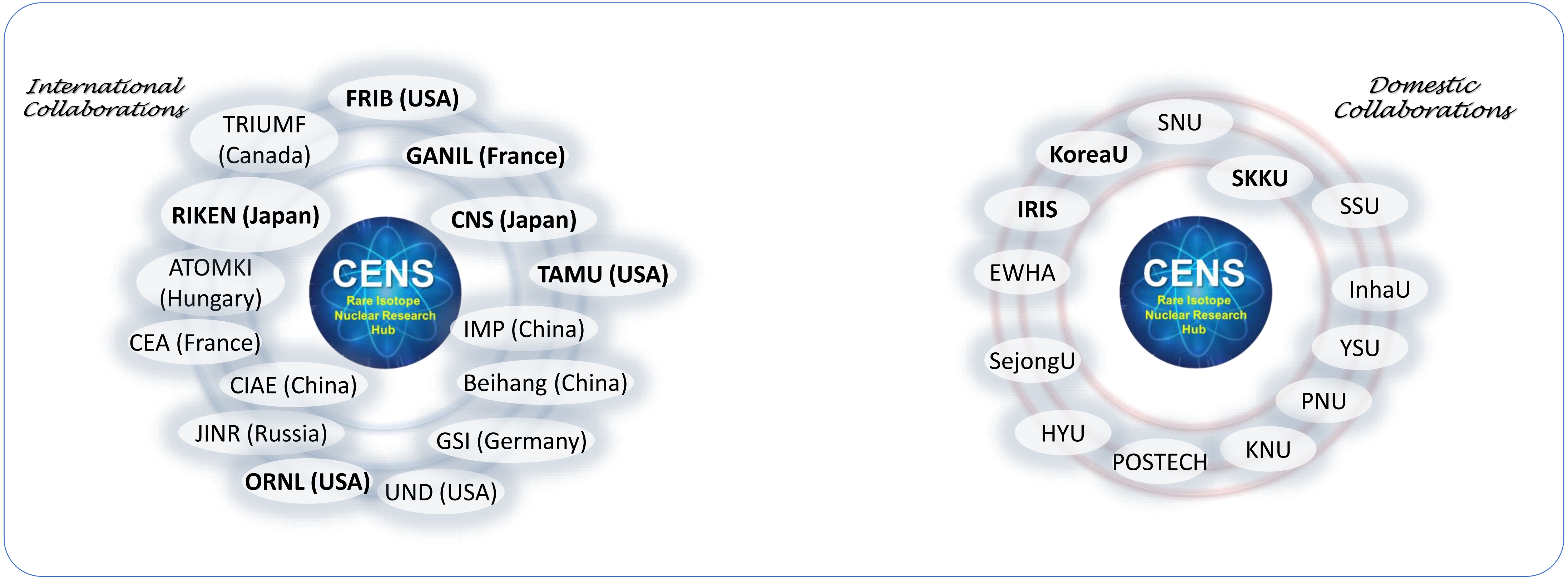
❖ We have developed major devices to be used at RAON and other RI accelerator facilities.
ATOM-X, STARK, CENS silicon detectors, CryoSTAR, JETTSTAR, Clover HPGe detectors, Wien Filter, etc

❖ We recently focus on (a,p) reactions related to the rp-process
Direct cross section measurements of **$^{14}O(\alpha,p)^{17}F$ and $^{34}Ar(\alpha,p)^{37}K$** reactions using TexAT_v2 and AToM-X at CRIB/CNS.

❖ We performed commissioning experiments at RAON last year.
Optical Model Potential study of **$^{40}Ar+p$ elastic scattering** at low energy region.

Acknowledgements

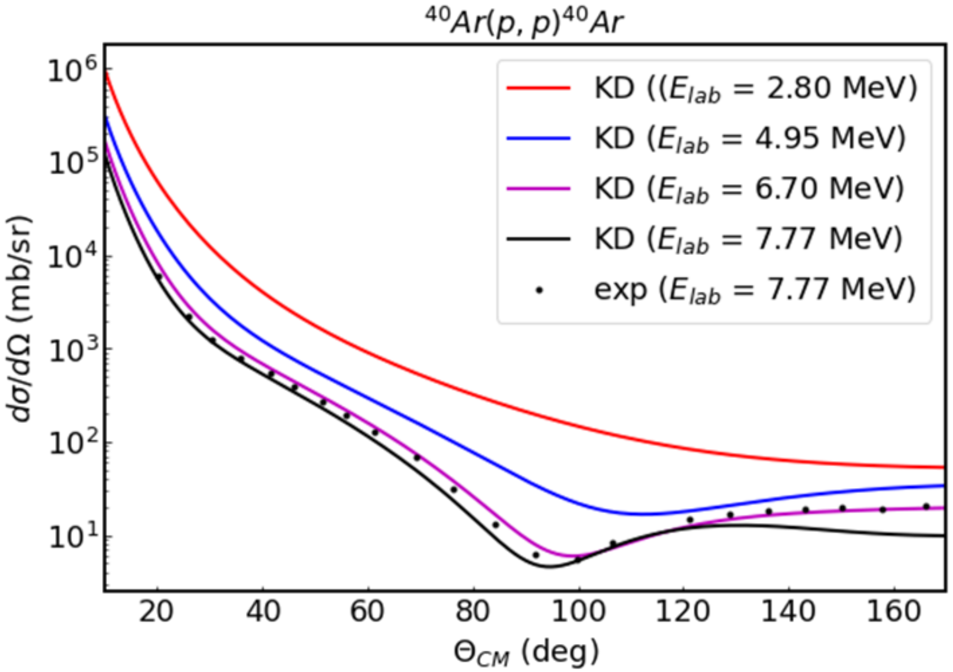
All the CENS members
&

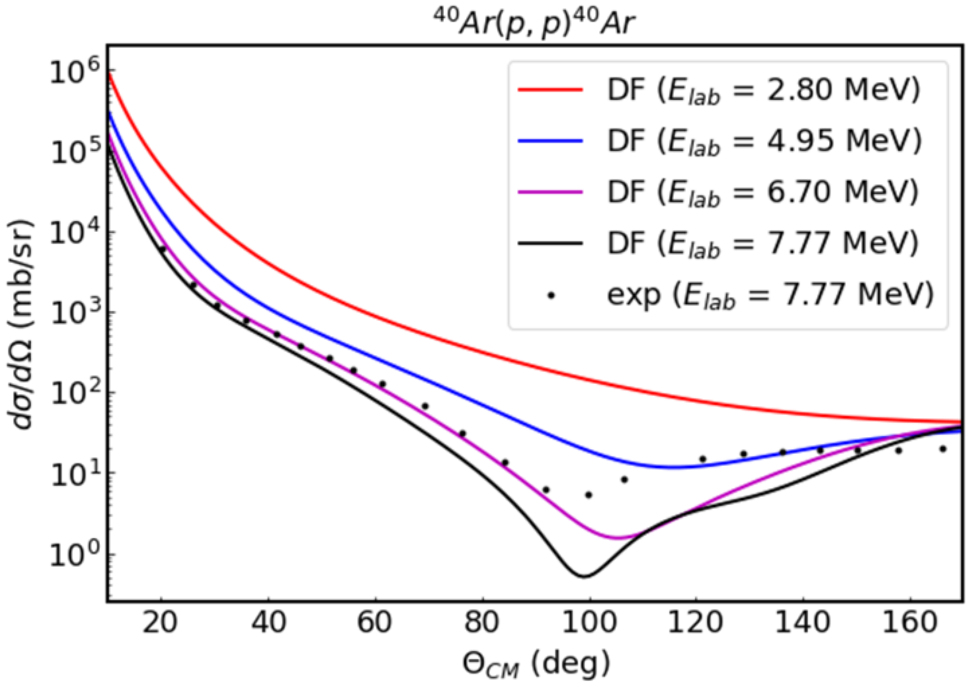


Thank you for your attention!

Optical Model Potential Study with ^{40}Ar + p elastic scattering

Theoretical predictions for the cross-section in KD and DF models at low energies (E_{lab} = 2.80, 4.95, and 6.70 AMeV)





Calculated by Dr. Y. H. Song (IRIS) and Myunghee Park (CENS)

[Main Goal] Compare the phenomenological and microscopic optical model for ^{40}Ar+p elastic scattering in lower energy region.

Experimental Setup

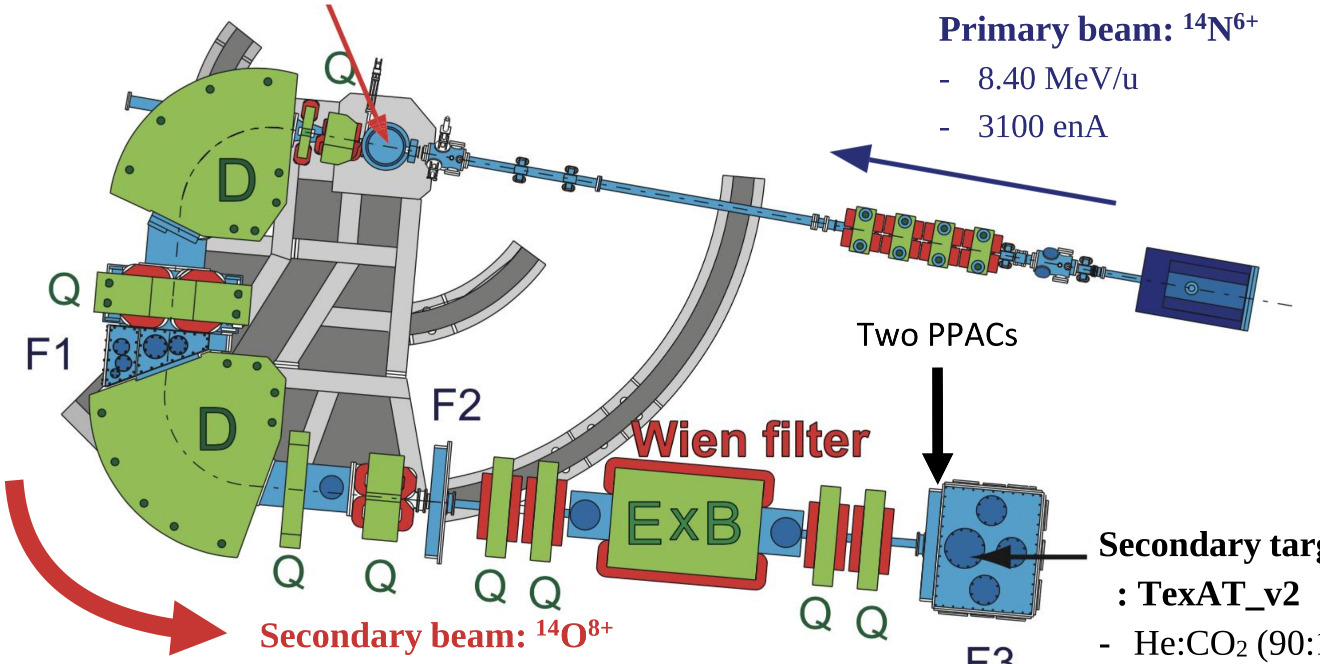
CRIB

CNS Radio-Isotope Beam Separator

F0 target: H_2 gas (90K, 80 mm, ~500 Torr)

Primary beam: $^{14}N^{6+}$

- 8.40 MeV/u
- 3100 enA



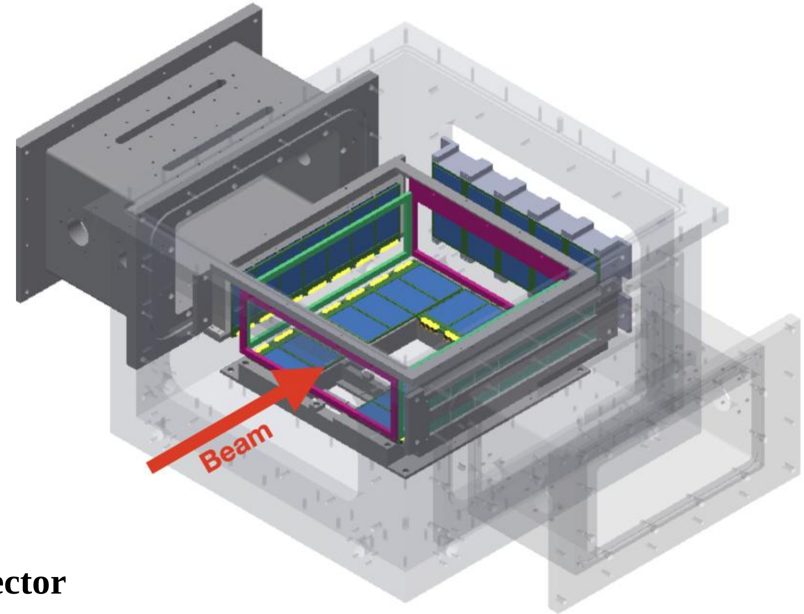
Secondary target / detector
: TexAT_v2

- He:CO_2 (90:10), 300 Torr

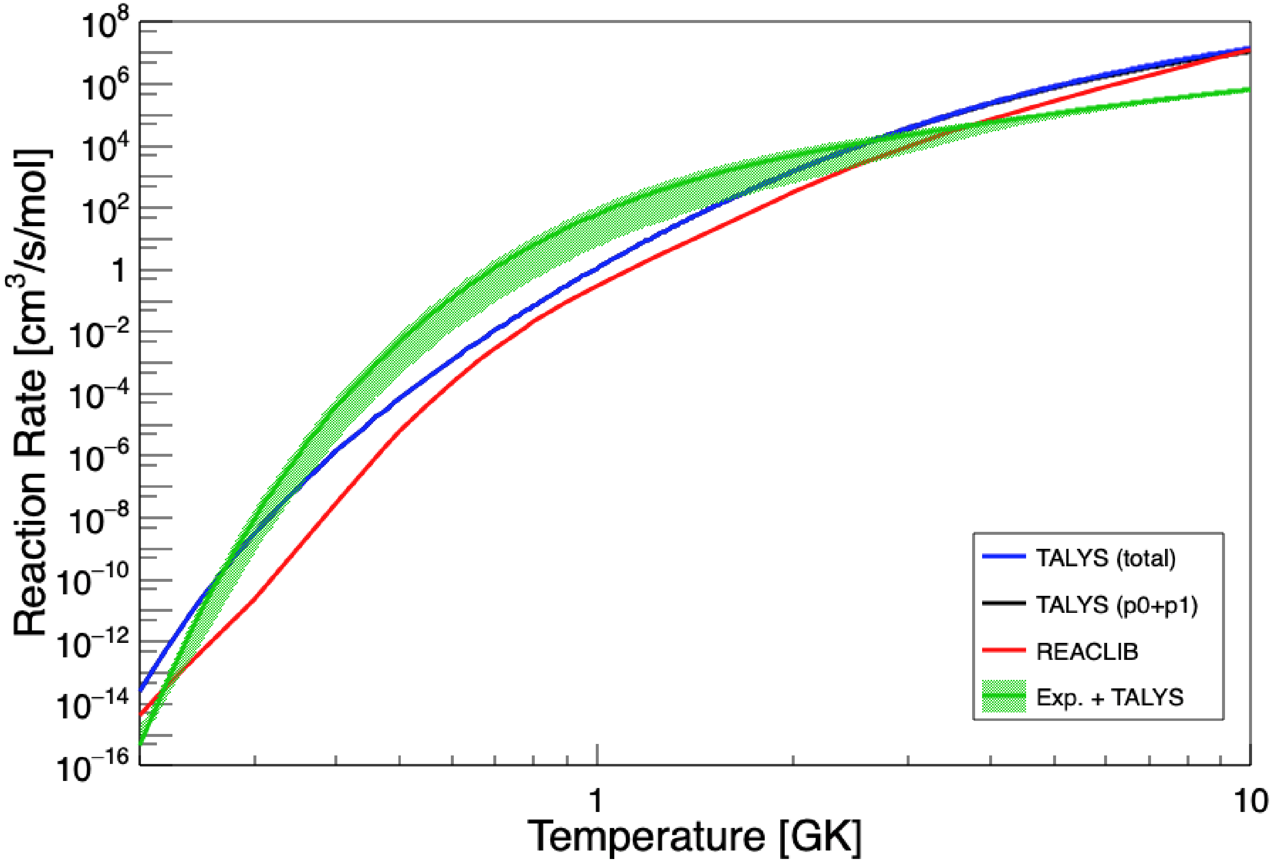
Secondary beam: $^{14}O^{8+}$

- 4.66 MeV/u
  → 3 MeV/u, 10^5 pps after thin scintillator

- TexAT_v2 (Texat Active Target TPC version 2)



Reaction Rate

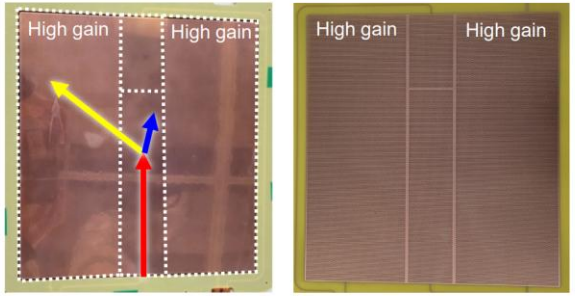


- 0.3 - 2 GK
  - Higher than REACLIB and TALYS
    ∵ Higher cross sections in the low energy region (Gamow window)

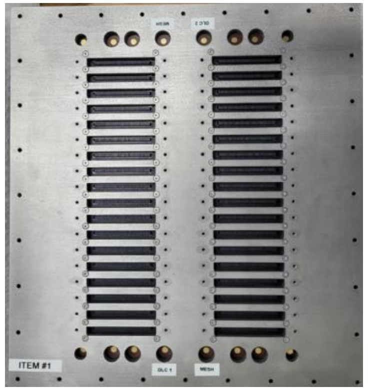
AToM-X: CENS Active Target TPC

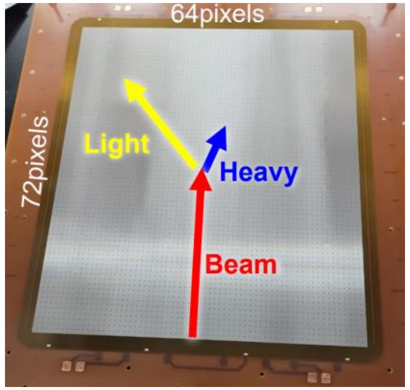
- AToM-X : Active target TPC for Multiple nuclear eXperiment
- Active area: 256(X) x 180(Y) x 288(Z) mm^3
- Scattering chamber: similar to TexAT chamber to make portable!
- Octagonal shape field cage, larger active area than TexAT Micromegas
- New micromegas with a good position resolution (0.5mm expected wt 4x4 mm^2 pixels)
- 5658 channels total (4608 from Micromegas plate and 1050 from aux detectors)
- GET electronics will be applied for signal processing: new AsAd board production.
- Online Data Analysis Cluster System (48 CPUs, 96GB Memory and 11 TB SSDs)

GEM (thickness256 um and 1mm)

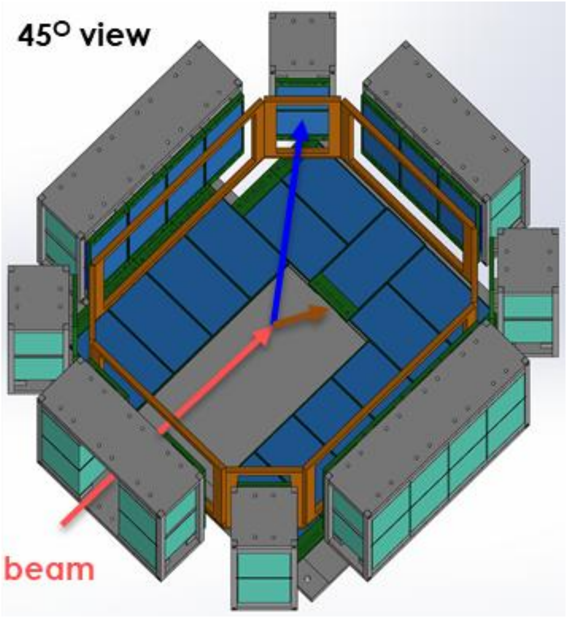


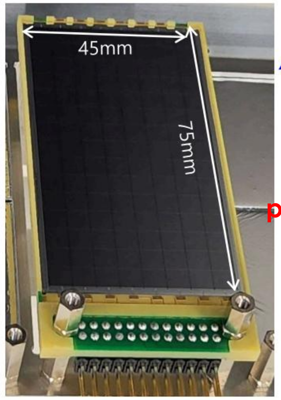
Top View of Micromegas



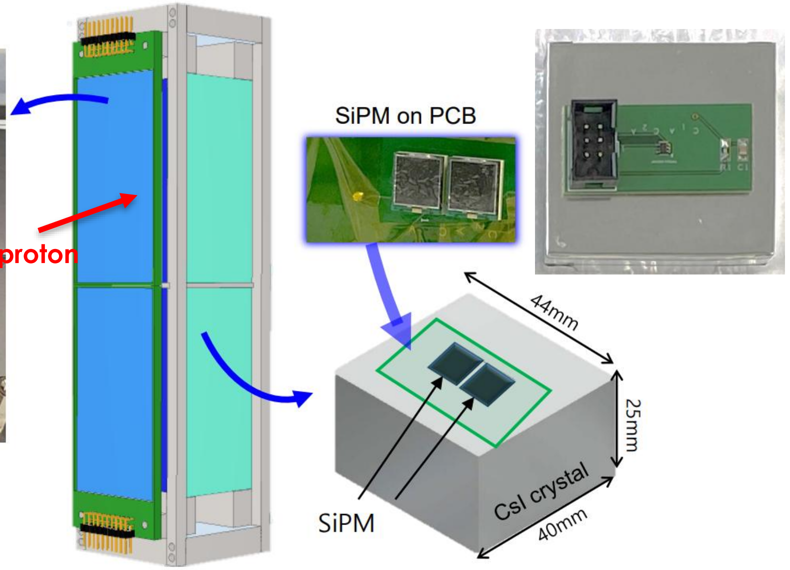


Bottom View of Micromegas





X6 Si. Det.
X. Pereira-Lopez *et al.*, NIMB (2023)



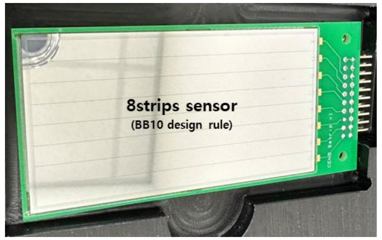
S. Bae *et al.*, NIMB (2023)

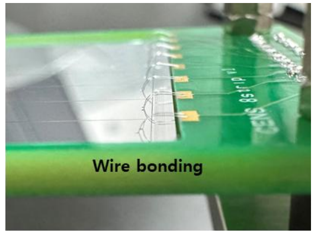
Side View of Si./CsI Det.

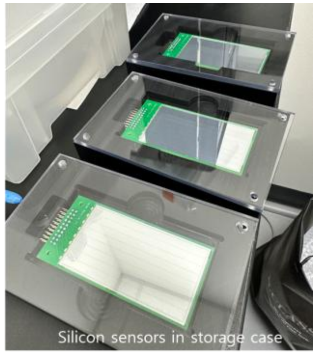
Development of CENS silicon sensors

- Silicon detectors: good efficiency, angular resolution and energy resolution

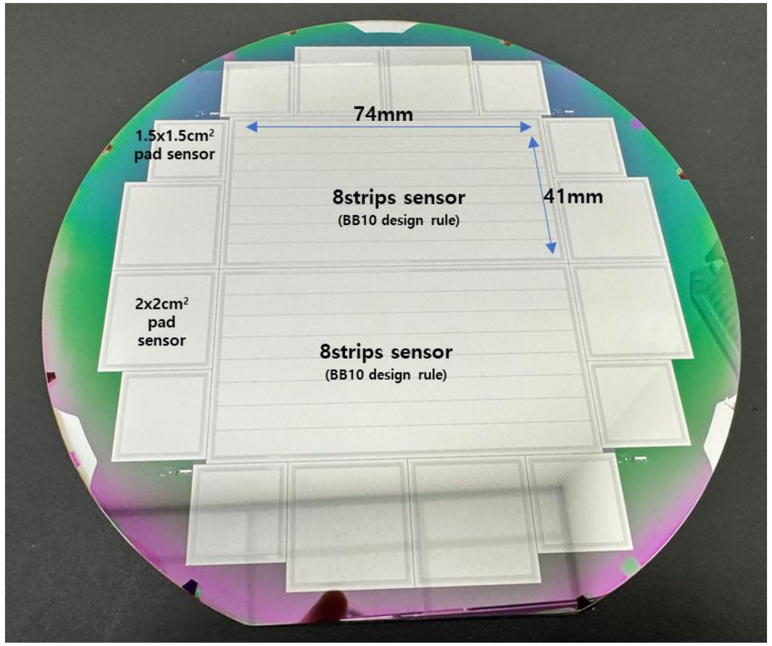
- Issues:
  - ✓ Most of them are made by Micron → expensive and difficult to customize
  - ✓ Few experts who can make them in the field of low energy experiments.



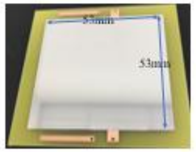
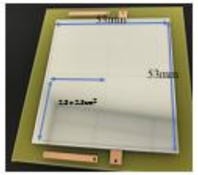
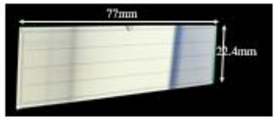


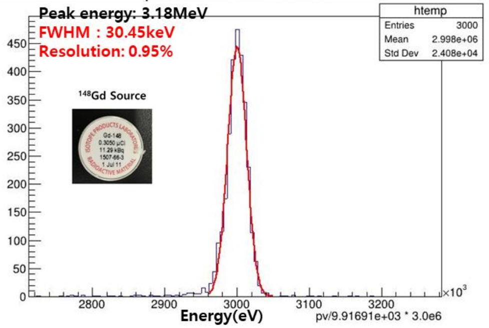


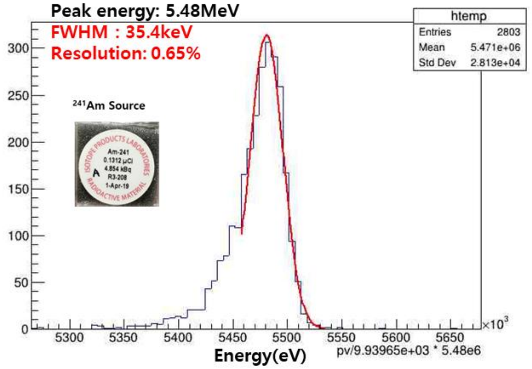
- Single-sided strip silicon sensors are developed at CENS (H.Y. Lee):
  - ✓ Pad design → Fabrication → Pad dicing → PCB design → PCB manufacturing → Assembly → Test



A fabricated 6-in silicon wafer

Active area: 50mm x 50mm Number of strip/detector: 1	
Active area: 25mm x 25mm Number of strip/detector: 4	
Active area: 2.46mm x 74mm Number of strip/detector: 8	
Active area: 4.86mm x 74mm Number of strip/detector: 4	

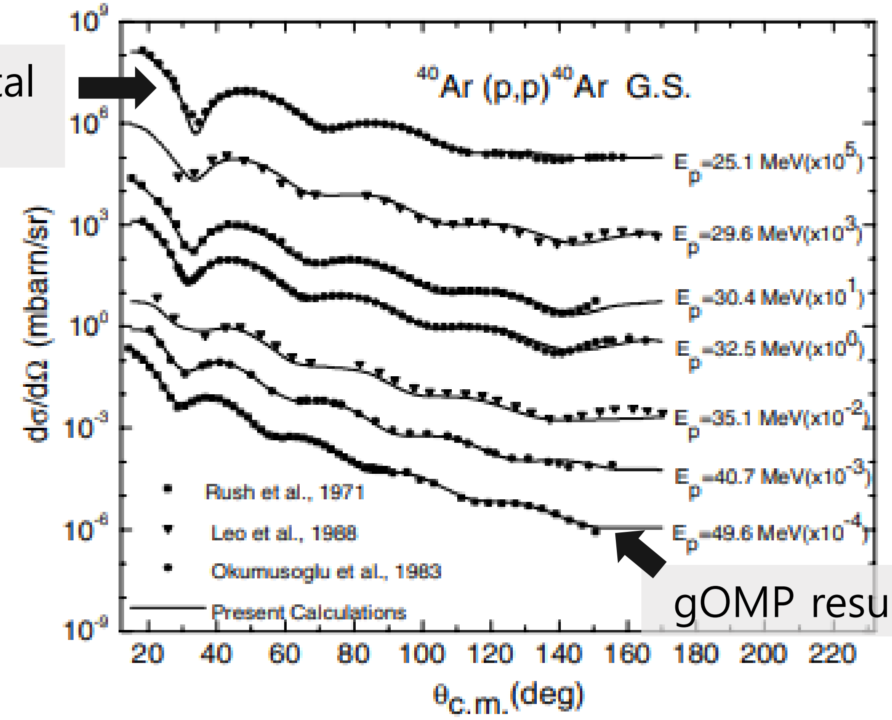




Optical Model Potential Study of ^{40}Ar + p elastic scattering

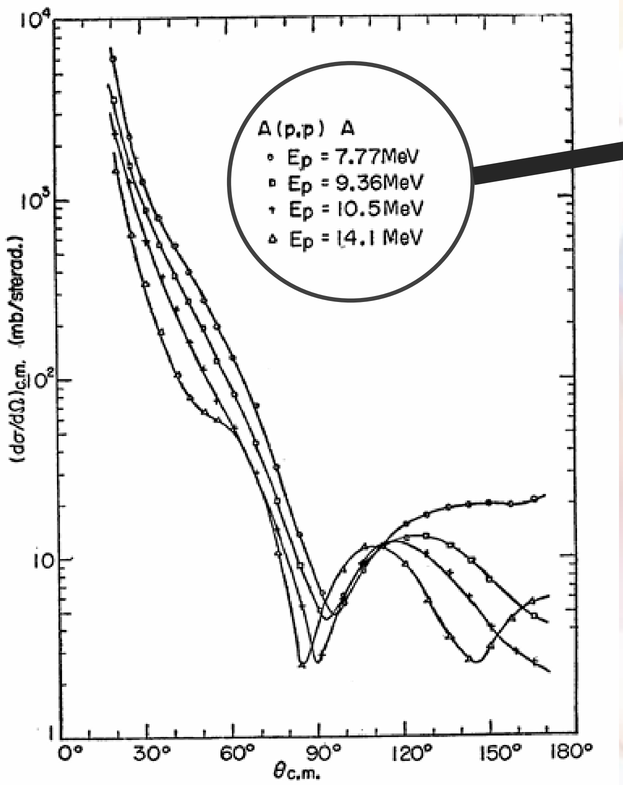
- Optical model potential (OMP) parameters are required to predict cross-section for each energy.
- Lack of optical model parameters at low energies, especially near the Coulomb barrier.

Experimental data



gOMP results

N. T. Okumuşoğlu et al., Phys. Rev. C 75, 034616 (2007).

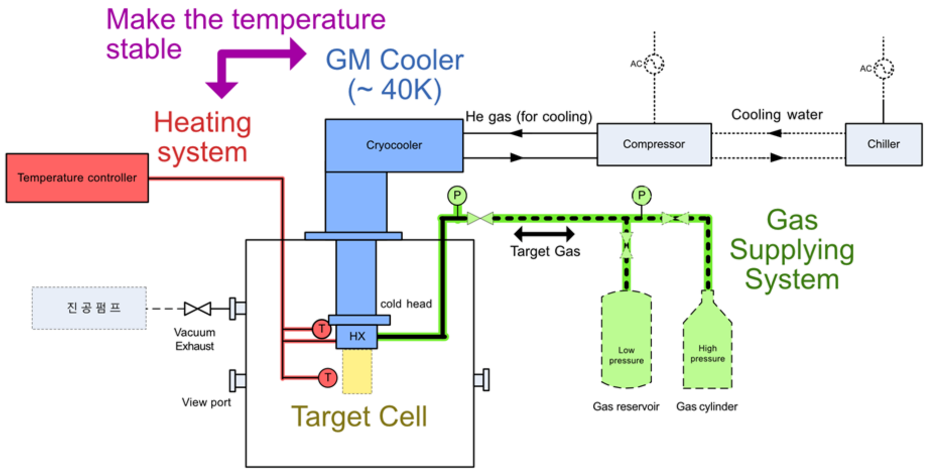


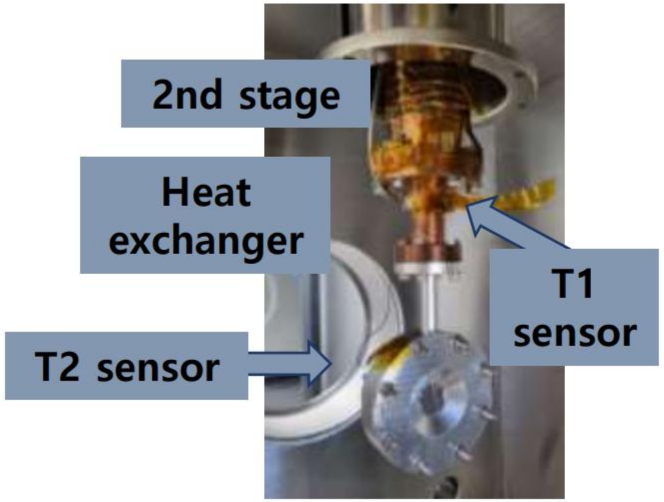
At lower energies,
No gOMP parameters were obtained.
(E_p < 7 MeV)
No data available near the Coulomb barrier.
(V_c = 4.1 MeV)

[Main Goal] Compare the global optical models with the experimental data in low energy region and extract OMP parameters.

Cryogenic Stable TARget (CryoSTAR)

- Goals: 40 K, 0.3~2 atm of $H_2/D_2/{}^3He/{}^4He$ gas
- Reaction Gas Cell Dimensions: 3/6 mm thick, 20 mmD with Havar/Mo/Ti/Mylar window (2~50 um)



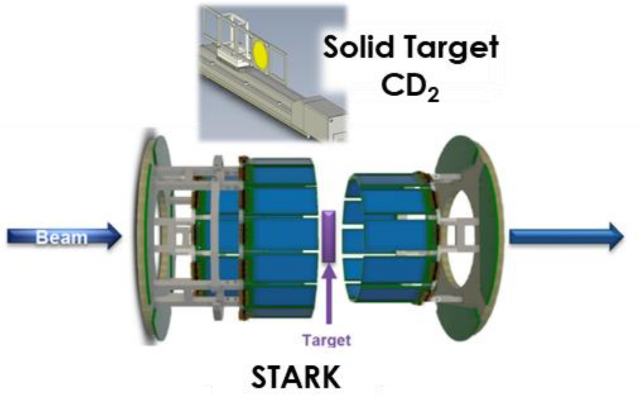


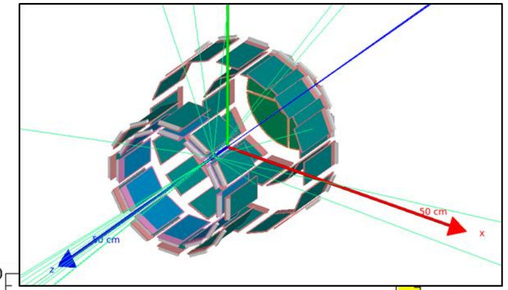
- ✓ **First performance test completed with He gas.**
- ✓ **40 K achieved with 1.3 bar Helium gas.**
- ✓ **To Do:**
  - **Various target test**
  - **target thickness measurement with alpha source**
  - **Performance test with light beams**

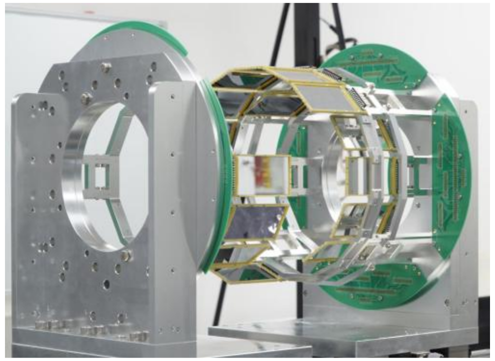
Neutron transfer reactions

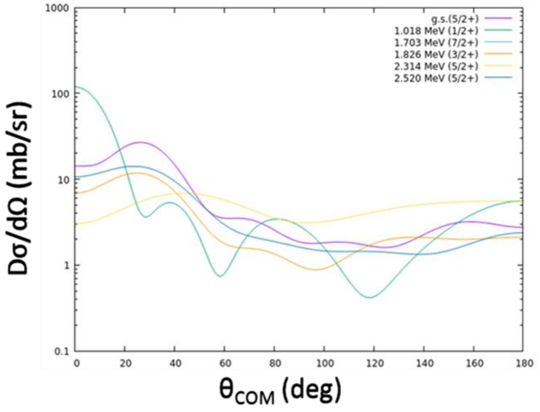
Proposed by S. Ahn

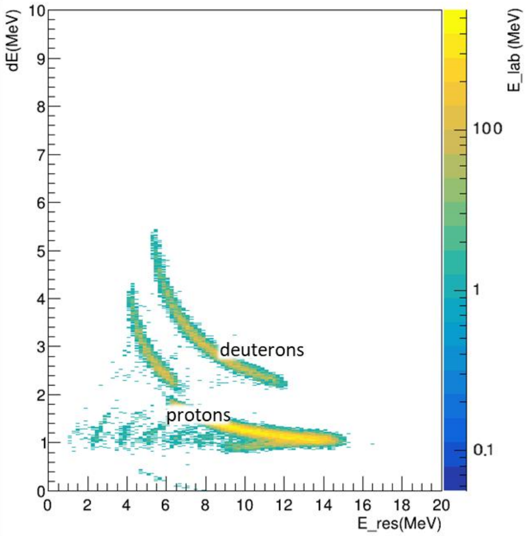
- The (n,ɣ) total cross section has a large uncertainty.
- The (n,ɣ) cross sections via discrete states or resonances.
- The (d,p) can provide direct capture part of the (n,ɣ) cross section.
  → We need spin/parity, excitation energy and spectroscopic factor.

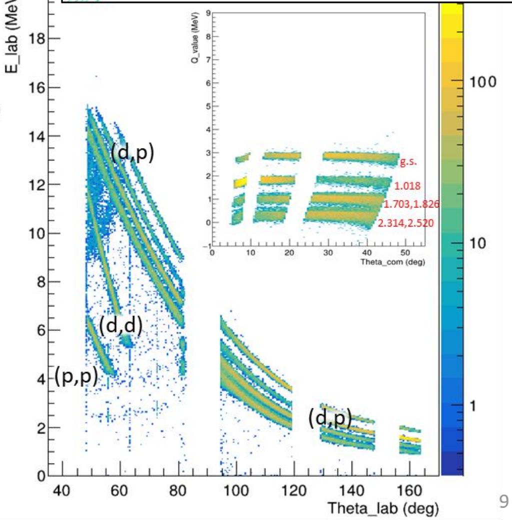












Sunghoon(Tony) Ahn