The measurements of (α,p) reactions on the waiting point nuclei using AToM-X

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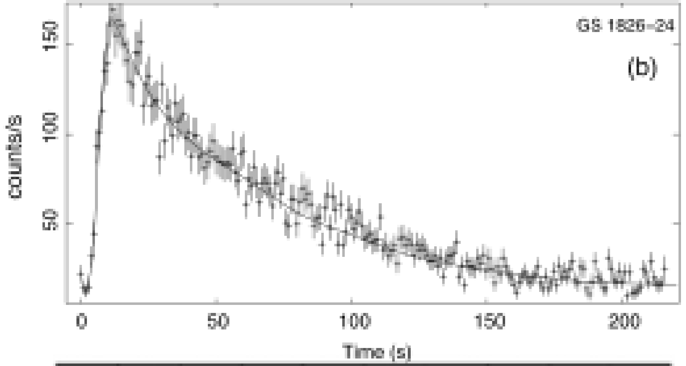
What are “X-ray bursts”?

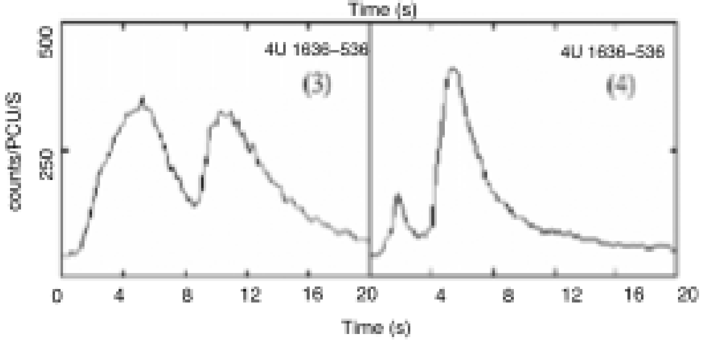
- X-ray bursts occur in binary systems where a neutron star and a less massive companion star orbit each other.
- The neutron star's strong gravity pulls hydrogen- and helium-rich material from the companion star, forming an accretion disk around it.
- When the temperature and pressure in the accumulated layer become high enough, hydrogen and helium nuclei undergo rapid nuclear fusion in a runaway reaction.
- This fusion process produces a sudden burst of energy in the form of X-rays.

Type I X-Ray Bursts:

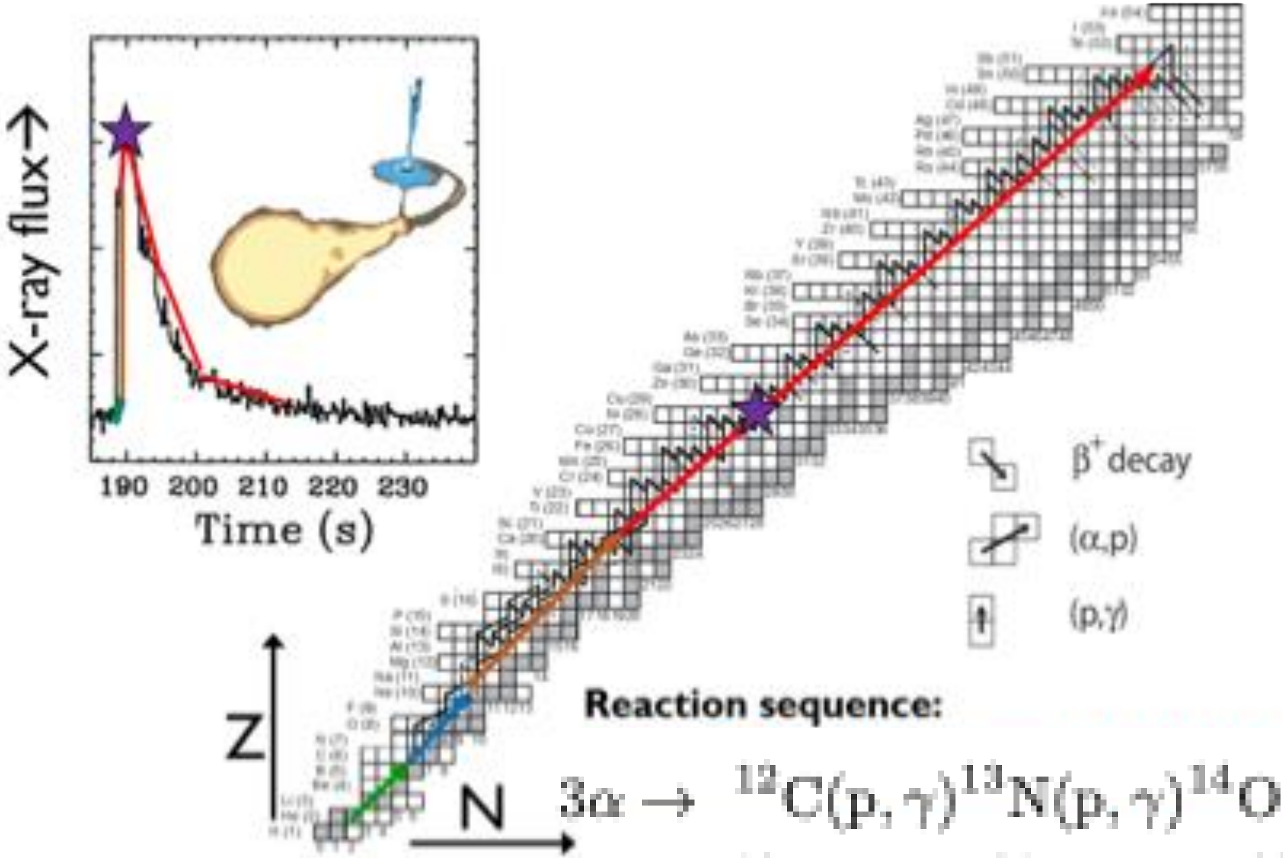
- Caused by thermonuclear burning of the accreted material.
- The most common type and well-understood.

⇒ It is crucial to understand the light curve since its rise and decay reflect the progression of thermonuclear reactions.





The nuclear reaction sequence powering type-1 X-ray bursts



- The sharp rise of the x-ray flux is understood to be powered by explosive helium burning on the neutron- deficient nuclei.
- Once ${}^{12}C$ is created by 3 α reaction, explosive nucleosynthesis continues through HCNO cycle and αp-process.
- (p,γ) reactions beyond ${}^{56}Ni$ strongly impact the late time light curve.
- Model calculations of X-ray burst light curves and nucleosynthesis have played an important role.

Reaction sequence:

$$3\alpha \rightarrow {}^{12}\mathrm{C}(p,\gamma){}^{13}\mathrm{N}(p,\gamma){}^{14}\mathrm{O}(\alpha,p){}^{17}\mathrm{F}(p,\gamma) \Rightarrow (\alpha,p)(p,\gamma) \Rightarrow \text{rp-process}$$

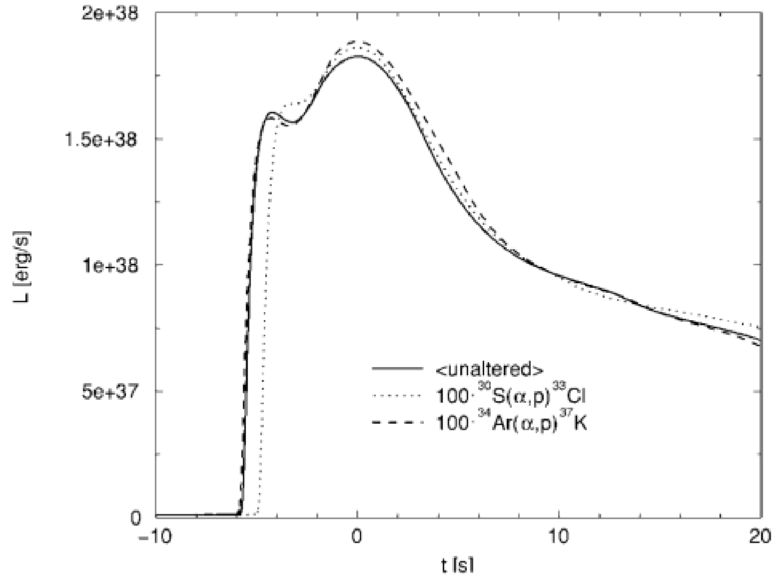
$${}^{18}\mathrm{Ne}(\alpha,p){}^{21}\mathrm{Na}(p,\gamma){}^{22}\mathrm{Mg}(\alpha,p){}^{25}\mathrm{Al}$$

αp-processes

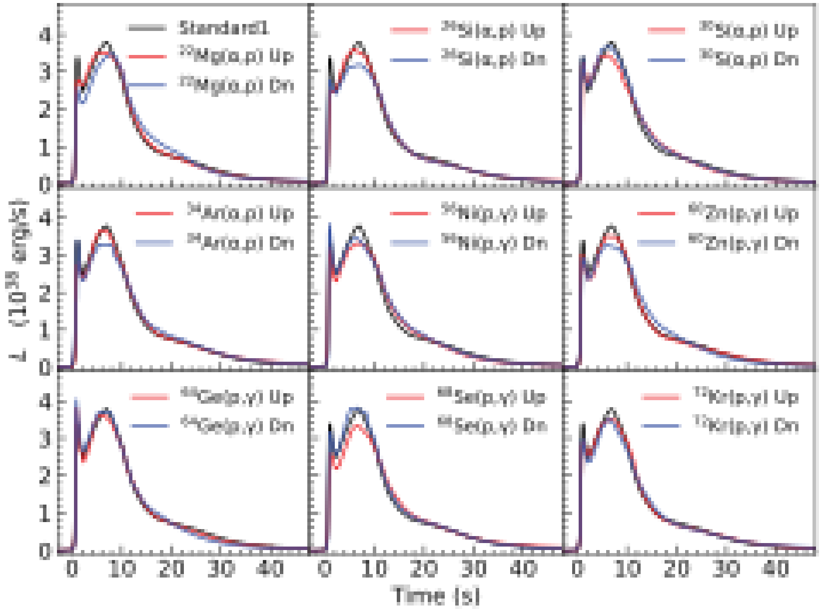
Waiting points in double peaked x-ray bursts

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

- Waiting points: The nuclei which enter (p,γ)-(γ,p) equilibrium due to low (p,γ) Q-value and have long beta decay half-life.
- ^{30}S and ^{34}Ar can be waiting points and the (α,p) reactions on them play a role to stall the reaction flow.



Fisker et al. ApJ 608 (2004)



L. Song et al. MNRAS **529,** 3103–3111 (2024)

- The reaction rates of ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K influence directly the shape of luminosity curve in X-ray bursts.
- It is crucial to determine the reaction rates of ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K for understanding the mechanism of X-ray bursts.

$^{30}S(\alpha,p)^{33}Cl$

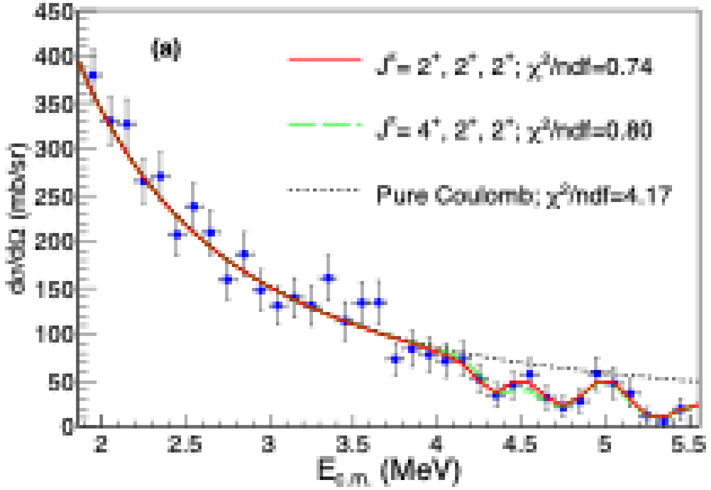
The peak XRB temperature : 1.3~2.0 GK => Gamow window : 1.7 MeV < $E_{c.m.}$<3.8 MeV
Compound nucleus :^{34}Ar

Reaction rate: $$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2} \times \sum_i (\omega\gamma)_i \exp\left(\frac{-11.605E_i}{T_9}\right)$$

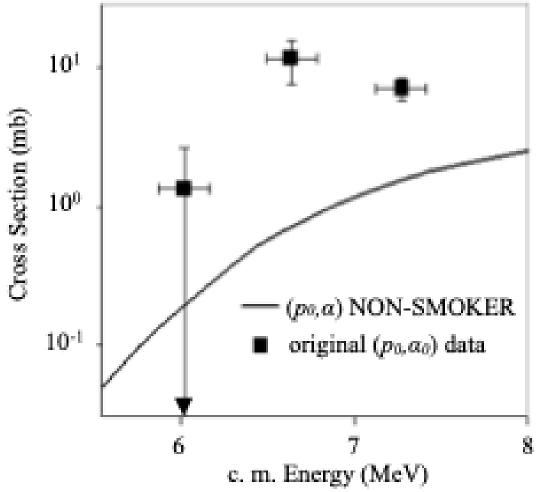
$$(\omega\gamma)_i = \frac{2J_i+1}{(2j_1+1)(2j_2+1)}\frac{\Gamma_a\Gamma_b}{\Gamma_{tot}}$$

$$\left(\Gamma_p \gg \Gamma_\alpha\ ,\ \Gamma_{tot}\simeq\Gamma_p\right)$$

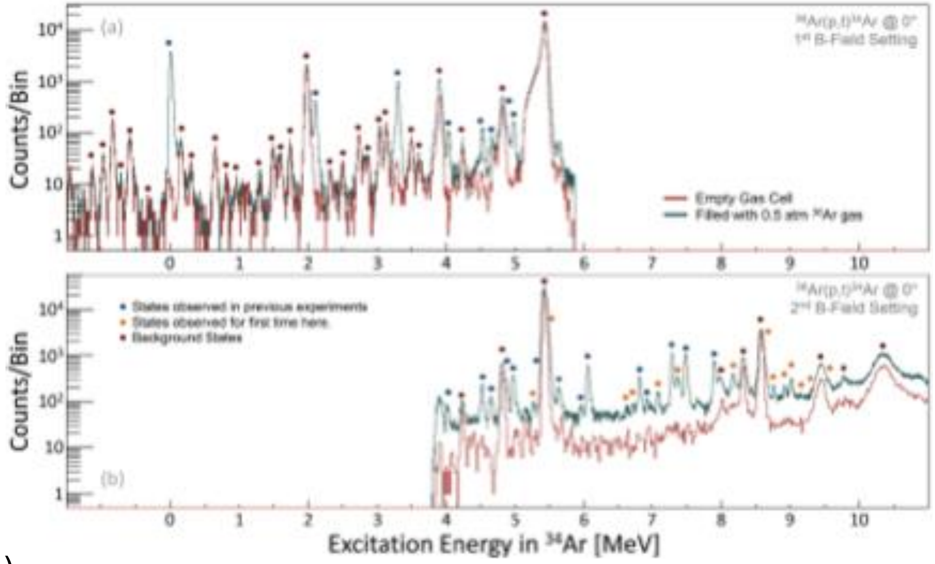
At low energy, α partial widths will be considerably smaller than corresponding proton partial widths. So, here, measuring alpha widths is crucial.



D. Khal et al, Phys. Rev. C 97 015802(2018)
$^{30}S+\alpha$ elastic scattering
⇒ The only experimental paper to measure Γ_α in ^{34}Ar



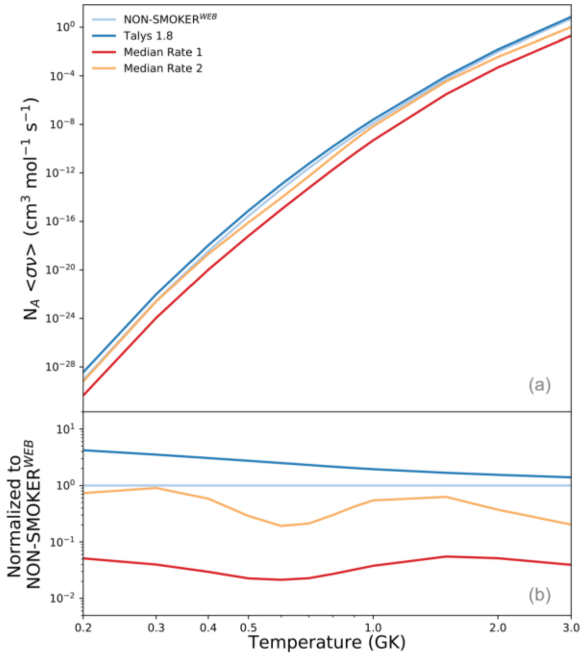
C. M. Deibel et al., Phys. Rev. C 84 045802(2011)
$^{33}Cl(p,\alpha)^{30}S$



A. Long et al., Phys. Rev. C 97 054613 (2018)
$^{36}Ar(p,t)$: No ^{34}Ar states were observed with a width larger than the resolution.

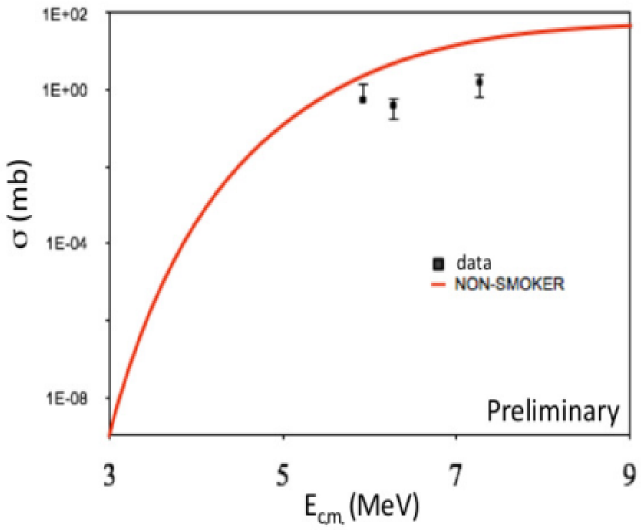
^{34}Ar(⟨,p)^{37}K

Gamow window: 1.6 MeV < $E_{c.m.}$< 4.1 MeV (1<T_9<2)
Compound nucleus : ^{38}Ca (E_x=7.71-10.21 MeV)



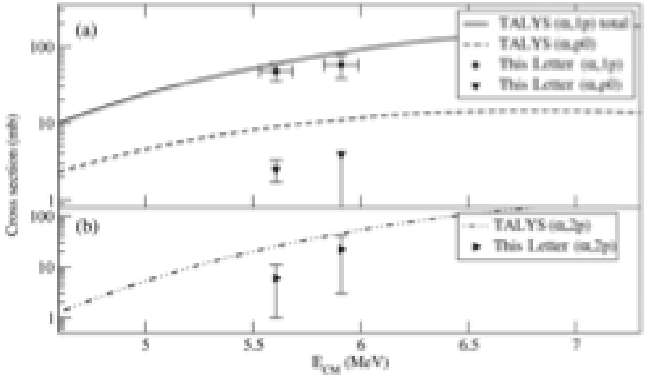
A. M. long *et al.*, Phys. Rev. C 95, 055803 (2017)

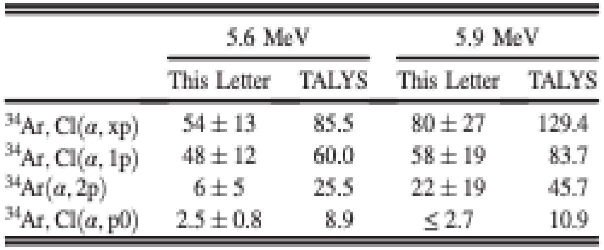
^{40}Ca(p,t)^{38}Ca



Time inverse reaction ^{37}K(p,α_0)^{34}Ar
at ANL (from A. Lauer Ph. D. thesis(2017))

First direct measurement of ^{34}Ar(α,p)^{37}K
using AT-TPC





	5.6 MeV		5.9 MeV	
	This Letter	TALYS	This Letter	TALYS
^{34}Ar, Cl(α, xp)	54 ± 13	85.5	80 ± 27	129.4
^{34}Ar, Cl(α, 1p)	48 ± 12	60.0	58 ± 19	83.7
^{34}Ar(α, 2p)	6 ± 5	25.5	22 ± 19	45.7
^{34}Ar, Cl(α, p0)	2.5 ± 0.8	8.9	≤ 2.7	10.9

J. Browne et al., Phys. Rev. Lett. 130, 212701(2023)

All previous studies didn't provide any resonance parameters except the resonance energies. Therefore, measuring the alpha widths as well as J^π or total cross section for determining the reaction rate is very important.

Goals

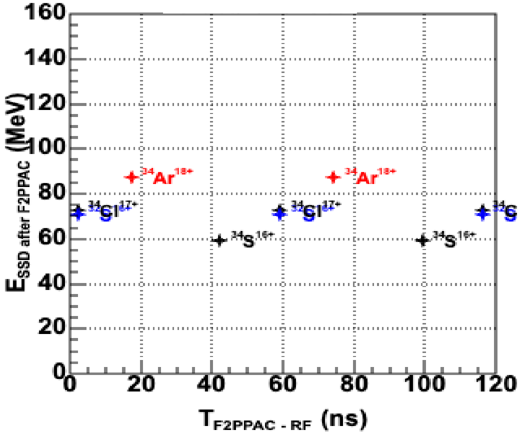
$$<\sigma v>=\sqrt{\frac{8}{\pi\mu}}\frac{1}{(kT)^{3/2}}\int_0^\infty \sigma(E)E\,e^{-\frac{E}{kT}}dE$$

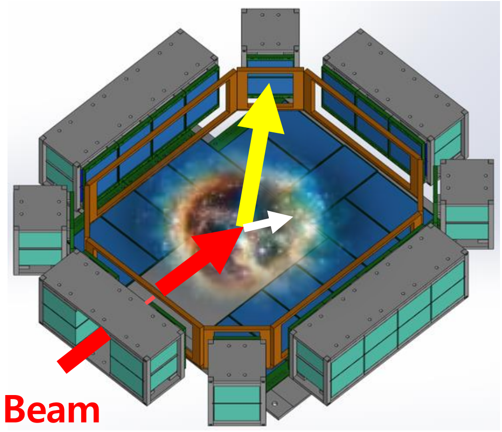
High Purity
RI Beam
^{34}Ar

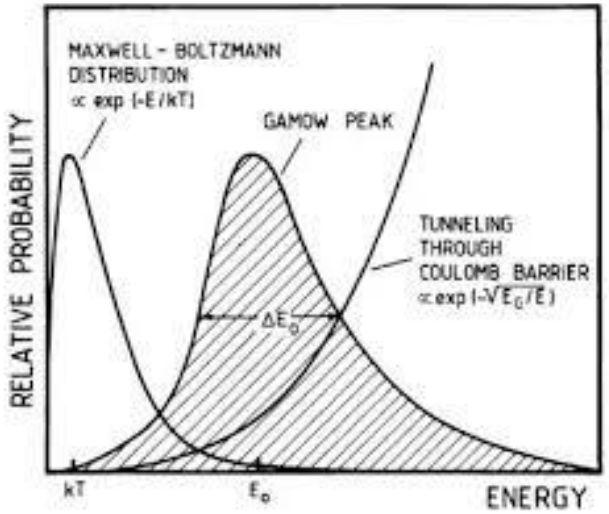
+

AT-TPC
Large Angular
Coverage

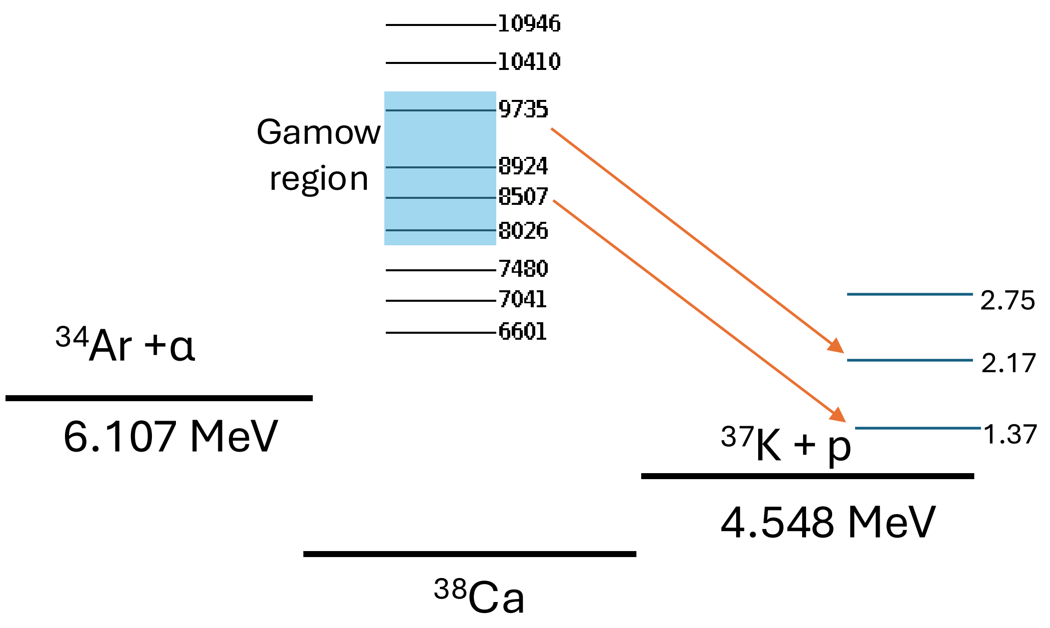
First Experimental
Reaction Rate of
^{34}Ar(α,p)^{37}K !!

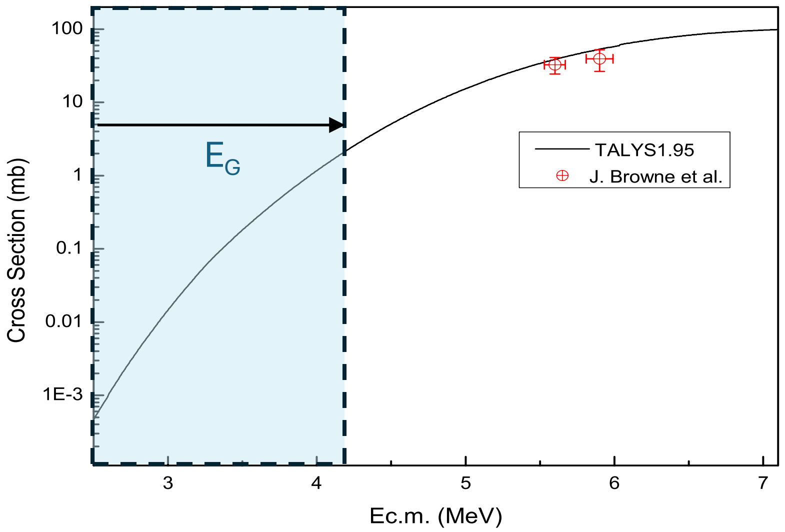






Direct measurement of ^{34}Ar(α,p)^{37}K





Calculated cross section of ^{34}Ar(α,p)^{37}K

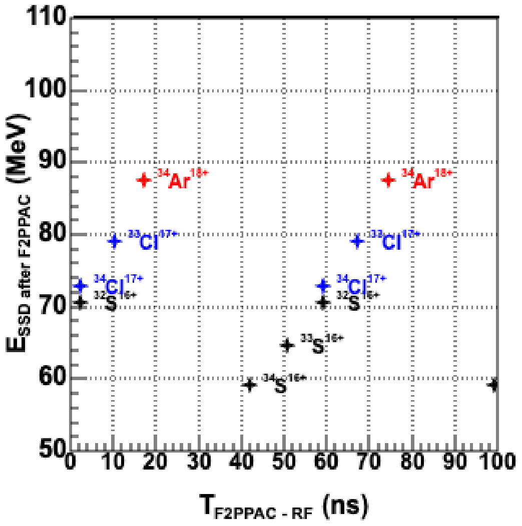
- We will measure the ^{34}Ar(α,p)^{37}K reaction in the region of $E_{c.m.} < 8.5$ MeV using a ^{34}Ar beam from CRIB and an active target time projection chamber.
- 14 days beam time was approved and 2 days beam time for RI beam production will be scheduled for April or September.
- Main run (12 days) will be performed at the beginning of 2026.

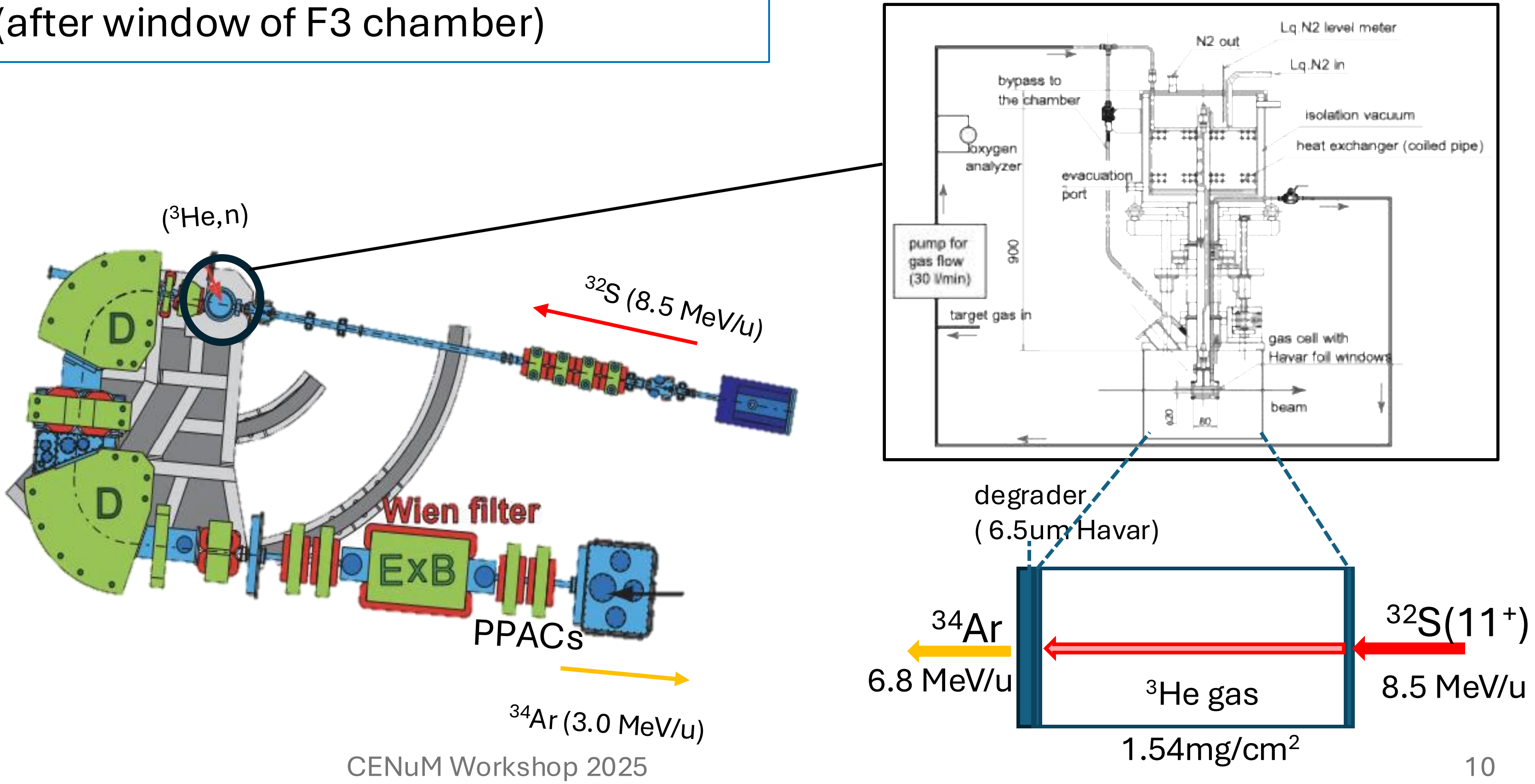
^{34}Ar beam production

- primary beam: ^{32}S (8.5 MeV/u => could be modified after the test run)
- primary target: ^{3}He gas (100K, 80mm length, 400 torr)
  =>1.54 mg/cm^{2}
- production reaction: (^{3}He,n)
- ^{32}S beam intensity : 100 pnA (50pnA was tried once.)
- ^{34}Ar beam intensity : ~10^{4} pps (from ^{28}Si(^{3}He,n)^{30}S)
- ^{34}Ar beam energy: 3.0 MeV/u (after window of F3 chamber)

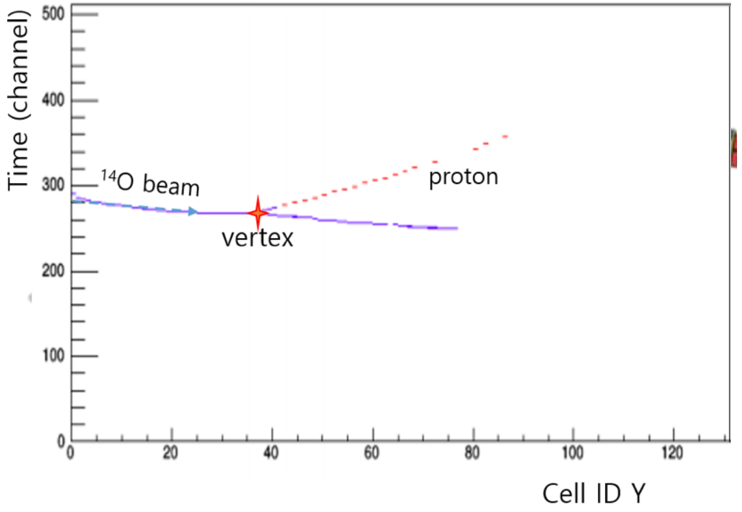
$$E = NqeV = \frac{(qeRB)^2}{2m} \qquad E \propto q^2$$

: We asked 11^{+} state of ^{32}S, but need to compromise between the charge state and the energy of beam.



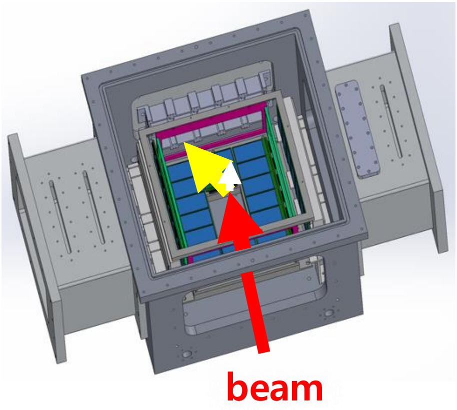


Detector and target - AToM-X (Active target TPC for Multiple nuclear eXperiment)



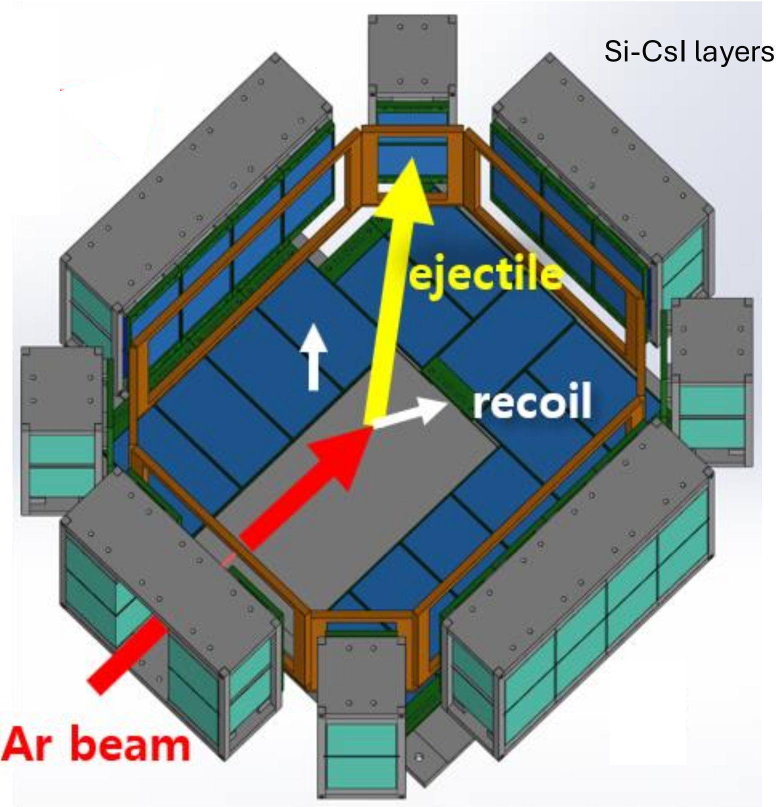
AToM-X is a device acting as both a target and a detector system

- ✓ Identification of the reaction vertex
- ✓ 3d-tracking available
- ✓ High efficiency (56 sets of Si-CsI layer)

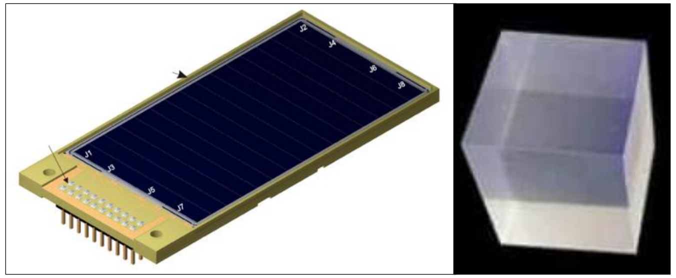


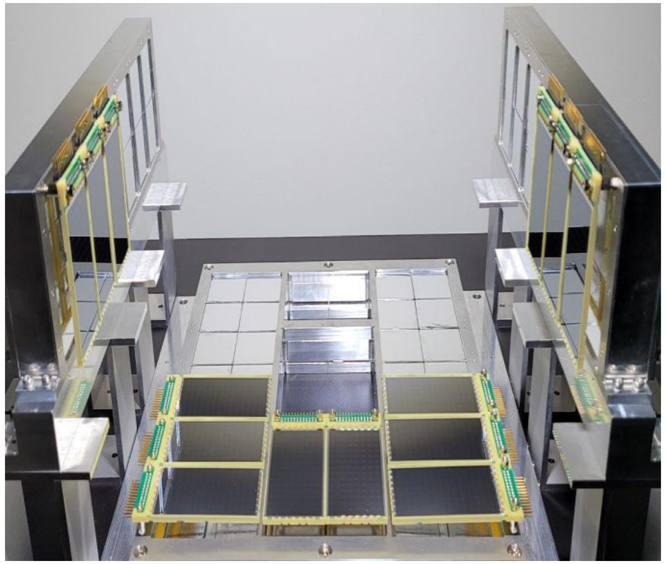
TexAT_V2 : Active target TPC at Texas A&M Univ.

upgraded



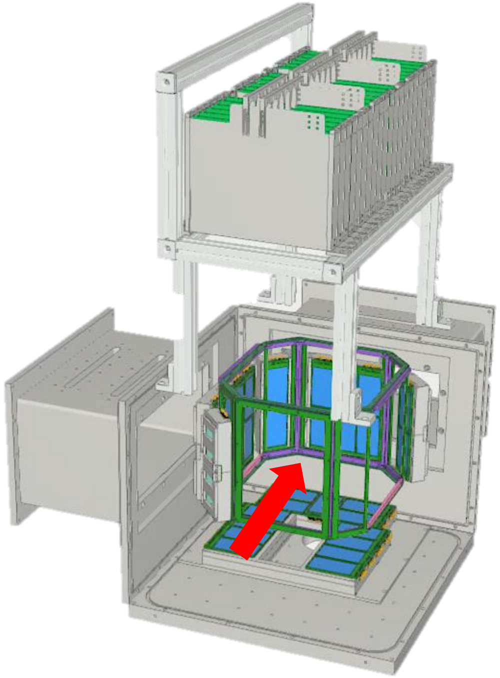
$He:CO_2$=97% : 3% mixture gas
(380 torr at room temp.)





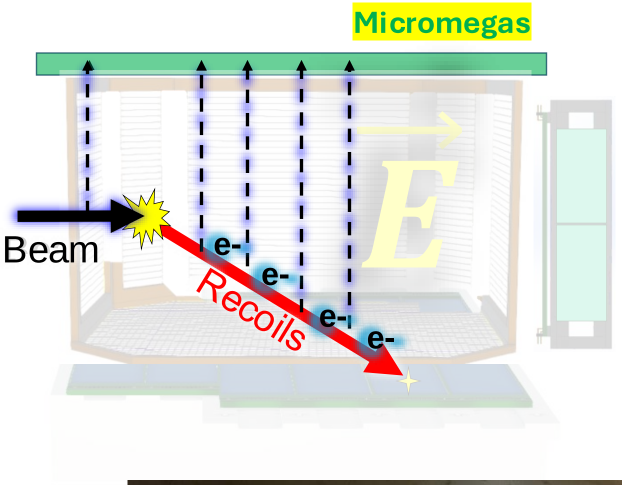
ATToM-X : Active target TPC for Multiple nuclear eXperiment

- **Components:**
  - **Field cage**
  - **Micromegas**
  - **Silicon and CsI detectors**
  - **Chamber, frames, Electronics(GET), DAQ, Softwares**
  - **5658 electronic channels in total**

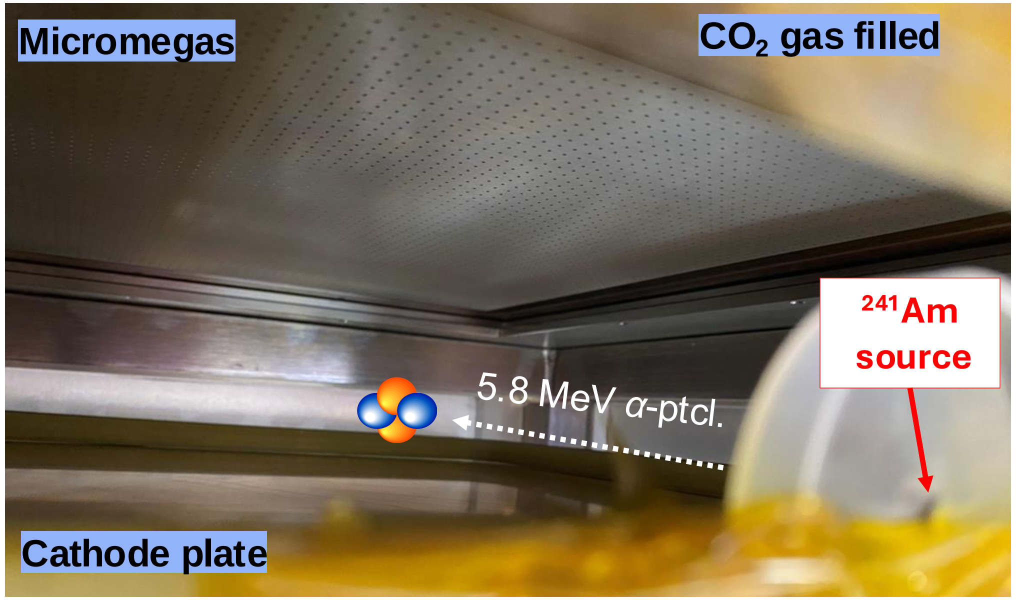


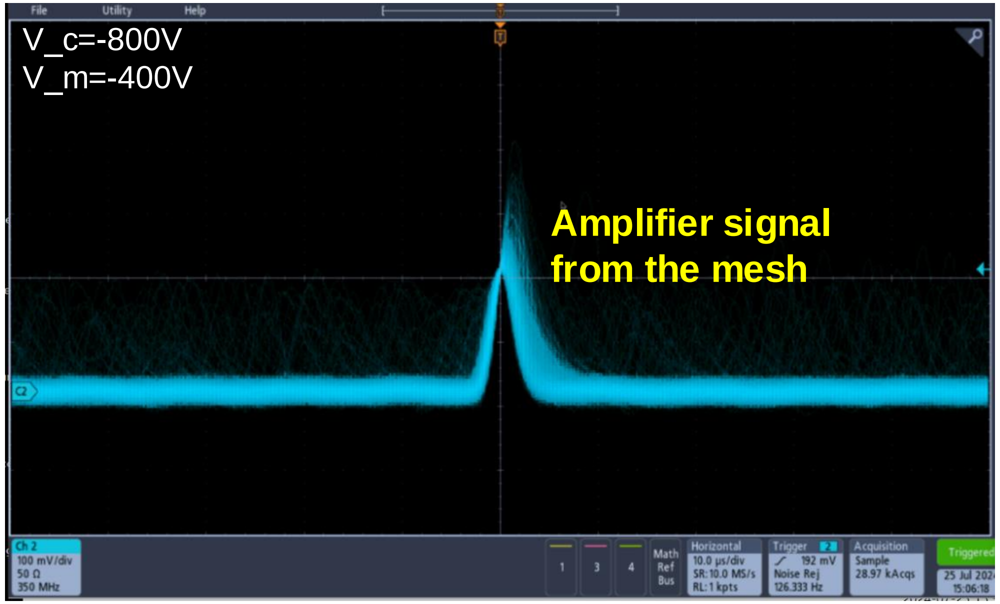
- **Dimensions :**
  - **Chamber : 504(X) x 417(Y) x 504(Z) mm^3**
  - **Wings for signal (ZAP) feed through : 236(X) x 270(Y) x 390(Z) mm^3**

Micromegas (MICRO MEsh GASeous detector system)



- **Tracking charged particles with readout pixels** *(beam, recoils, ...)*
- **Micromegas as a chamber flange**
- **Drift electrons from the ionization are amplified b/w mesh & readout.**
- **pixel size : 4 x 4 mm^2**
  - ✓ **Type-1 : Resistive** *(AsAd board protection from the spark)*
  - ✓ **Type-2 : Resistive + Capacitive sharing** *(~1mm position resolution expected)*




V_c=-800V
V_m=-400V

Amplifier signal from the mesh

Ch 2
100 mV/div
50 Ω
350 MHz

Horizontal
10.0 µs/div
SR: 10.0 MS/s
RL: 1 kpts

Trigger 2
192 mV
Noise Rej
126.333 Hz

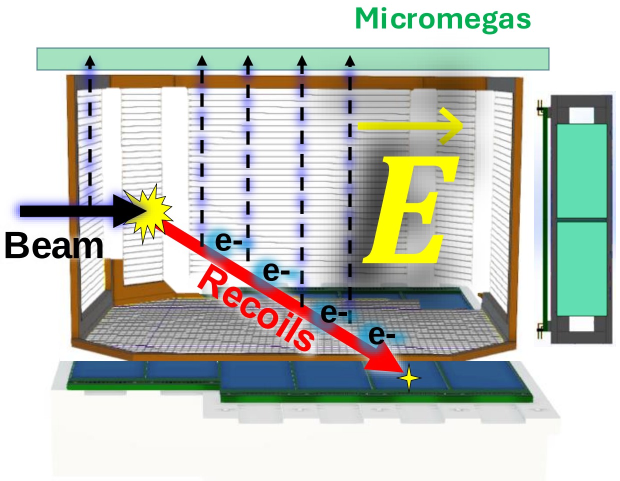
Acquisition
Sample
28.97 kAcqs

Triggered
25 Jul 202
15:06:18

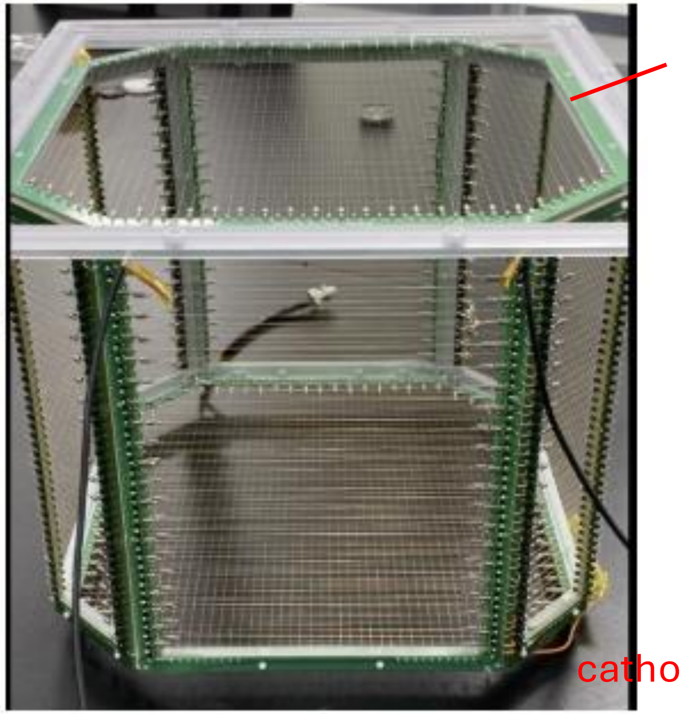
✓ **Checked analog signals on the mesh using a ^{241}Am α source and a cathode plate**

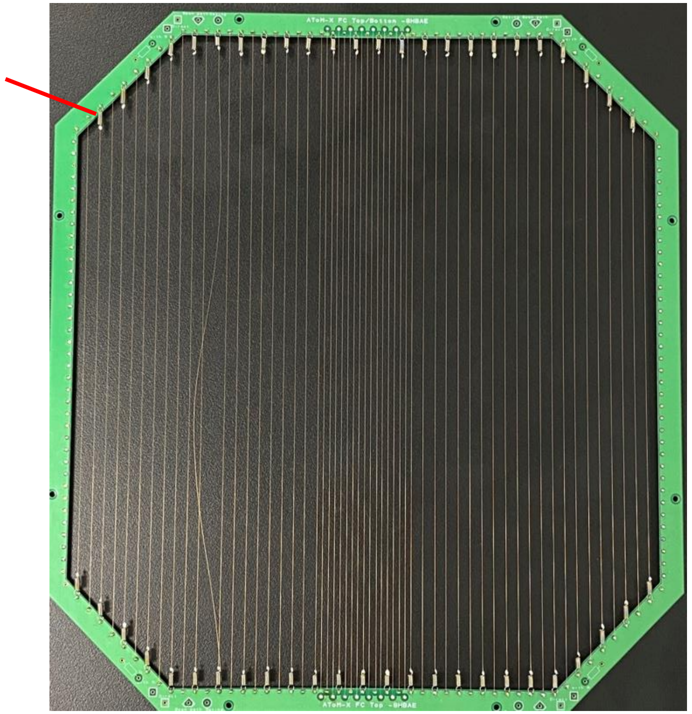
(taken from S. M. Cha)

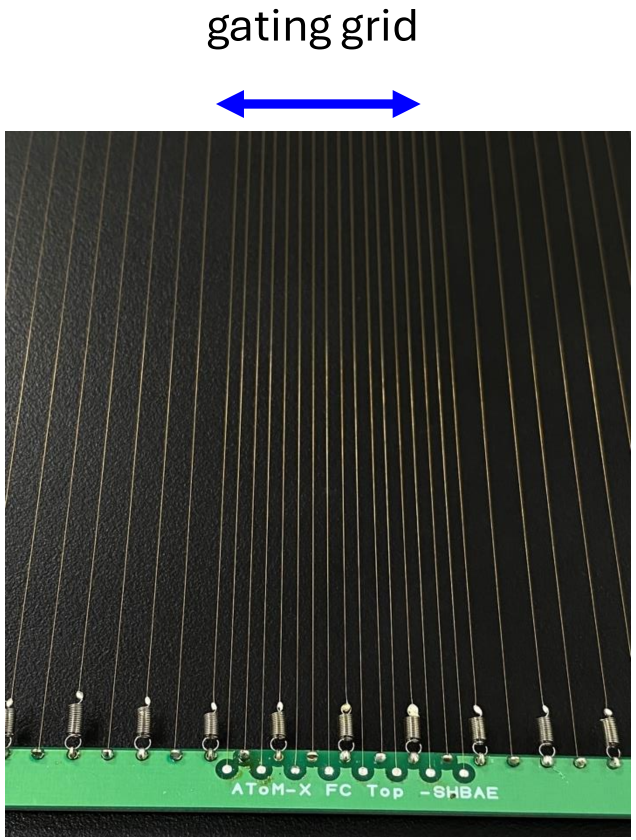
Field cage with Au-plated tungsten wires



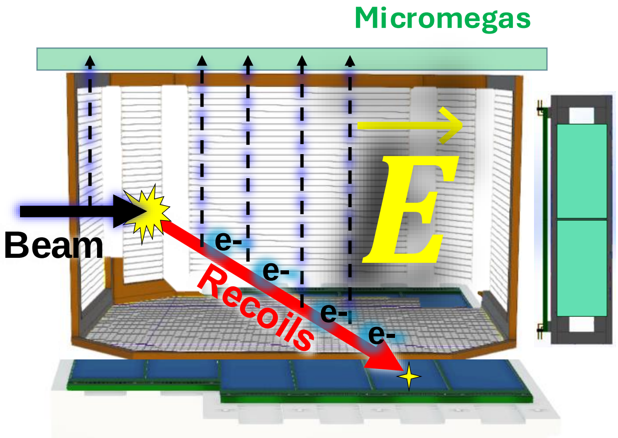
- Providing uniform electric field in the active volume
- cathode + anode + side planes (41 wires, 10mm gap)
- PCB boards + Polycarbonate frame
- All fabrication was done and the test with alpha source is on going.





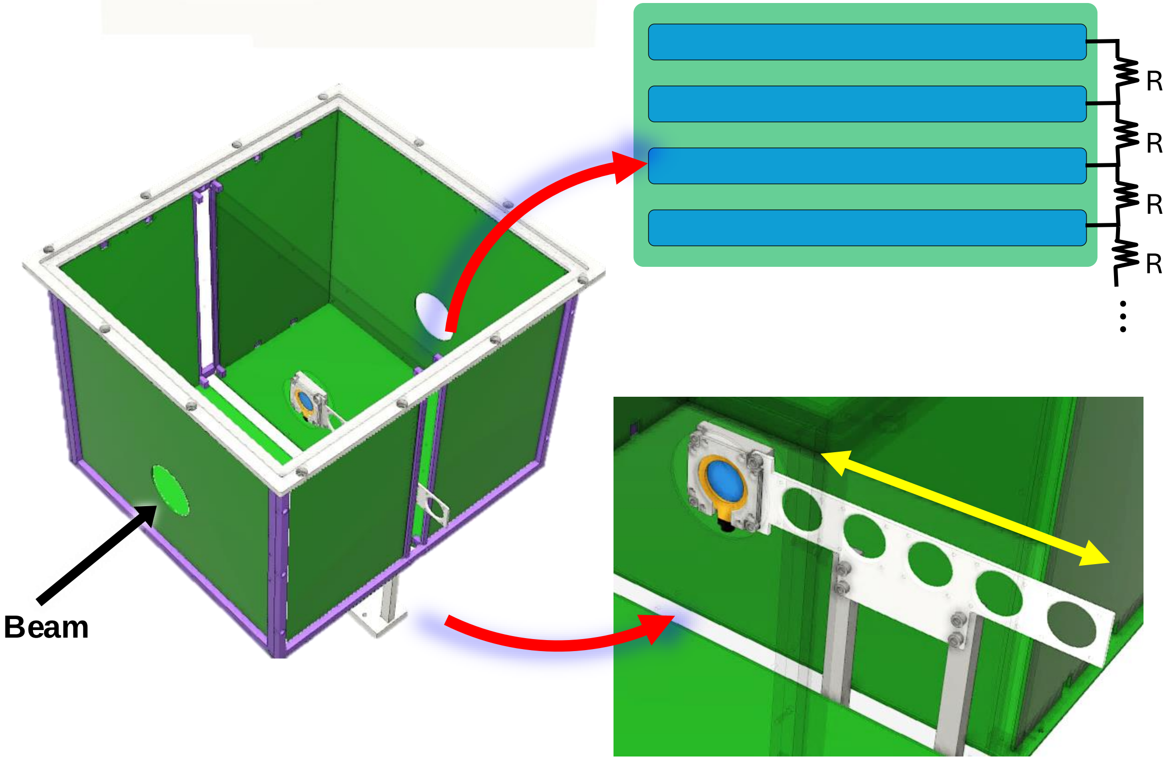


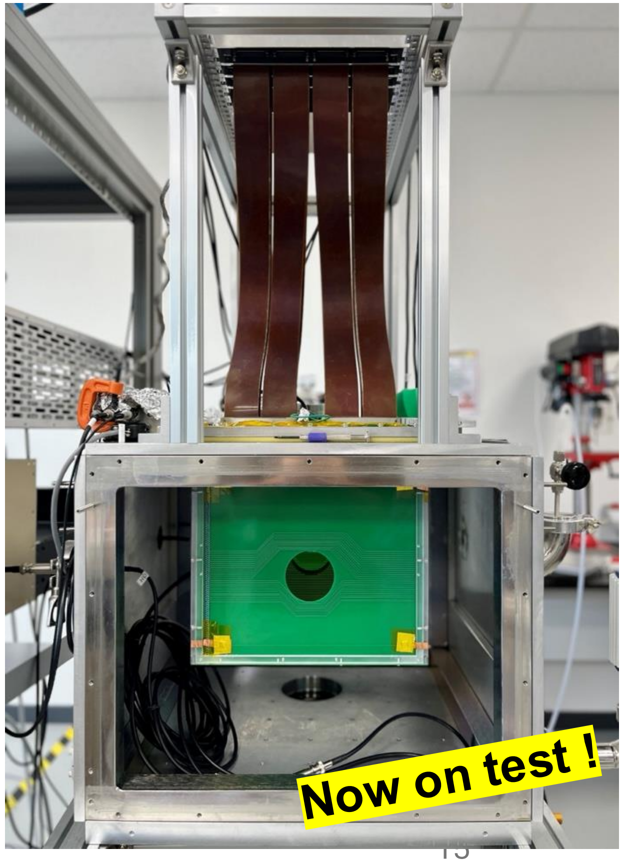
Field cage



- Providing uniform electric field in the active volume
- cathode + anode + side planes
- PCB boards + Polycarbonate frame

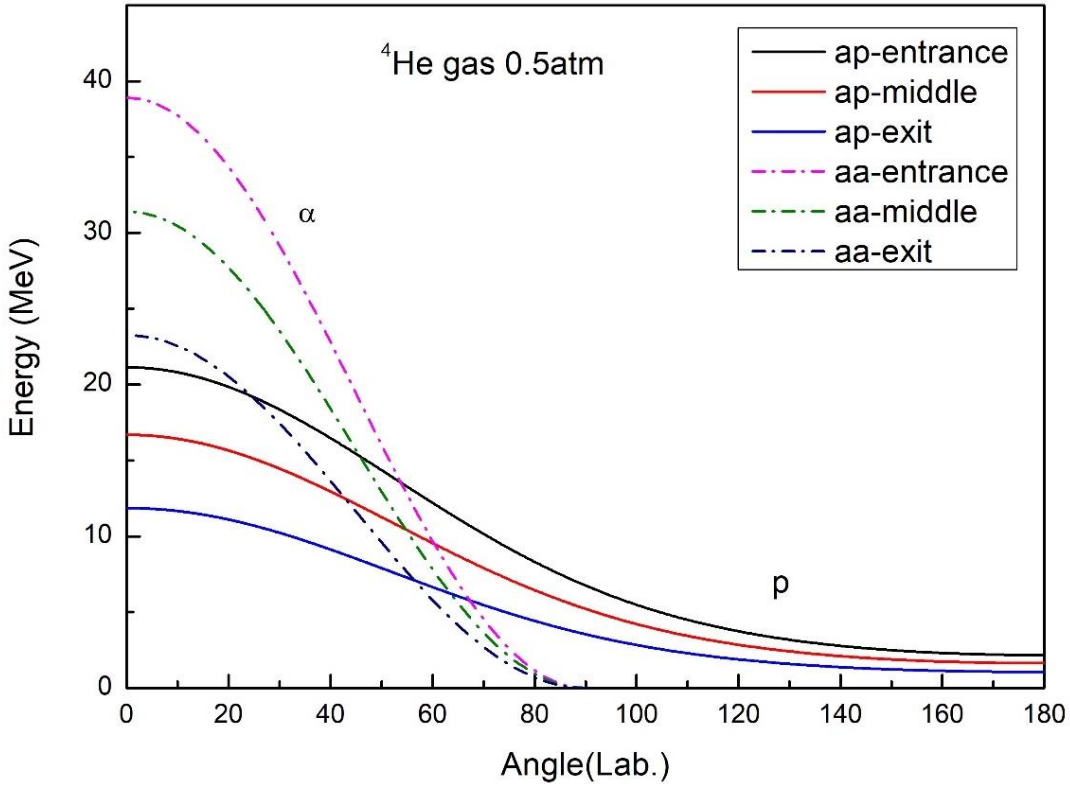
- Type-2 : Segmented copper plates on PCB
  ex) $^{12}C(p,p')^{12}C$, $^{3}He+^{208}Pb$, …





(taken from S. M. Cha)

Kinematics for $^{34}Ar + \alpha$

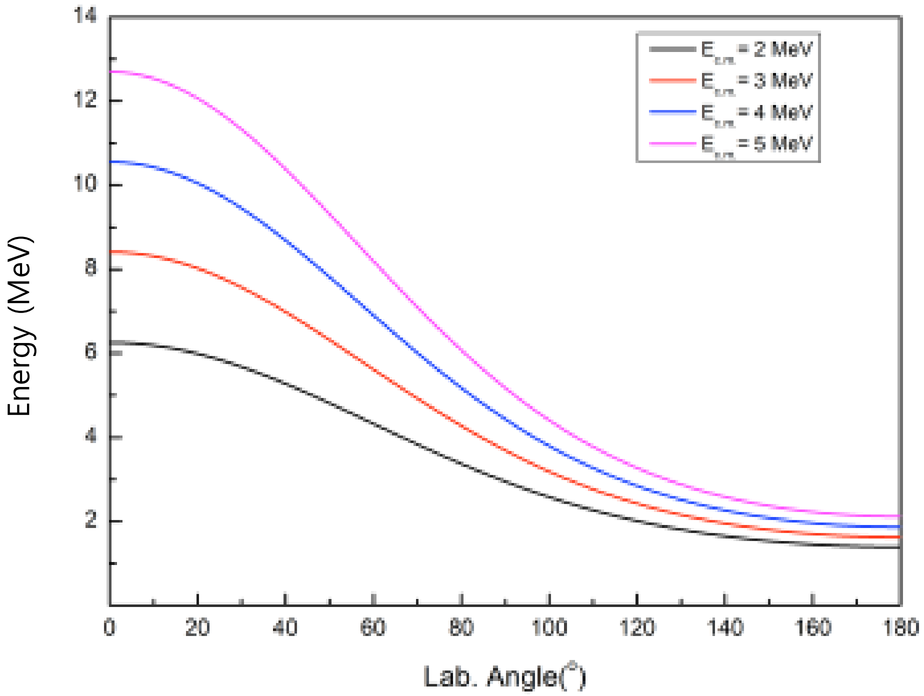


- For the PID, the recoiled particles (α and p) should reach Si detectors through ^{4}He gas.

- All alpha particles with $E_\alpha > 5$ MeV can reach Si detectors, but it is difficult to detect high energy alpha particles because the gain is set to protons.

Proton energy distribution from $^{34}Ar(\alpha,p)^{37}K$

2 MeV < $E_{c.m.}$ < 5 MeV



Most of protons from the reactions reach Si detectors.

$E_{c.m.}$ = 1 MeV

AToM-X

^{4}He :CO_2 =97%:3%

(Z=190mm)

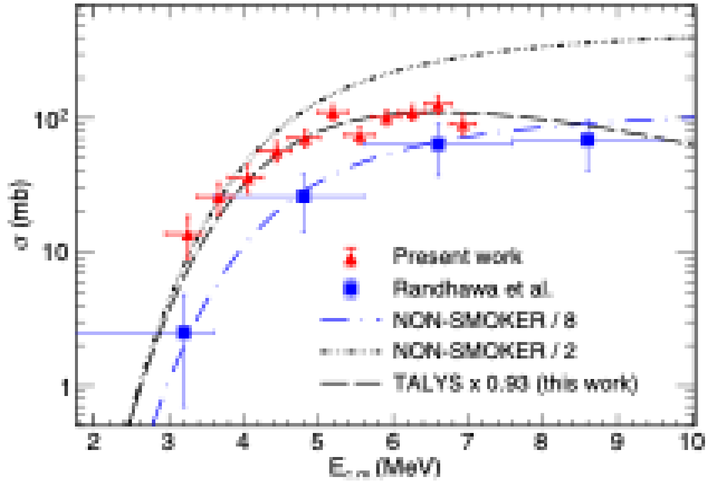
Angle	Ep(Mev)	$E_{remained}$(MeV)
0	4.2	4.04
50	3.4	3.18
100	2.0	1.73
150	1.3	0.59

Most of protons can reach Si (1mm-thick).

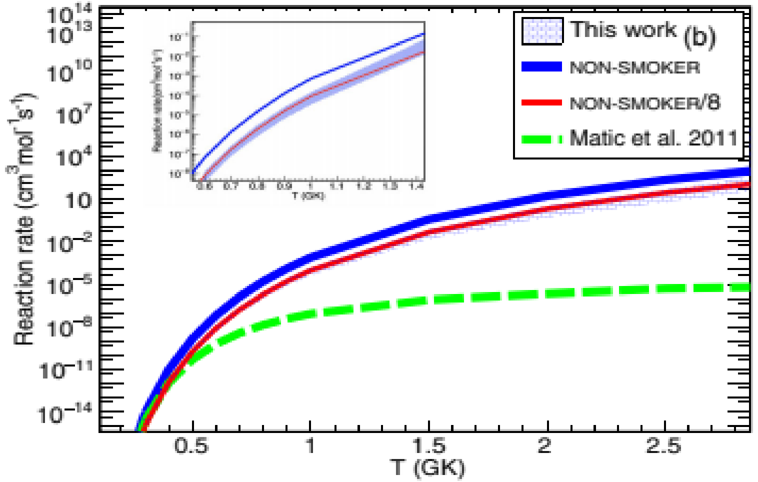
Even very few events near $E_{c.m.}$=1 MeV are mostly detectable by Si.

Reaction rate : How to access very low energy (astrophysical) region?

Even we can have full angle coverage using AT-TPC, it is very difficult to see the meaningful events less than $E_{c.m.}$~1MeV



H. Jayatissa et al., Phys. Rev. Lett. 131, 112701



J. S. Randhawa *et al.*, PRL 125, 202701(2021)

^{22}Mg(α,p)^{25}Al using AT-TPC (performed at NSCL and ANL)

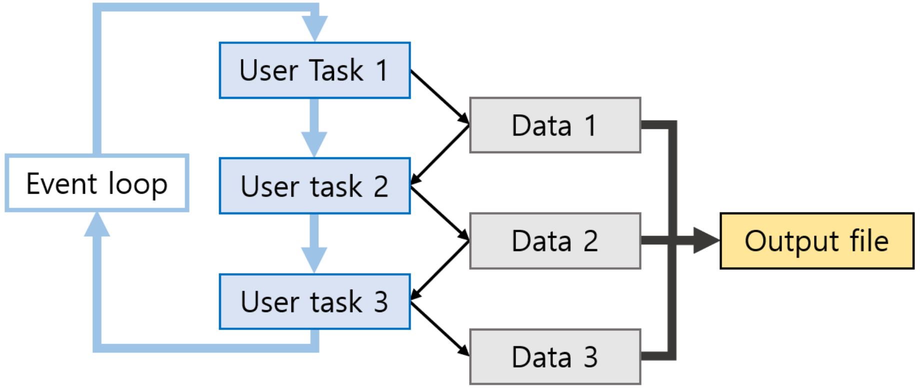
Gamow window: E_G~ 2.4 MeV (Δ=1.5MeV) at T_9~2)

- The lowest measured points are located at upper end of Gamow window for a 2GK temperature.
- Extrapolation to lower energies was performed for obtaining the reaction rate at the relevant temperature range.
- TALYS code was optimized for reproducing the experimental data. => Modified αOMP values were implanted into TALYS.
- (Even if we do not see protons at very low energies) we can try to achieve the cross section data using extrapolation if we measure protons even near the Gamow window.

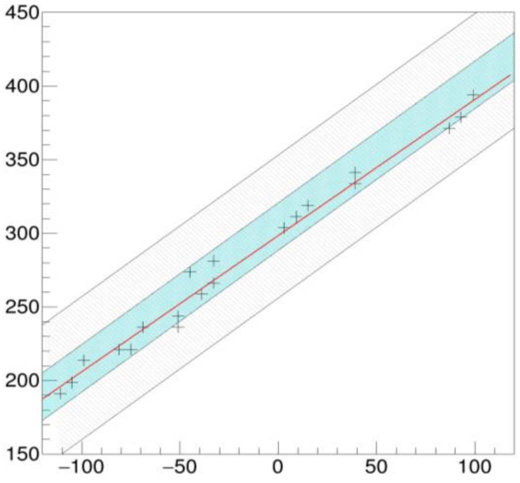
Analysis and Simulation

- Analysis software package : LILAK (Low and Intermediate energy nucLear experiment Analysis toolKit)
  - ✓ task-based analysis toolkit
  - ✓ contains general classes for MC simulation, reconstruction (pulse shape analysis, Hough transform, RANSAC, ...), and so on.

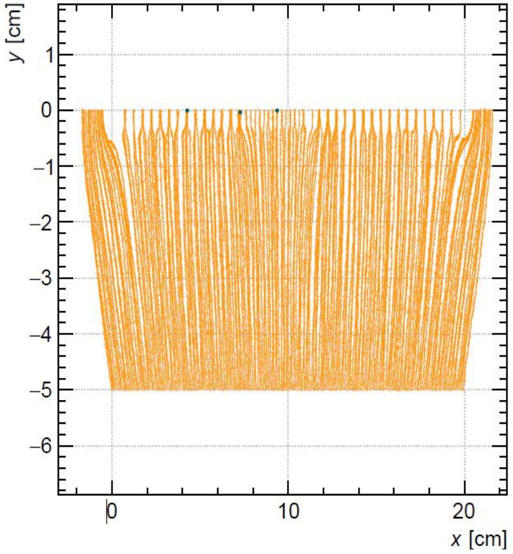
=> J. W. Lee (CENS)



Event loop
User Task 1
User task 2
User task 3
Data 1
Data 2
Data 3
Output file



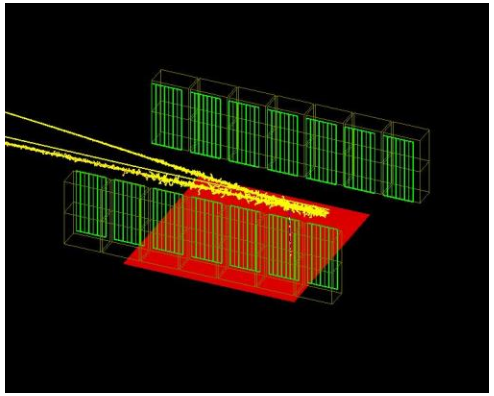
Track reconstruction using Hough transform



Garfield simulation for electron drifts with gating grid on the field cage

- Garfield++ simulation for electric field (2D & 3D) and electron drift.
- GEANT4 & NP tool simulation for kinematics and detection efficiency.

=> S. K. Do (Korea Univ.)



AT-TPC
(Active Target-Timing Projection Chamber)

A good tool for low energy nuclear physics for studies of exotic nuclei

⬇

Providing kinematics of interaction observables for data analysis through its ability of 3D-particle tracking

➡

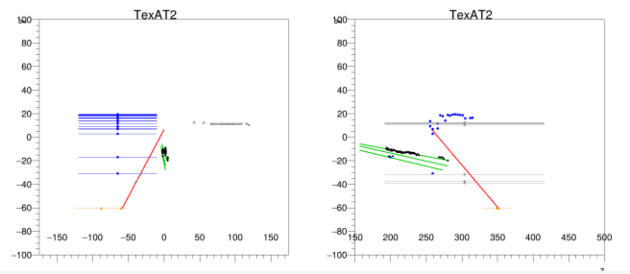
However, rare events of interest & a large backgrounds limit accuracy and effectiveness of the data analysis

⬇

In general, the method to build track and vertex reconstructions in AT-TPC for the data analysis can be divided into a traditional approach using a mathematical model and a data-based machine learning method.

LILAK (Low- and Intermediate- energy nucLear experiment Analysis toolKit)

The track & vertex reconstruction algorithm in LILAK using Hough transform needs to establish an appropriate model and decide its parameter for events in a TPC chamber

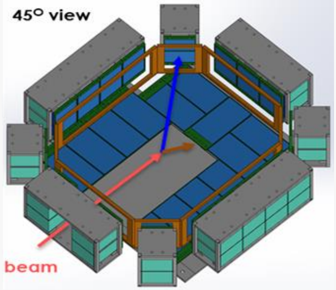


Particle tracks are found using LILAK for data obtained by TeXAT (Texas AT-TPC).

AToM-X (Active Target for Multiple nuclear eXperiments)

Unlike LILAK, a deep learning technique will be applied to the particle identification for the data analysis in the ^{34}Ar(α,p)^{37}K experiment using AToM-X detector in which it trains over simulated events without a complicated tracking model.

→ It is expected to give a more effective way



AToM-X

(taken from J. Y Huh)

Planned experiments using AToM-X

- **Direct measurement of astrophysically important reactions**
  - **^{34}Ar(α,p)^{37}K** — A. Kim *et al.*, (RIBF NP-PAC-24, **accepted**)
  - **^{10}Be(p, α)^{7}Li** — M. J. Kim *et al.*, (RIBF NP-PAC-25, **accepted**)
- **Elastic/Inelastic scattering**
  - **^{12}C(p,p')3α reaction for triple-α process** — J.W- Lee *et al.*, (JAEA PAC2024, **accepted**)
- **Direct measurement of nuclear fusion reaction of exotic nuclei**
  - **^{6,8}He + ^{40}Ar fusion, …**

Future plans

1. RI beam(^{34}Ar) production run will be performed in April or September.

2. Main run for 12 days will be performed at the beginning of 2025.

3. αOMP will be extracted from the experimental data of alpha elastic scattering on ^{36}Ar and ^{40}Ar.
(=> T. S. Park)

4. The proposal for the measurement of ^{40}Ar + α at KOBRA will be submitted.

5. The study for measurement of (α,p) reaction on ^{30}S using AToM-X will be prepared.