Study of alpha clusters in 12C and 16O using RAON and Recent Activities for China-Korea collaboration

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Nuclear Astrophysics Experiments with HIAF Meeting

Huizhou, Sept 3, 2025

RAON - RIB facility in Koea

- **R**are Isotope **A**ccelerator complex for **O**N-line **E**xperiments
  - *RAON* means joyful in Korean
- Located in Daejeon
- Started operation in 2024
- Second year (2025) run will begin very soon with stable beams of Ne-20 and Ar-40 beams at low energy around 10 MeV/u

2025 CALL FOR PROPOSALS & LETTERS OF INTENT

January 10, 2025 to February 20, 2025
Institute for Rare Isotope Science
Asia/Seoul timezone

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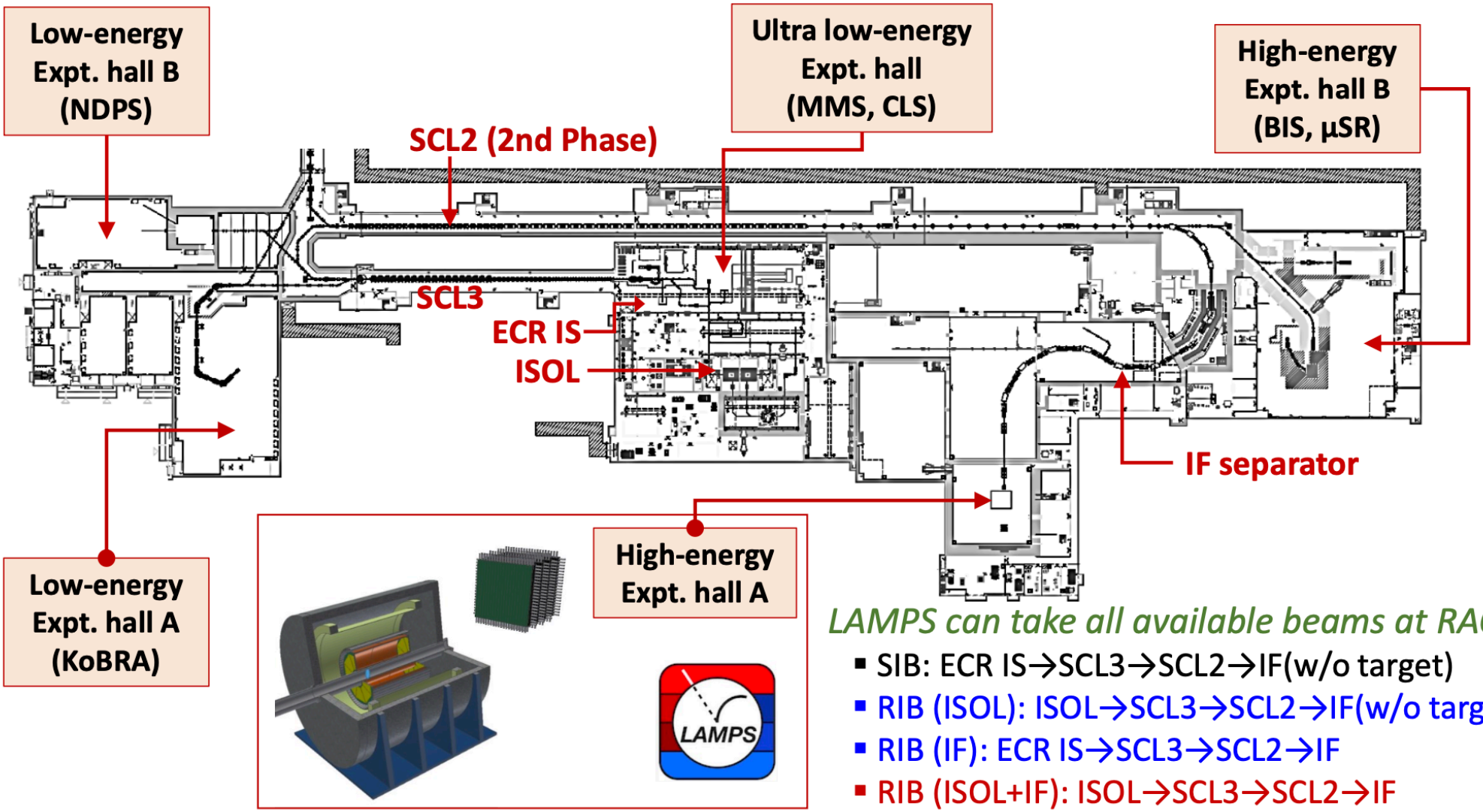
Overview
2025 users Registration
Call for Proposals
Facility Information
KoBRA
MRTOF-MS
Cyclotron
CLaSsy
NDPS
User's Guide

CALL FOR PROPOSALS & LETTERS OF INTENT

The Institute for Rare Isotope Science (IRIS) invites proposals for beam time for domestic Korea users. Proposals accepted should be able to run in RAON beam time periods that will be scheduled in 2025 and 2026. These are expected to be three(3) months from September to November in 2025 and five(5) months in 2026.

The stable beams available in 2025 will be Ne-20 and Ar-40 accelerated by the superconducting linac SCL3 at energies of ~18 MeV/u or less with an intensity of 10^5 ~ 10^10 pps. Proton beams from 40 to 70 MeV can be provided by the cyclotron with a beam power of up to 10 kW. Reaccelerated RIB of Na-25 will be available at ~18 MeV/u or less with an intensity of ~10^5 pps.

LAMPS experiment

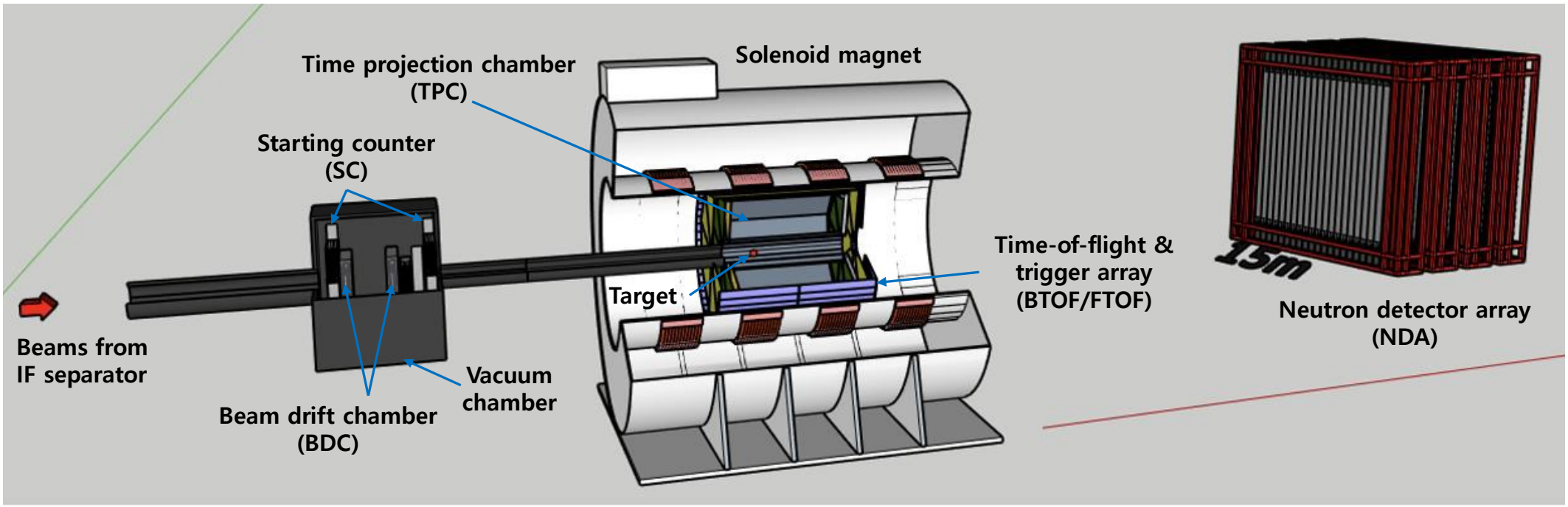


LAMPS can take all available beams at RAON!

- SIB: ECR IS→SCL3→SCL2→IF(w/o target)
- RIB (ISOL): ISOL→SCL3→SCL2→IF(w/o target)
- RIB (IF): ECR IS→SCL3→SCL2→IF
- RIB (ISOL+IF): ISOL→SCL3→SCL2→IF

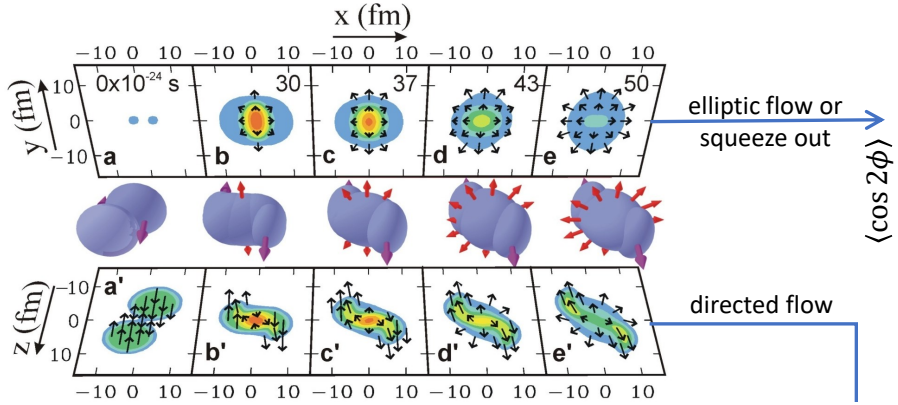
- Low energy ALMPS experiment for ~10 MeV beam
- High energy LAMPS experiment for ~100 MeV beam (SCL2 upgrade in future)

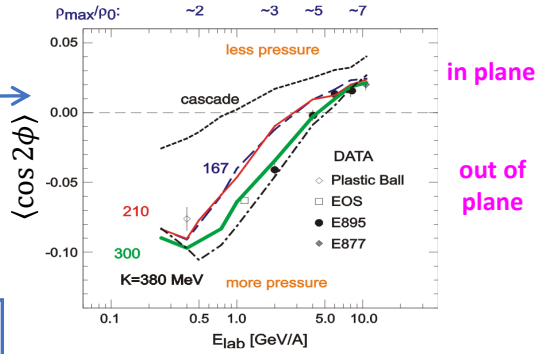
High Energy LAMPS experiment



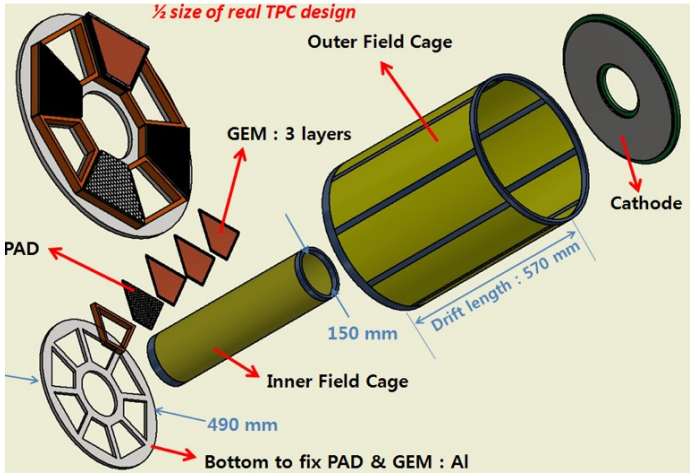
- **LAMPS**: **L**arge **A**cceptance **M**ulti-**P**urpose **S**pectrometer
  - TPC with ~3π sr acceptance for tracking charged particles
  - Beams with energies up to 250 MeV/u for ^{132}Sn and intensity as large as 10^8 pps
  - *Useful system not only for nuclear EoS, but also for nuclear structure studies*

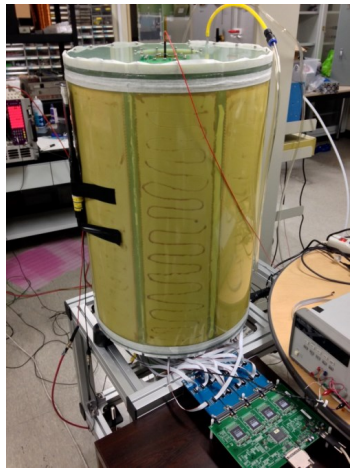
Danielewicz et al.,
Science 298,1592 (2002)

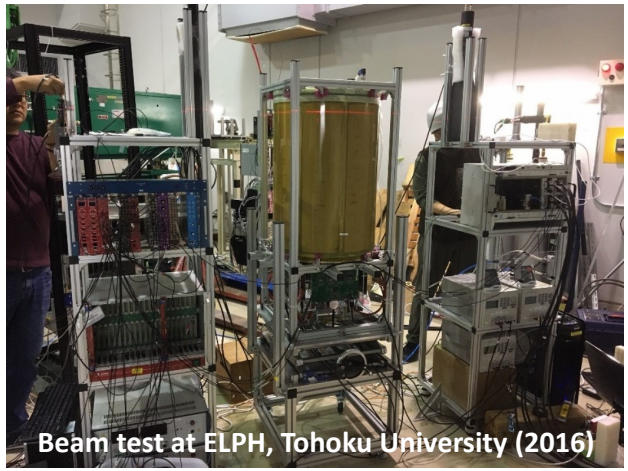




High Energy LAMPS experiment





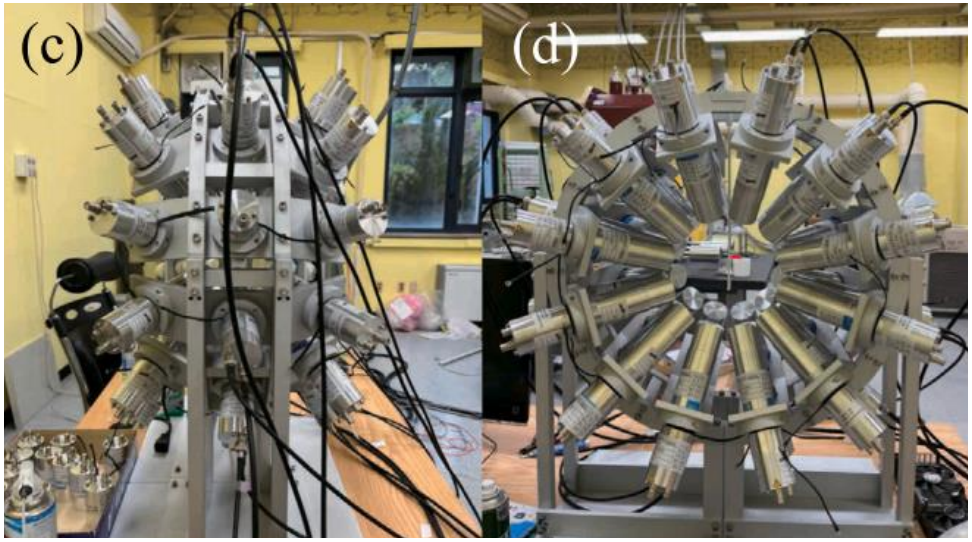

Beam test at ELPH, Tohoku University (2016)


Assembled detector system at the Sejong Campus of Korea Univ.

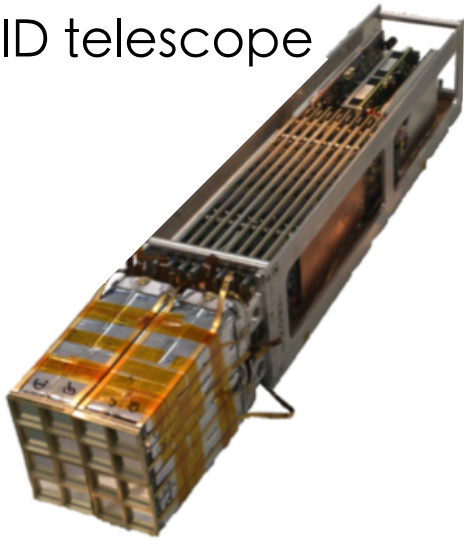

First station assembled at the high-energy experimental hall of the RAON site

Low-Energy LAMPS experiment

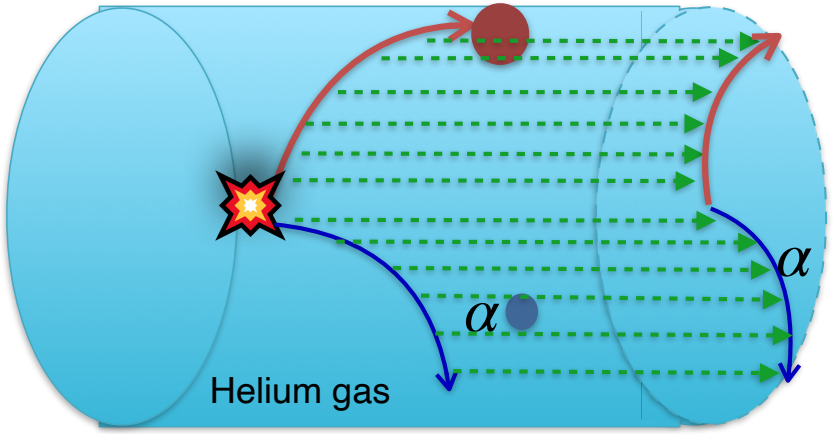
LaBr3 gamma detector w/ precise



Silicon CsI PID telescope



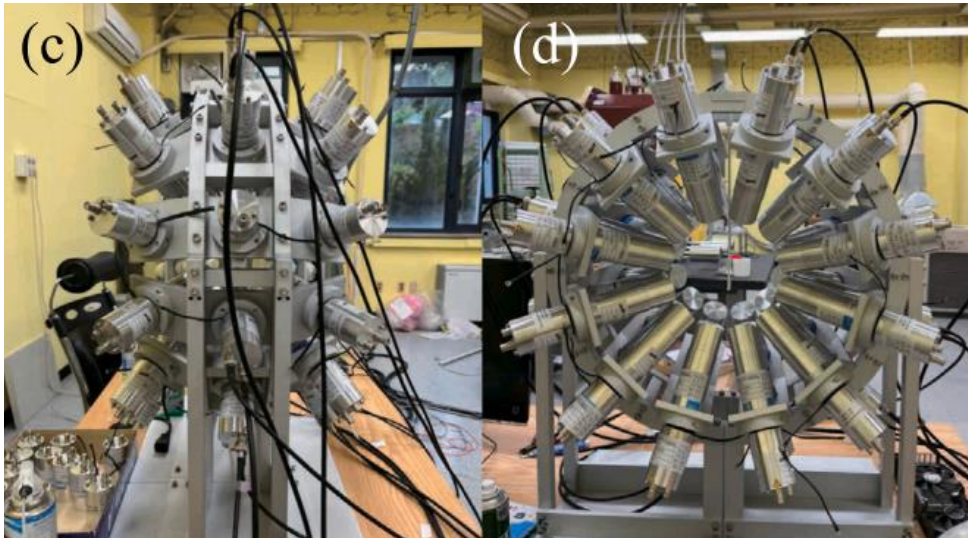
1.5 T SC magnet



Active target time projection chamber

Active Target TPC

LaBr3 gamma detector w/ precise



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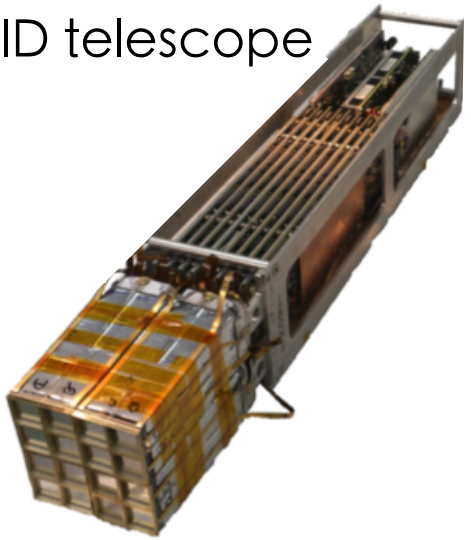
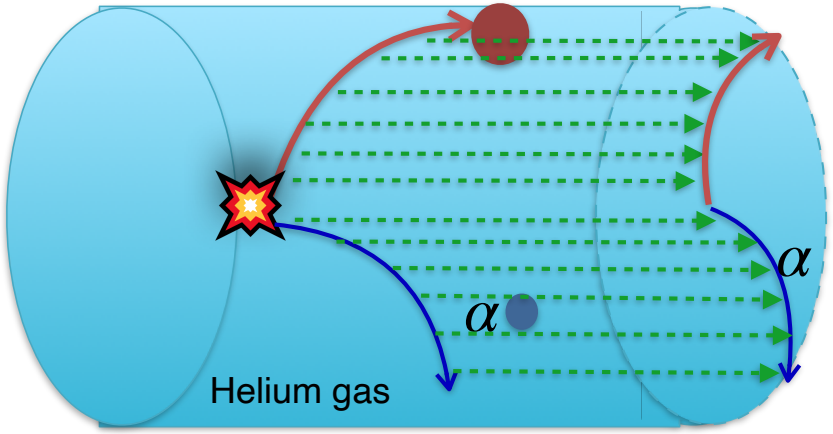


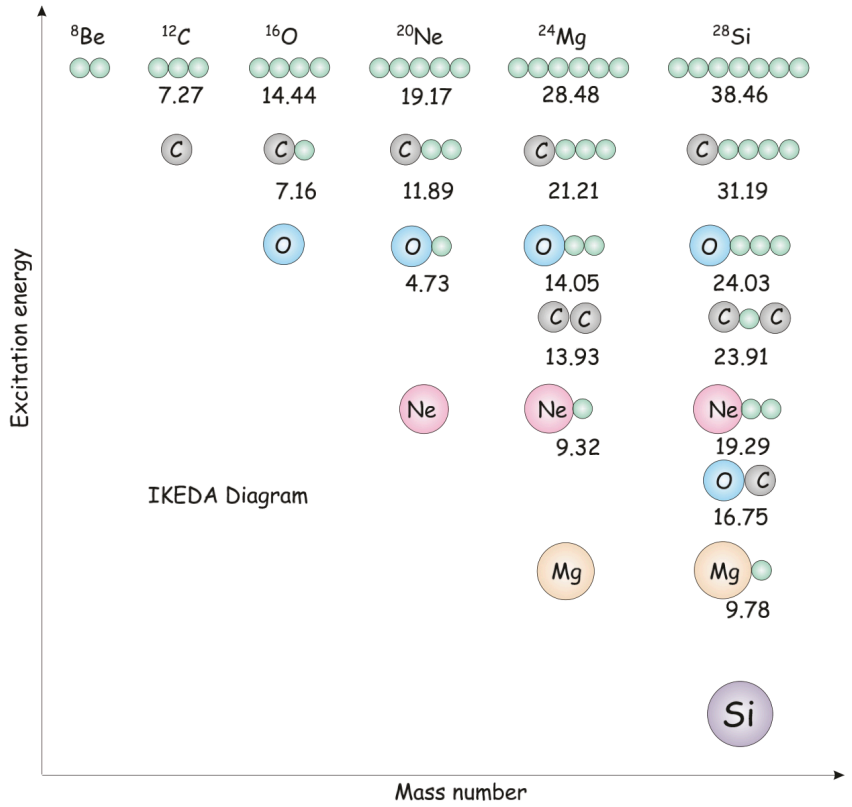
1.5 T SC magnet

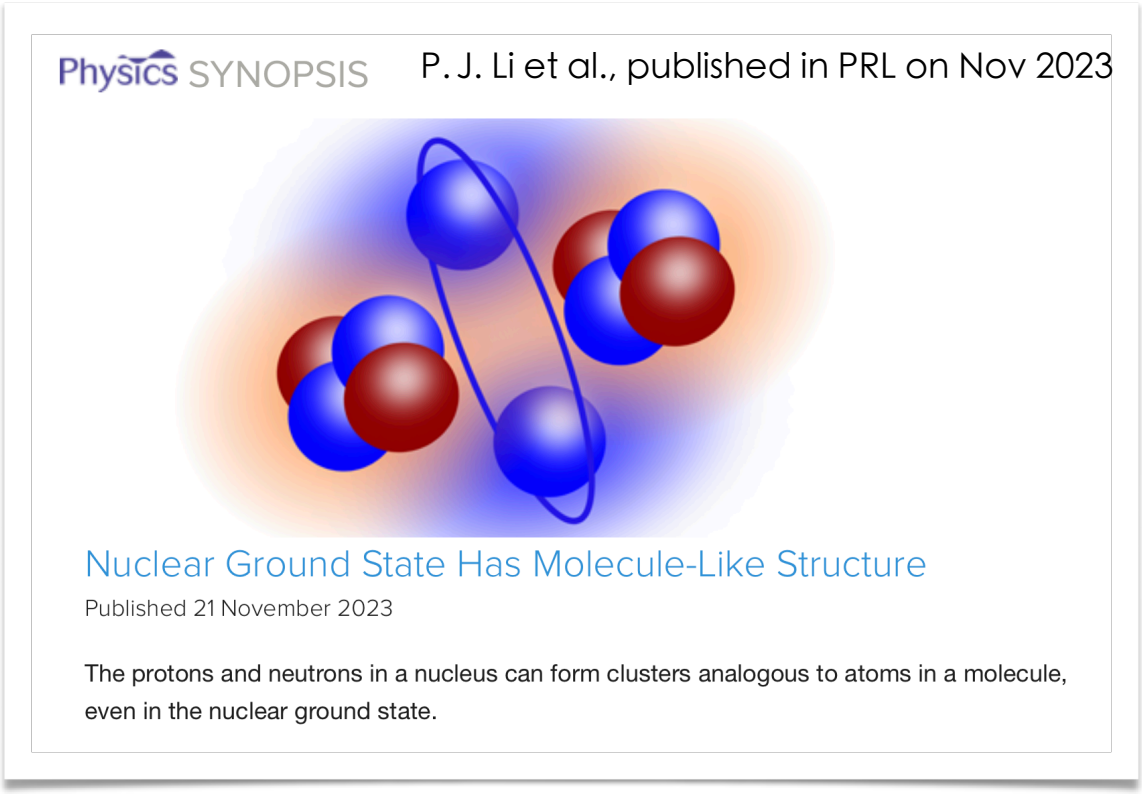
This talk will focus on this part!



Active target time projection chamber

Alpha clusters in nuclei



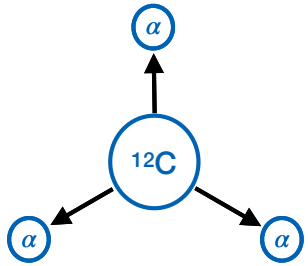


- Clustering phenomena in alpha-conjugate nucleus and molecular states with alpha cores are of interest for low-E LAMPS experiment
- Search for linear chain and exotic geometry of alpha clusters will be studied as well
- LMAPS AT-TPC is designed to measure alpha tracks all the way down to the collision vertex

Observables

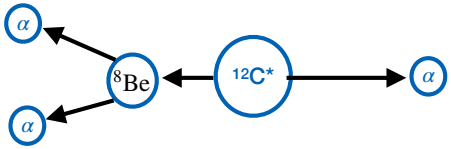
Search for Direct 3α decay

$^{12}C_{Hoyle} \rightarrow \alpha + \alpha + \alpha$



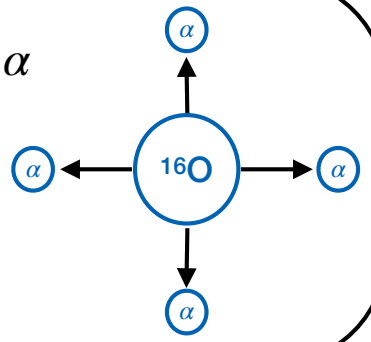
- Signature of BEC-like alpha condensate
- No statistically significant observation was made
- Major background is sequential decay

$^{12}C_{Hoyle} \rightarrow {}^{8}Be + \alpha \rightarrow \alpha + \alpha + \alpha$

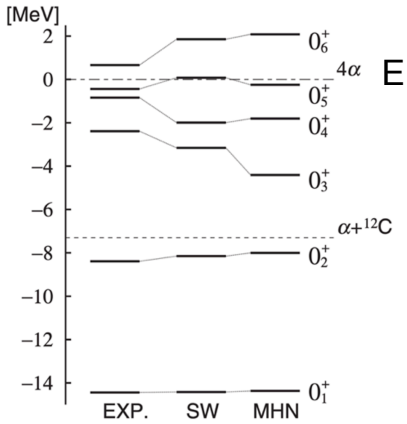


Search for Hoyle-like state in ^{16}O

$^{16}O* \rightarrow \alpha + \alpha + \alpha + \alpha$

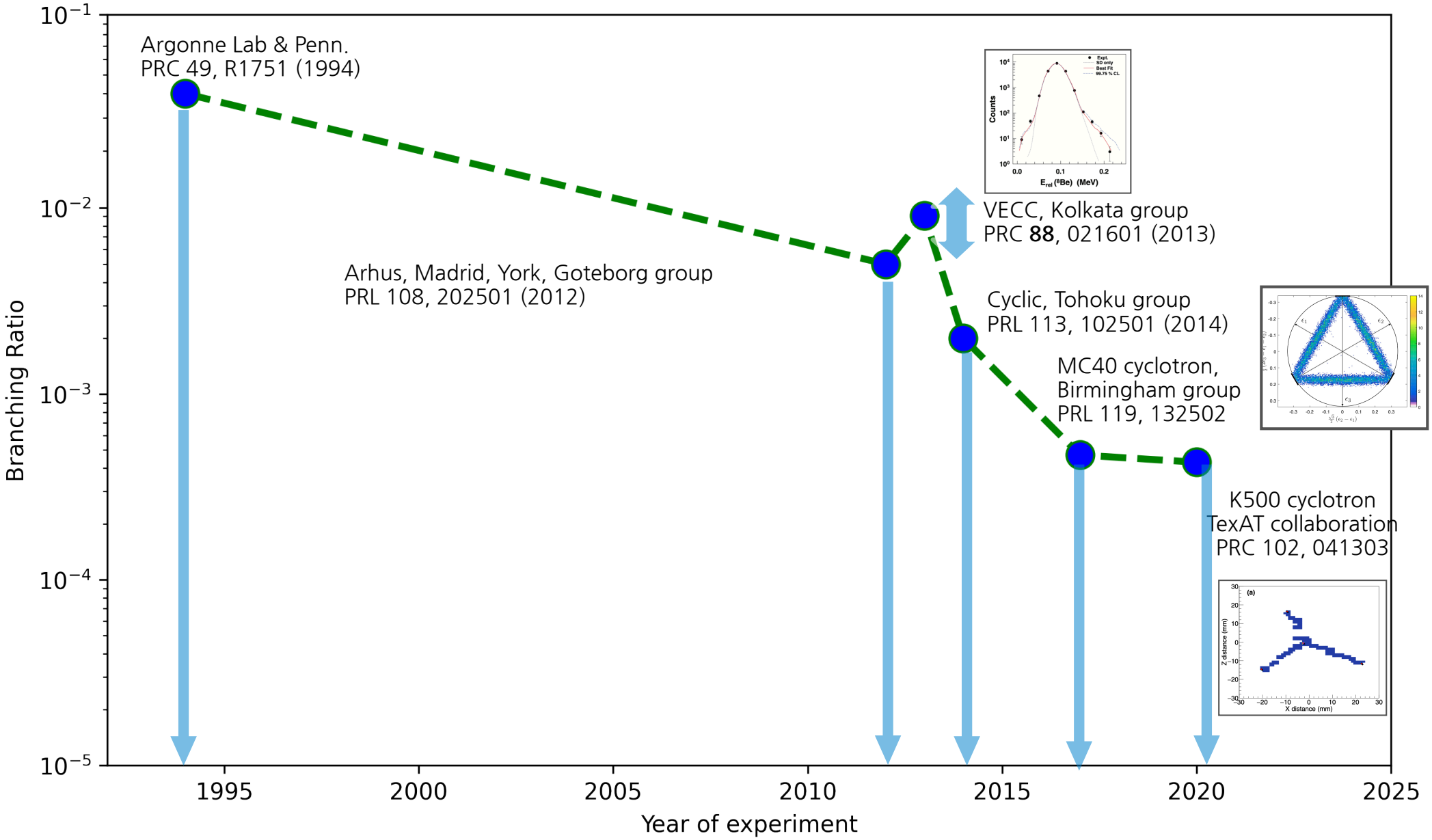


- Strong candidate for α-cluster of in ^{16}O
- If exists, 4α decay must be observed
- 4α threshold E = 15.1 MeV



E = 15.1 MeV

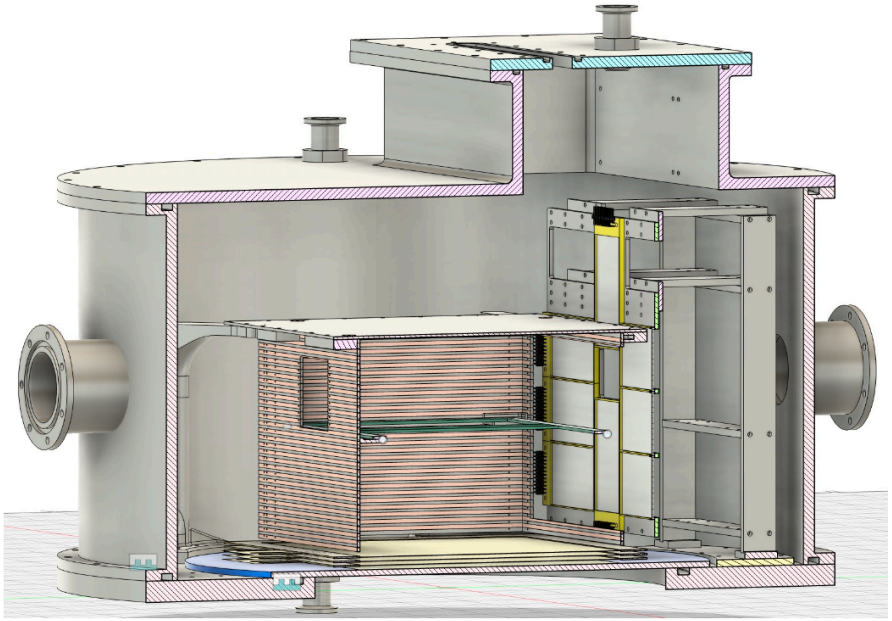
Branching Ratio of direct decay in Hoyle state

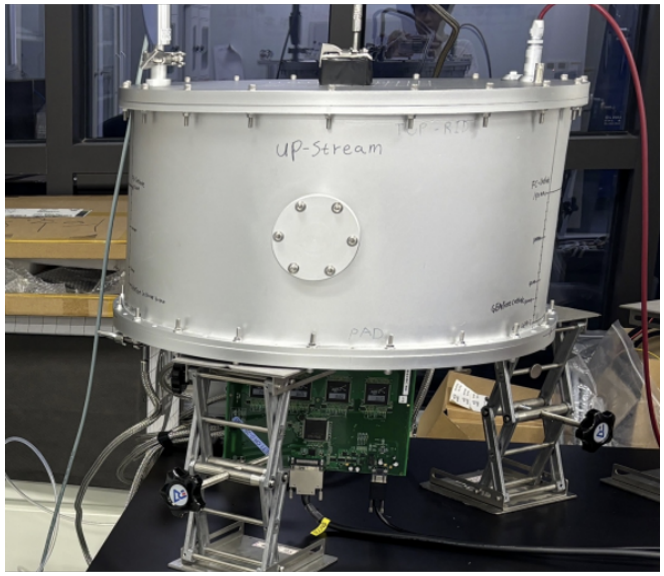


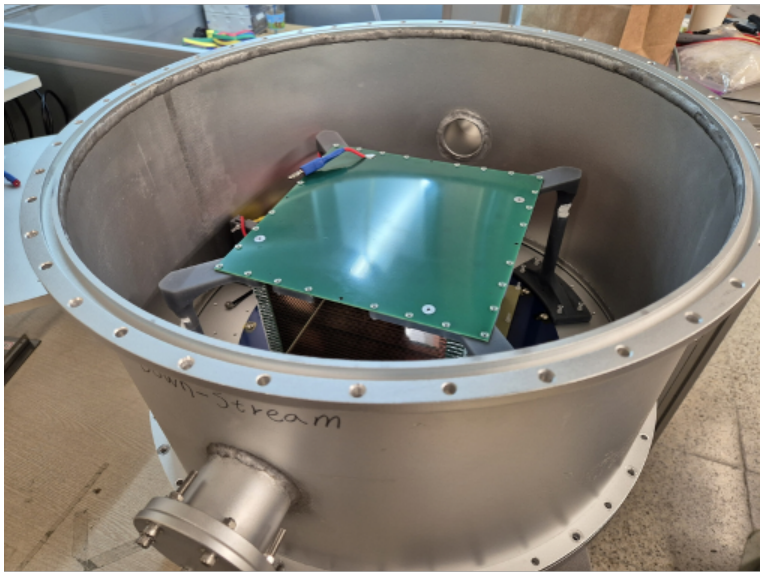
Dedicated detector

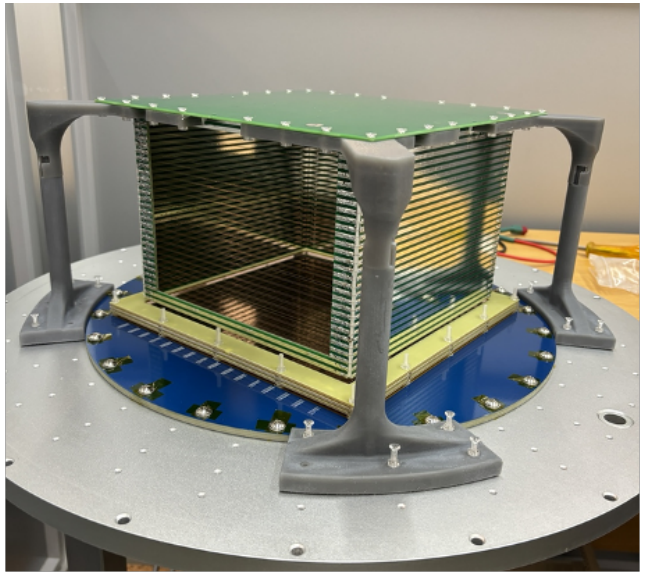
TPC-Drum

- Active target TPC (768 ch)
- 8 Si-CsI array (176 ch)
- He (90%) + CO_2 (10%) gas
- GET electronics (4 AsAd + 1 CoBo)









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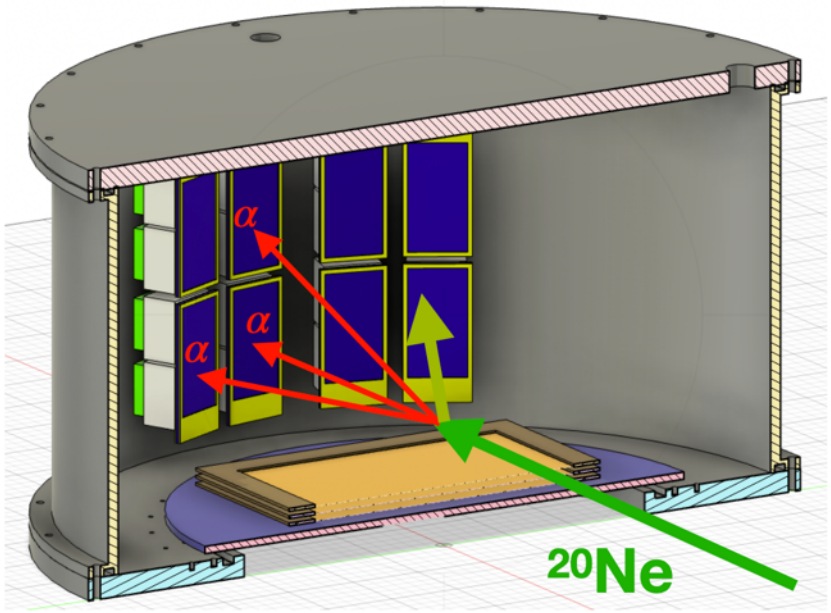
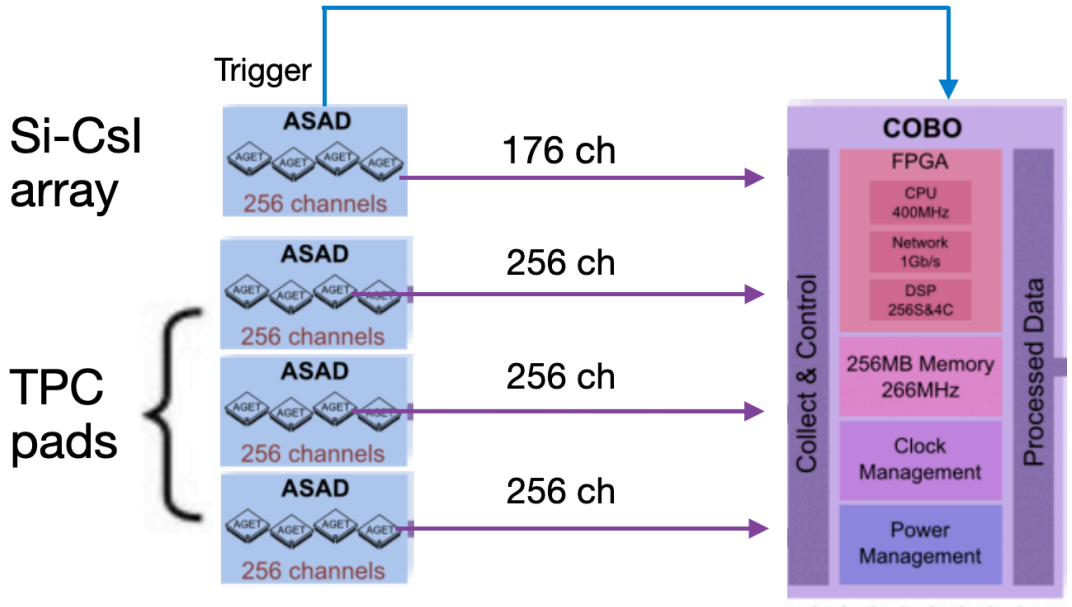
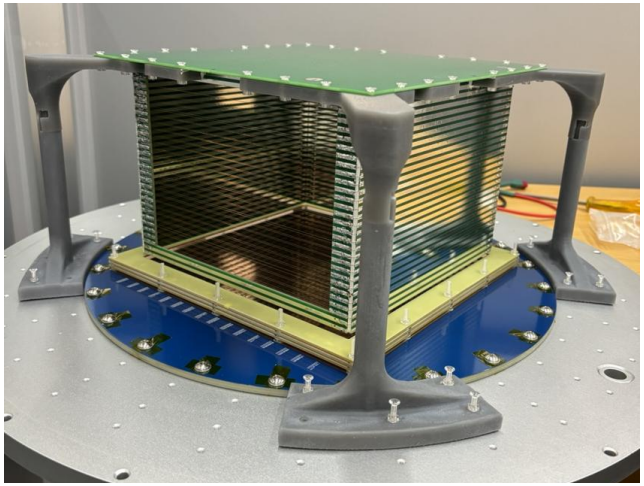
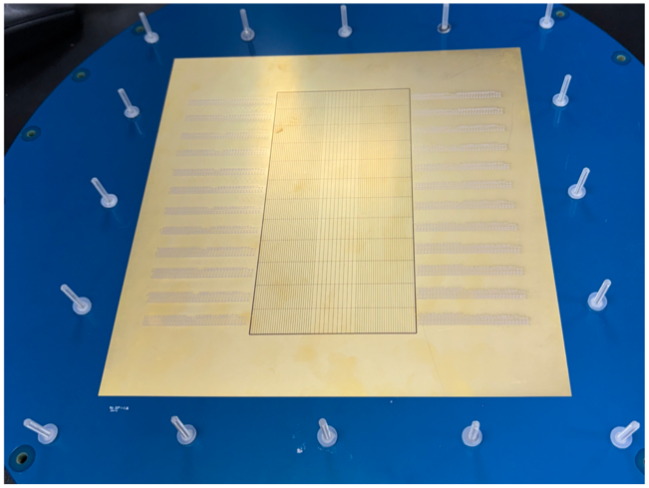


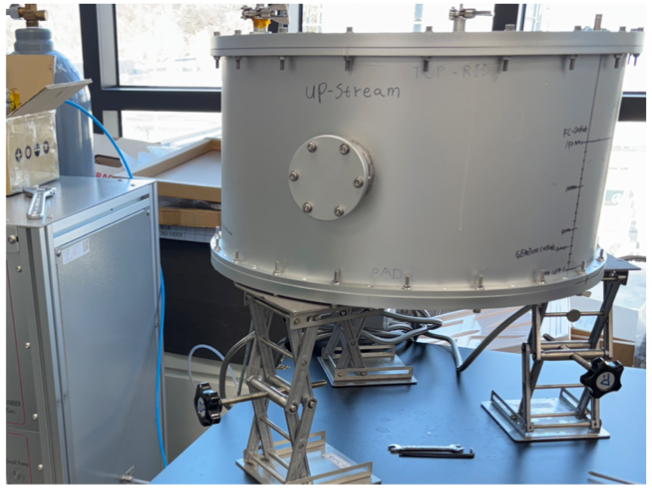


- Collision system : ^{20}Ne + α at 10 MeV/u
- The detector must measure multiple α's with high precision
- Energy will be measured using Si (thickness = 1 *mm*)
  - Resolution for α is 40 - 50 keV
- Momentum vector will be determined by TPC part
  - A spatial resolution ~150 μm translates to an angular resolution of ~0.004 $mrad$

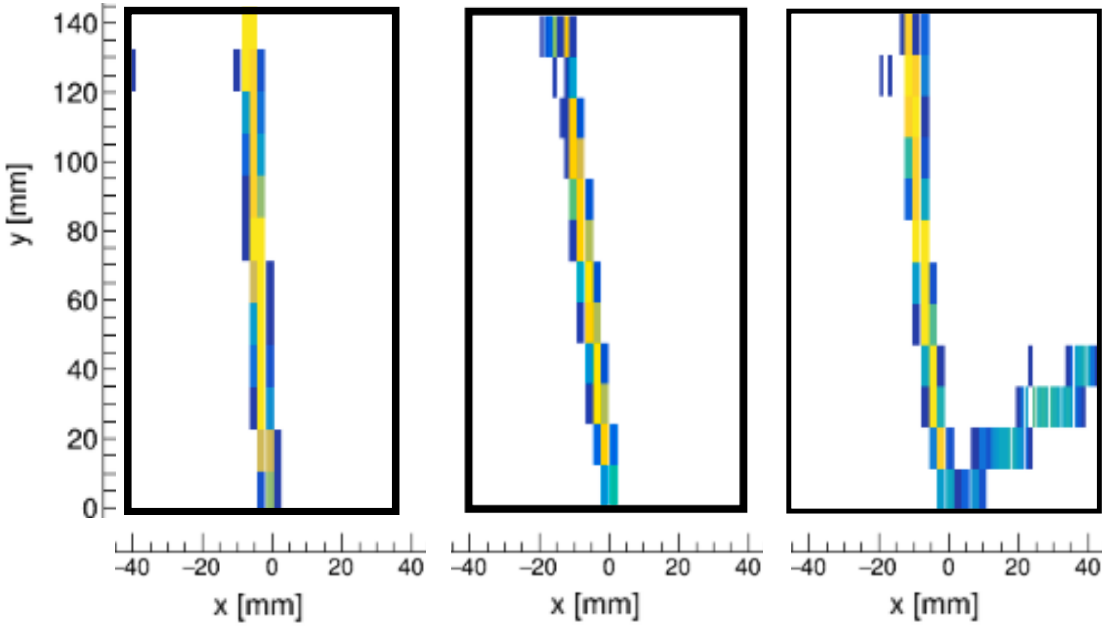
Detector status







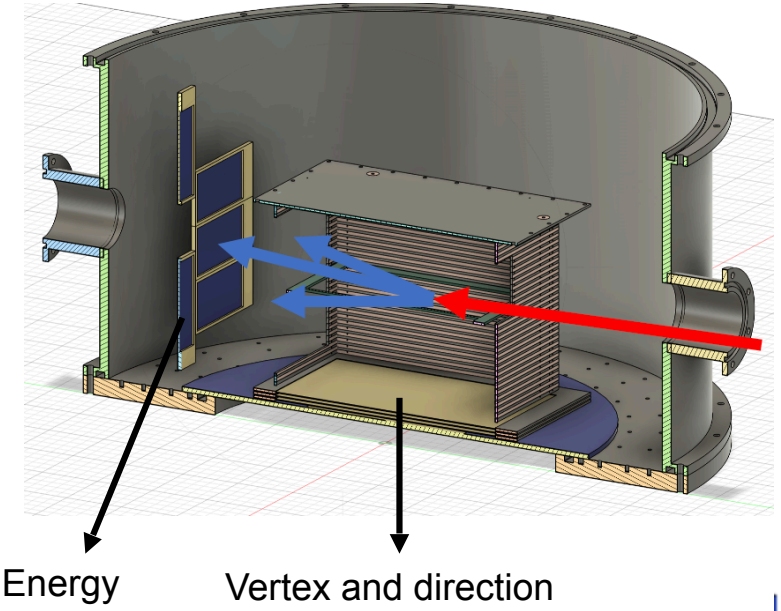
- Ready for experiment
  - Tested with cosmic ray and Am-241
  - Position-dependent calibration for triple-GEM gain using Fe-55
- Alpha track measurement
  - Am-241 (E = 5.44 MeV, 5.49 MeV)
  - Average track length is 11.5 cm, consistent with SRIM simulation
  - Cluster size in data is close to that of MC
    - Good grip for resolution!

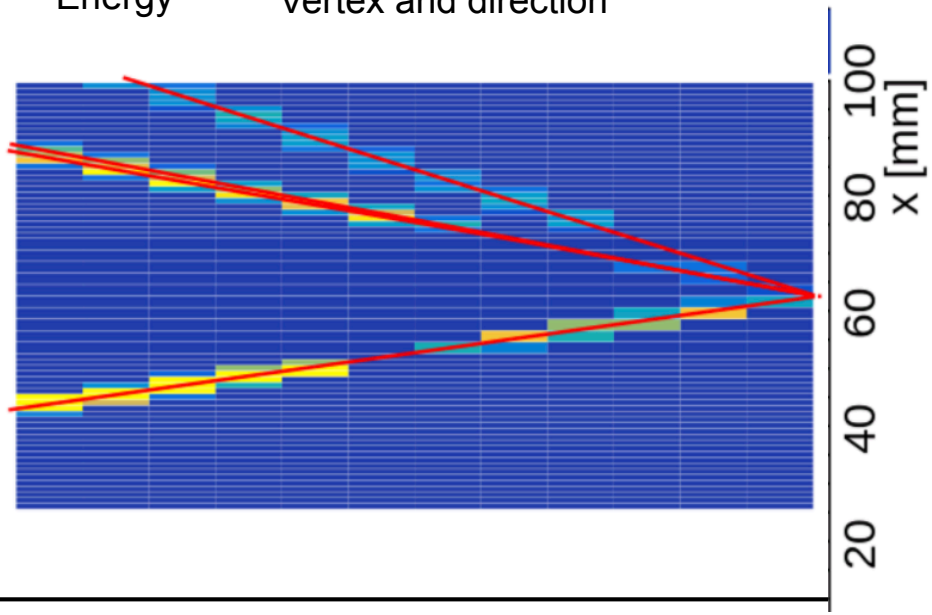


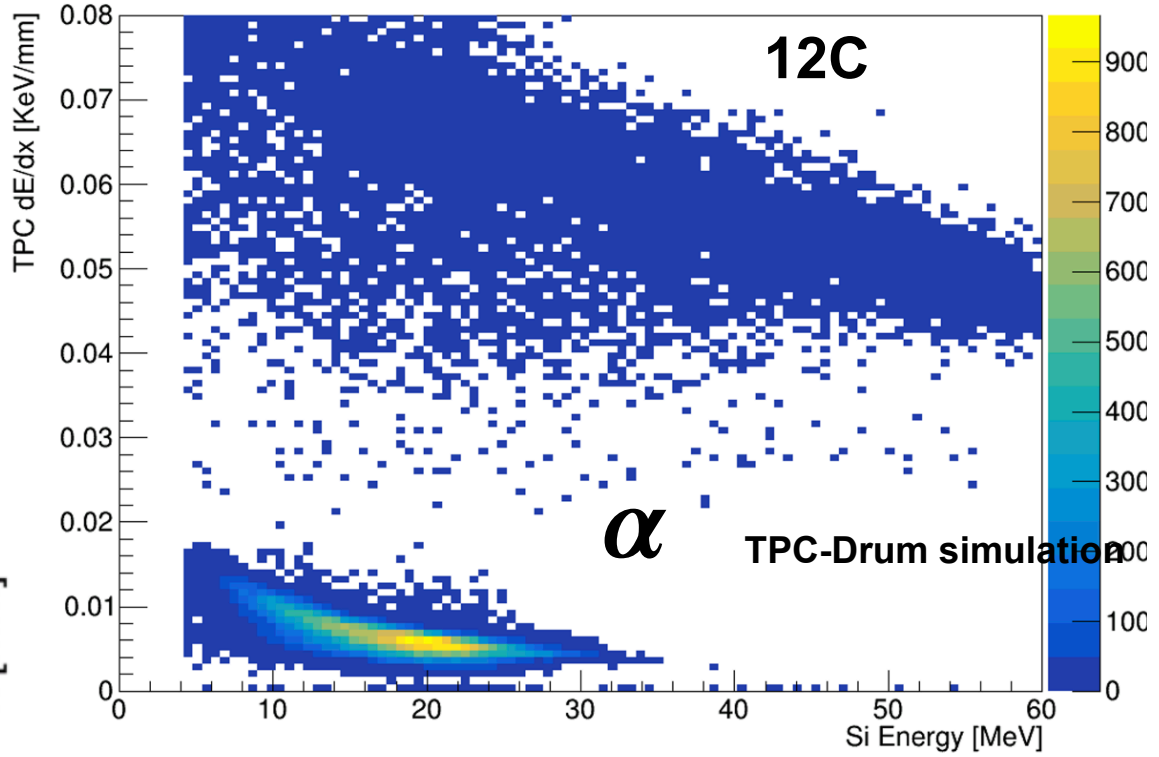
Event displays for measured one- and two-α tracks using Am-241 source

Detector design and simulation

- Simulation of $^{20}Ne + \alpha \rightarrow {}^{12}C + {}^{12}C_{Hoyle} \rightarrow {}^{12}C + 3\alpha$



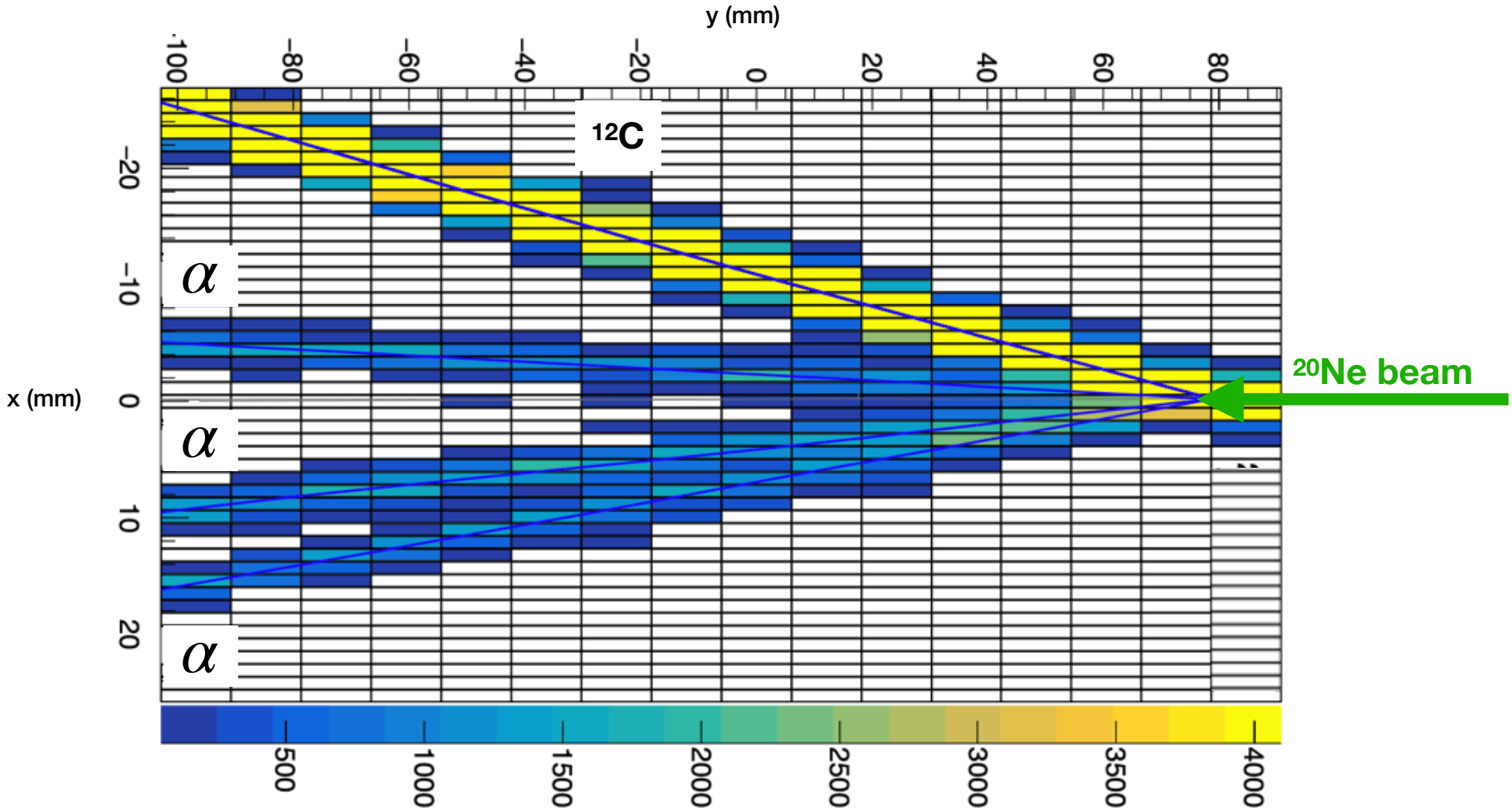




- Four-momentum can be calculated using TPC ($\vec{p}$/p) and Si (E)
- α particles are distinguishable

Detector simulation

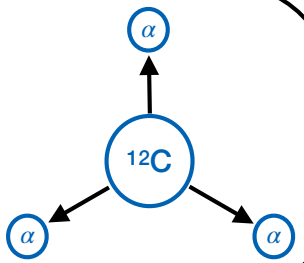
- Simulation of $^{20}Ne + \alpha \rightarrow {}^{12}C + {}^{12}C_{Hoyle} \rightarrow {}^{12}C + 3\alpha$



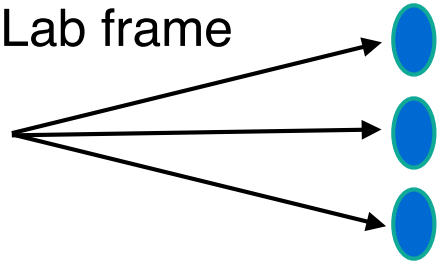
Reconstruction of invariant mass

Hoyle state

$^{12}C_{\mathrm{Hoyle}} \rightarrow \alpha + \alpha + \alpha$



Lab frame



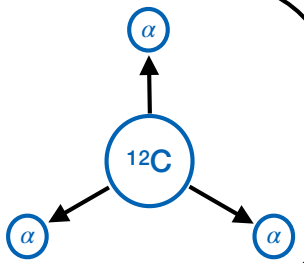
4-vector of α particles are obtained

- E measured by Si part
- $\vec{p}/|\vec{p}|$ measured by TPC part
- $|\vec{p}|$ calculated using α mass

Reconstruction of Hoyle state

Hoyle state

$^{12}C_{Hoyle} \rightarrow \alpha + \alpha + \alpha$



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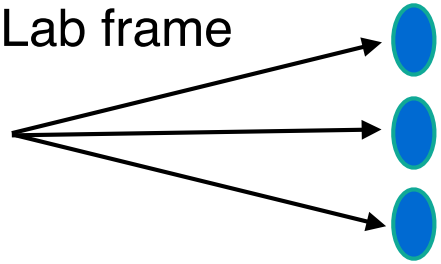
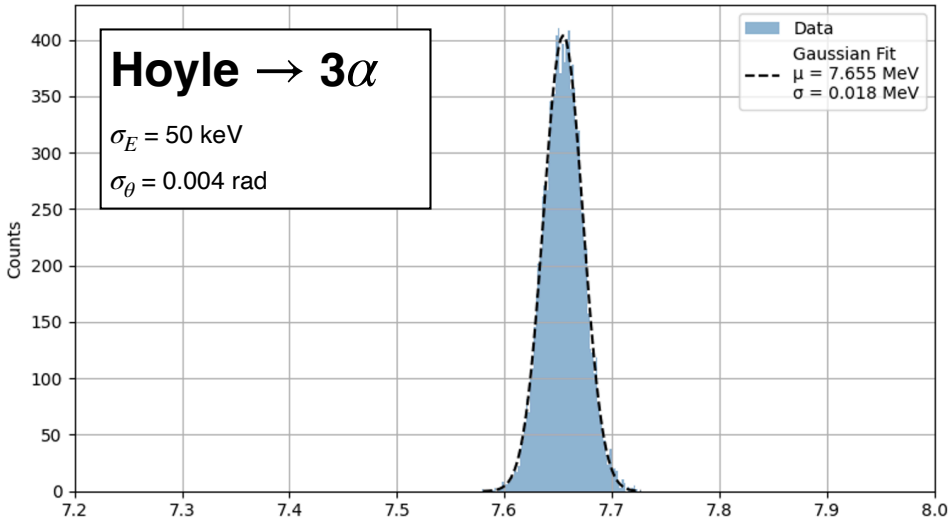


TPC-Drum (Toy MC simulation)



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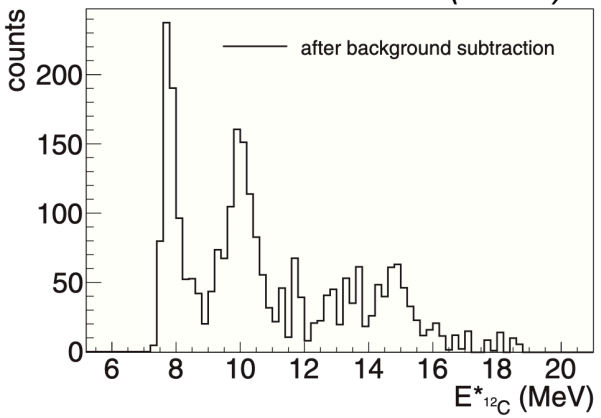
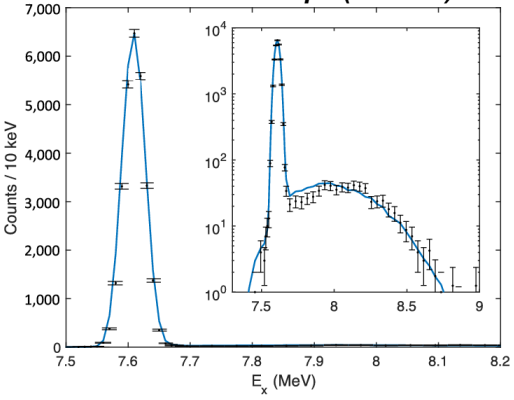
Barbui (2018)



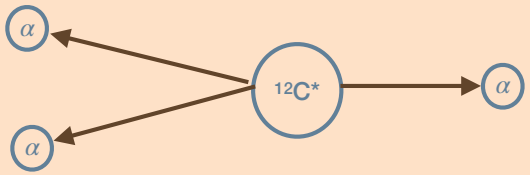
Bishop (2017)



Separation of Signal to Background

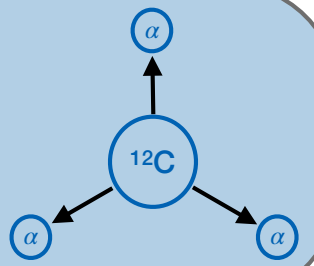
Background: Sequential decay

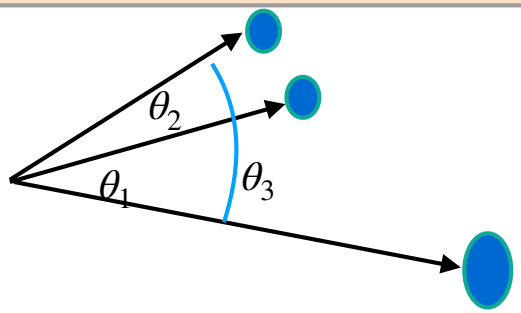
$^{12}C_{Hoyle} \rightarrow {}^{8}Be + \alpha \rightarrow \alpha + \alpha + \alpha$



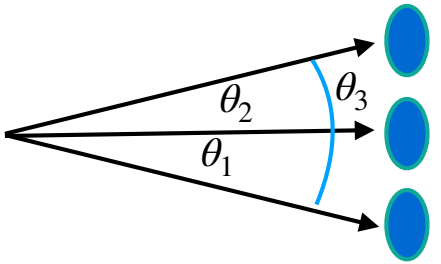
Signal: Direct decay

$^{12}C_{Hoyle} \rightarrow \alpha + \alpha + \alpha$





Lab frame



Separation of Signal to Background

Background: Sequential decay

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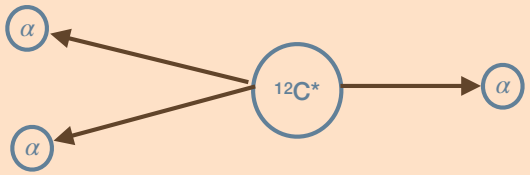
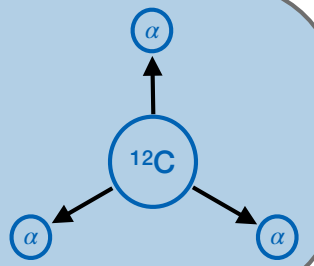
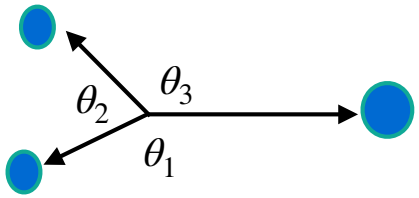


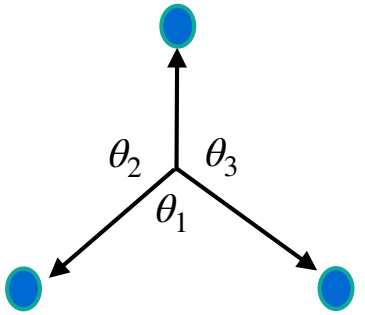
Signal: Direct decay

$^{12}C_{Hoyle} \rightarrow \alpha + \alpha + \alpha$





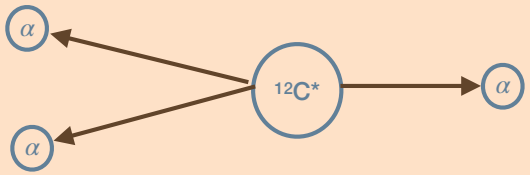
Reconstructed in $^{12}C^*$ frame



Separation of Signal to Background

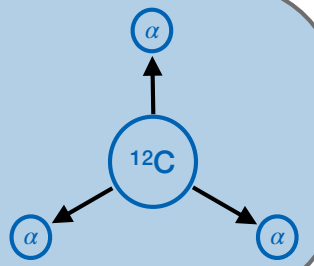
Background: Sequential decay

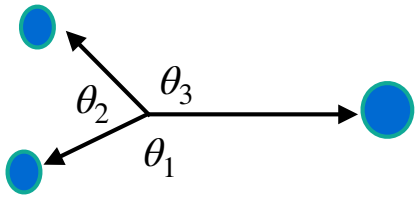
$^{12}C_{Hoyle} \rightarrow {}^{8}Be + \alpha \rightarrow \alpha + \alpha + \alpha$



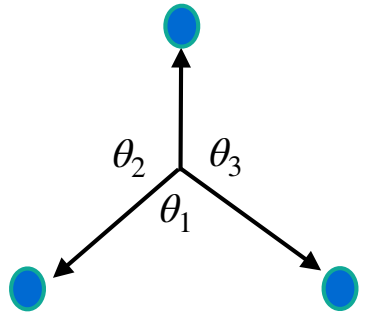
Signal: Direct decay

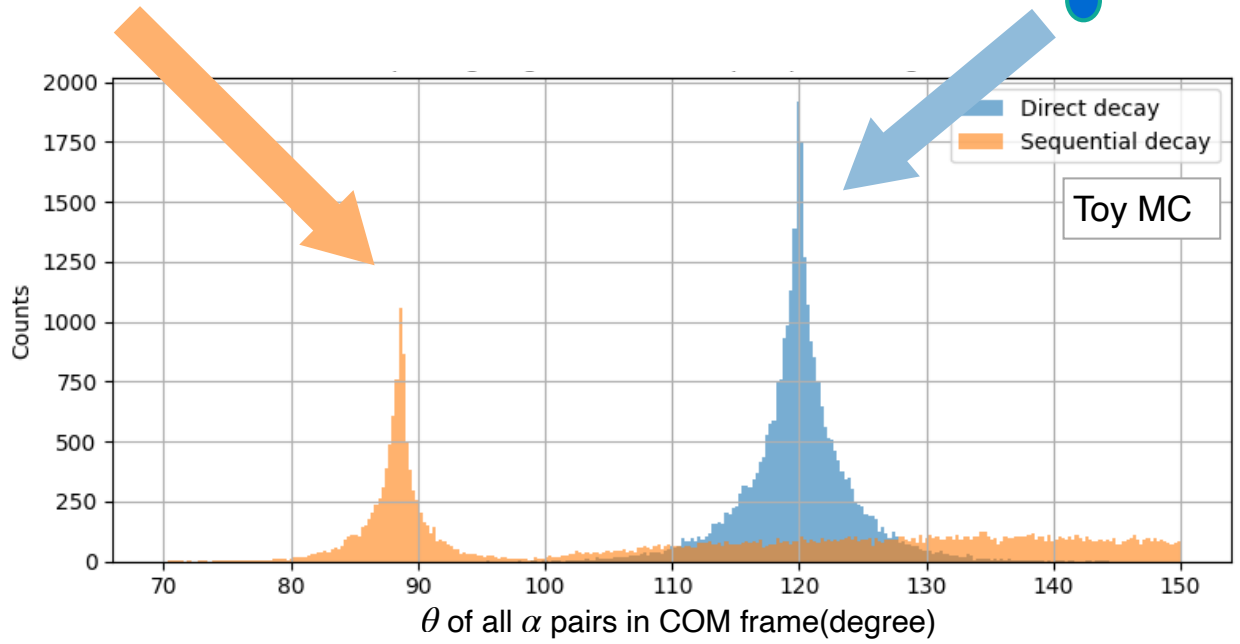
$^{12}C_{Hoyle} \rightarrow \alpha + \alpha + \alpha$





Reconstructed in $^{12}C^*$ frame



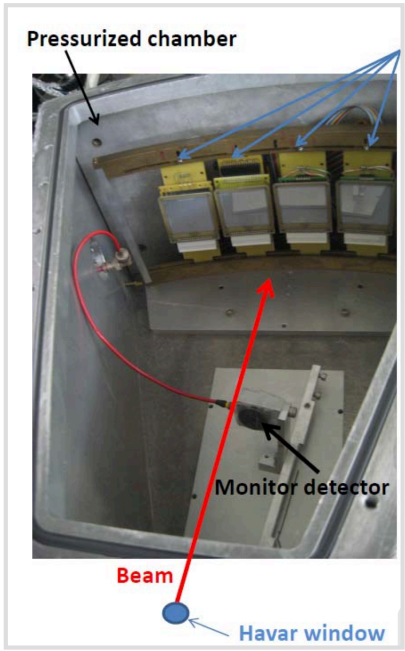


Caveat - signals and backgrounds are generated by same numbers (10k).

Experiment at RAON

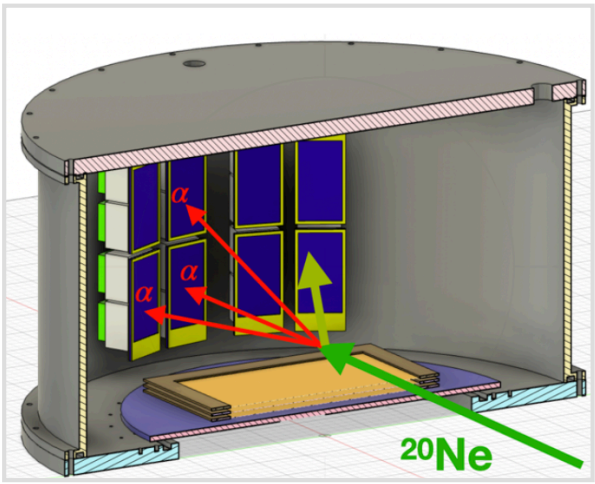
- **Extrapolation from Barbui (2018) [1]**
  - ^{20}Ne, E = 9.7, 12 MeV/u
  - ^{4}He gas as the active target
  - Obtained ~1,000 Hoyle states from 3.82×10^{10} Ne particles
  - Si telescope located at the similar position with TPC-Drum

- **Beam time at RAON**
  - We got 5 days (= 40 hours) of beam time at RAON in Spring 2026
  - We proposed to take 10^5 pps Ne beam at 10 MeV/u
  - Expect to get ~10k Hoyle states and ~200 16O $\rightarrow 4\alpha$ events



PRC 98, 044601 (2018)

extrapolate



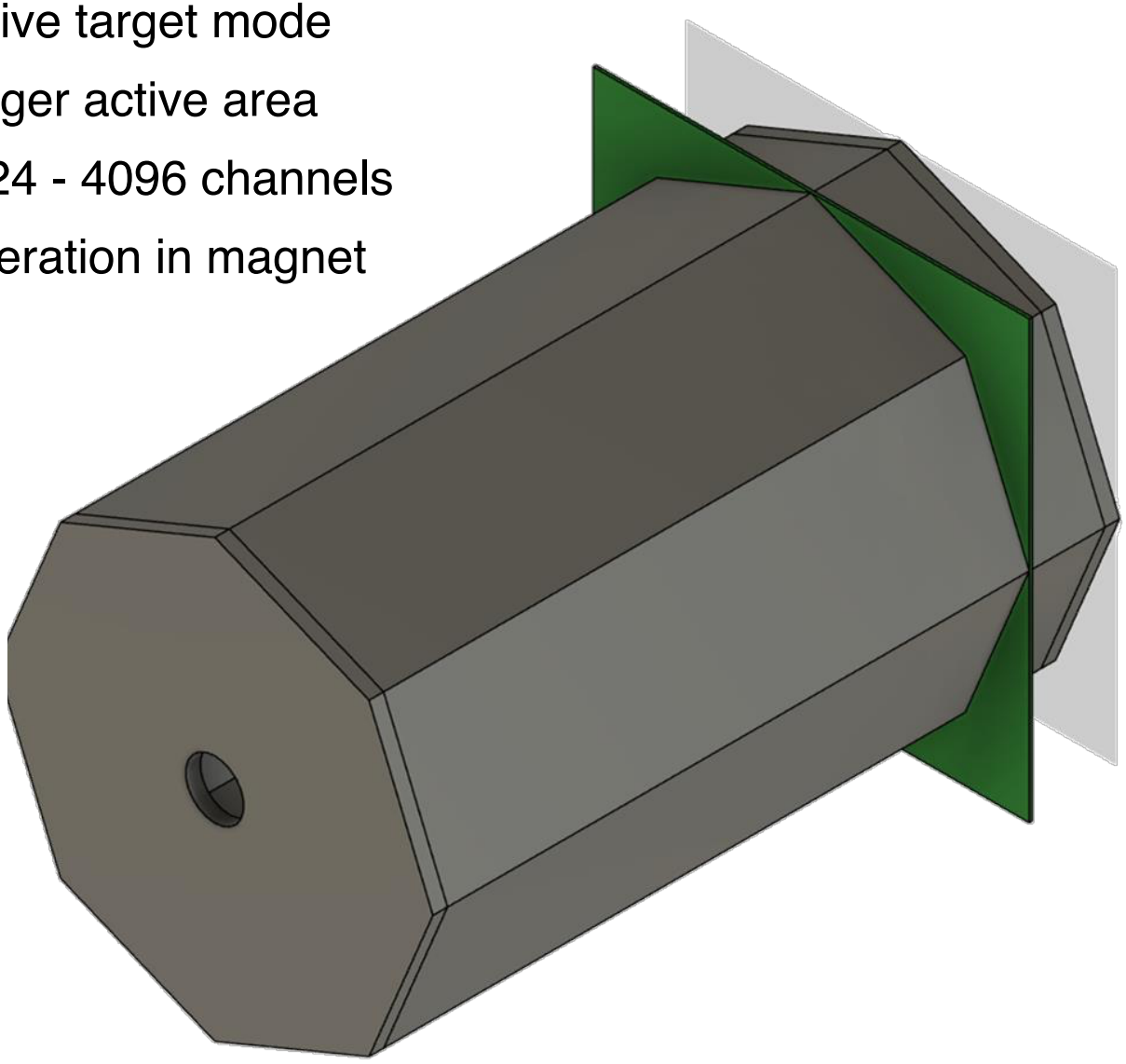
	Barbui (2018)	For this experiment
^{20}Ne + ^{4}He collisions	3.82 x 10^{10}	2.7 x 10^{10}
Collected Hoyle state	~1000	~10,000
Collected ^{16}O (15.1 MeV)	~20	~200

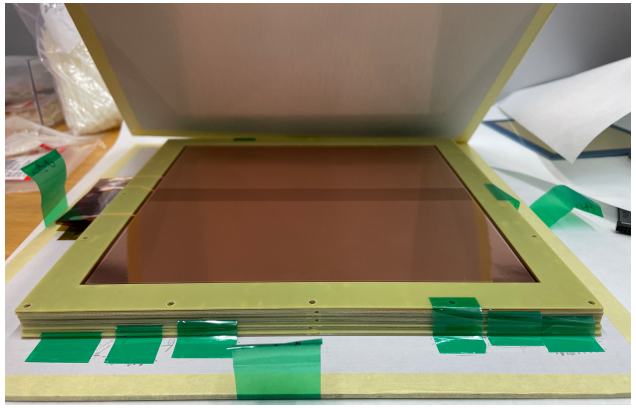
[1] *Phys.Rev.C 98 (2018) 4, 044601*

Next generation LAMPS AT-TPC

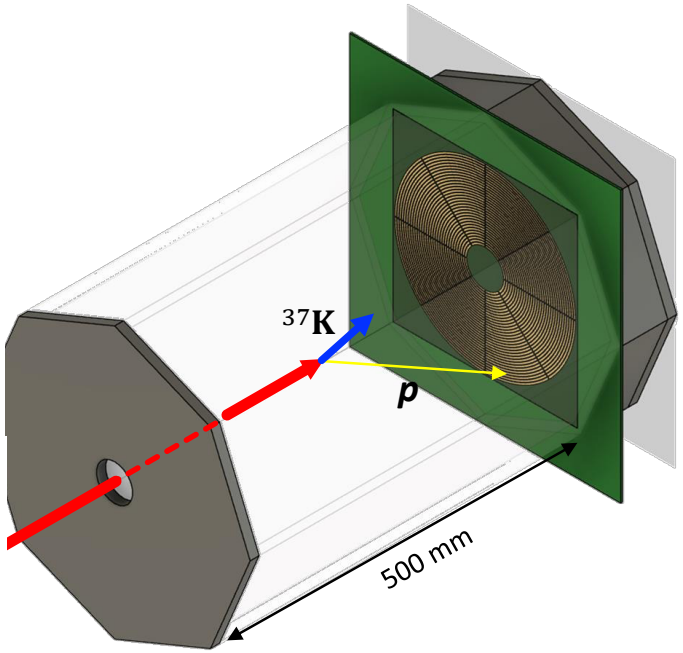
Signature of Ver.3

- Active target mode
- Larger active area
- 1024 - 4096 channels
- Operation in magnet





20x20 cm^2 GEM foils



OO collision at LHC

Chinese Physics C Vol. 47, No. 2 (2023) 024105

Signals of α clusters in ^{16}O+^{16}O collisions at the LHC from relativistic hydrodynamic simulations*

Chi Ding (丁驰)[1] Long-Gang Pang (庞龙刚)[1†] Song Zhang (张松)[2,3‡] Yu-Gang Ma (马余刚)[2,3§]

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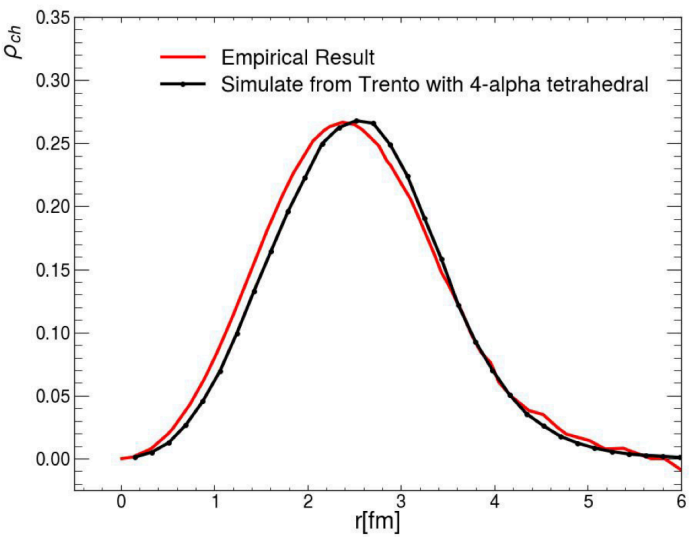
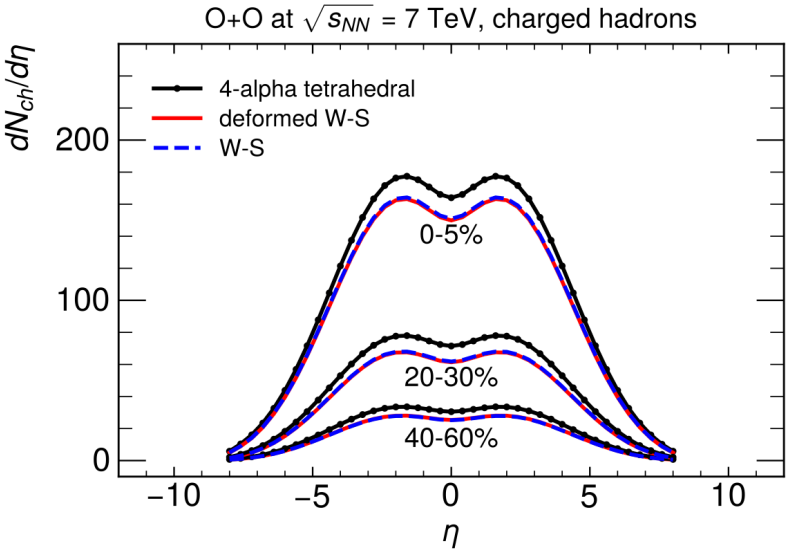
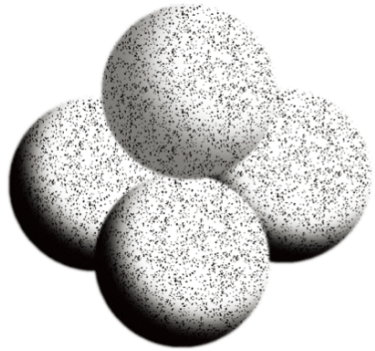
[2]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[3]Shanghai Research Center for Theoretical Nuclear Physics NSFC and Fudan University, Shanghai 200438, China





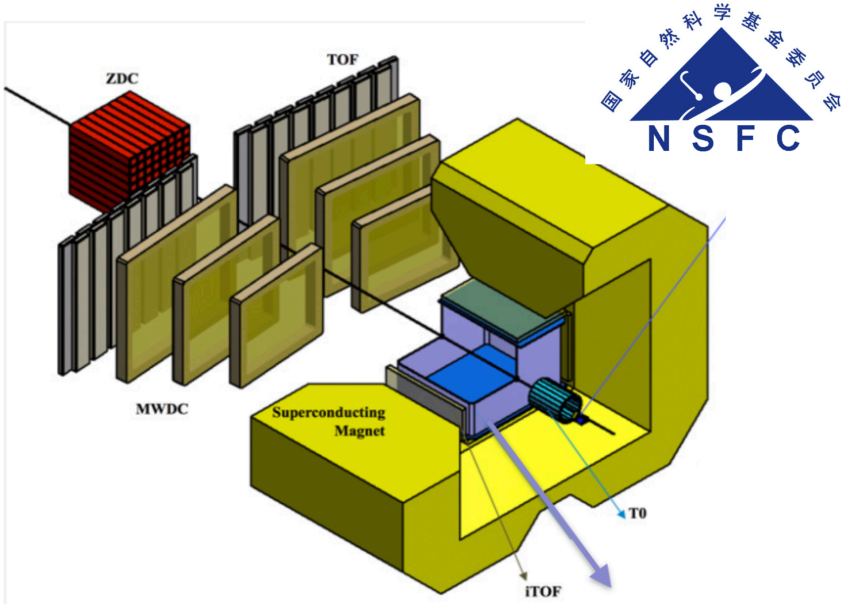
$$\rho(r) = \rho_0\left(1 + w\frac{r^2}{R^2}\right)\left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-}$$



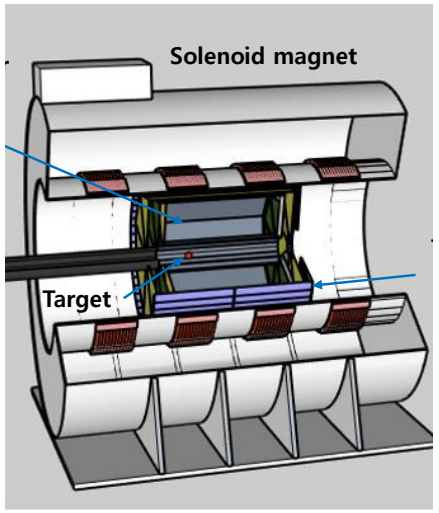
- Simulation study shows the deformation signal of ^{16}O can be observed from the multiplicity distribution in OO collision at LHC energy
- Clustering structure is of interest for two energy extremum (10 MeV and 10 TeV), providing unique complementarity

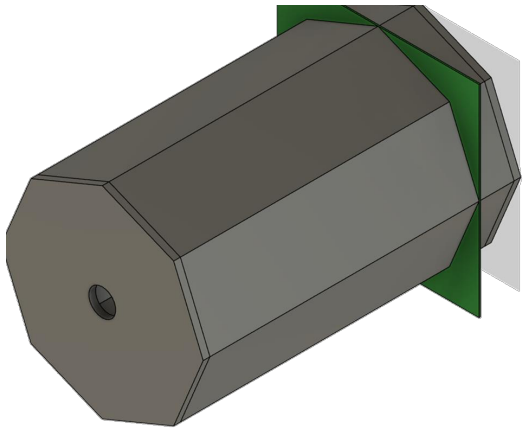
China-Korea Bilateral collaboration project

- Selected as a NSFC-NRF supported project for 2023 - 2025 to promote the experimental and theoretical collaboration for nuclear physics research
- PI: Yongsun Kim (Korea), Zhaoqing Feng (SCUT)



TPC





CEE Detector at HIAF

- Symmetry energy measurement O(1) GeV
- TPC working in the dipole magnet

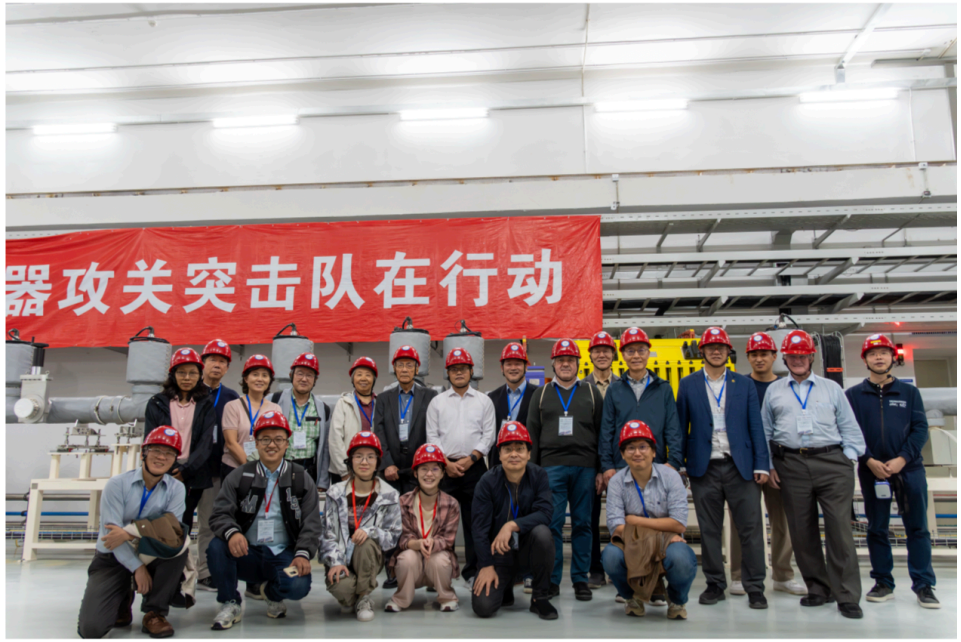
TPC and AT-TPC at RAON

- Symmetry energy at O(200) MeV
- Both are cylindrical shapes and operates in 1 T and 1.5 T solenoid

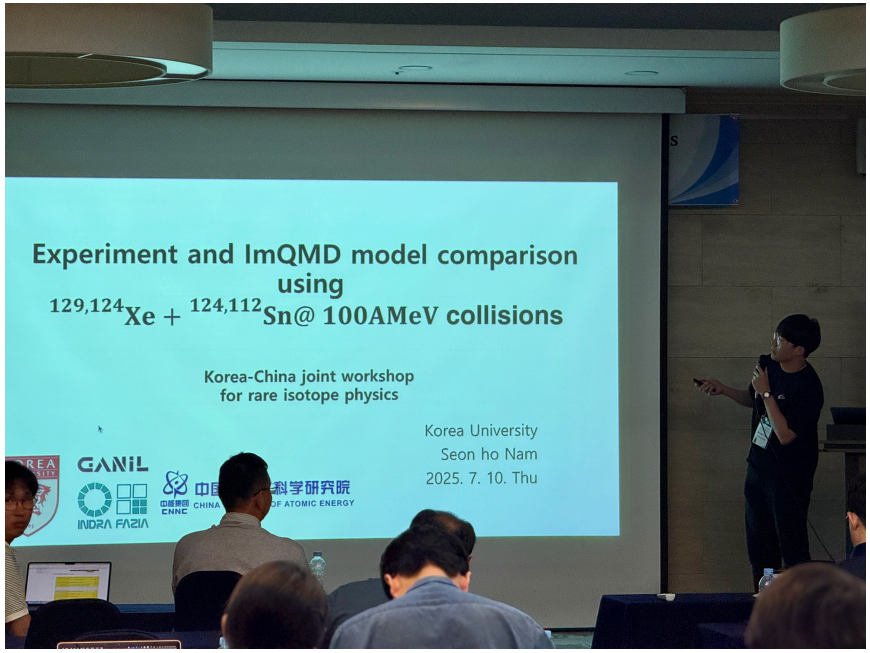
We have many common physics topics and technical challenges!

China-Korea Bilateral collaboration project

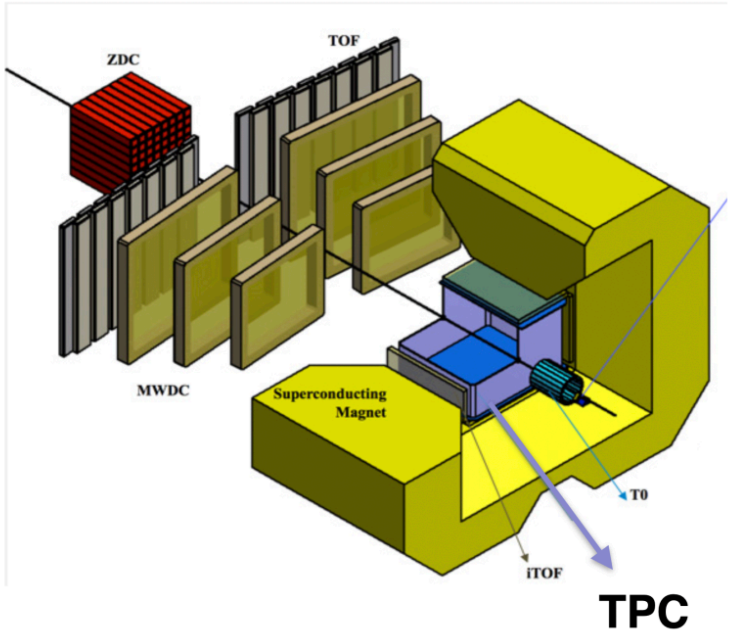
- 1st in Lanzhou Nov. 2023
- 2st in Seoul August 2024
- 3rd in Guanzhou Nov. 2024
- 4th in Jeju island July 2025

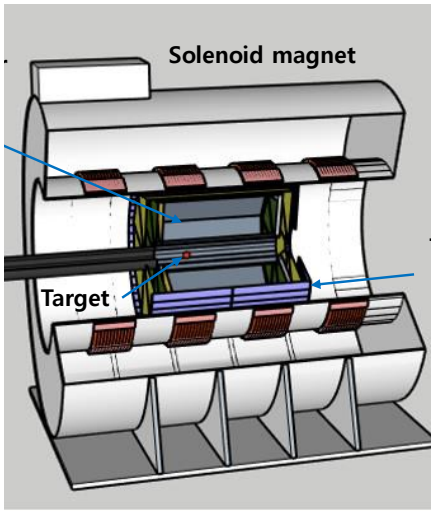


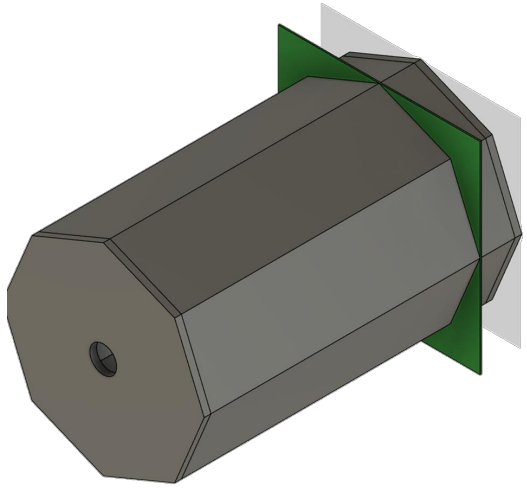
China-Korea Bilateral collaboration project



Prospect collaboration in future





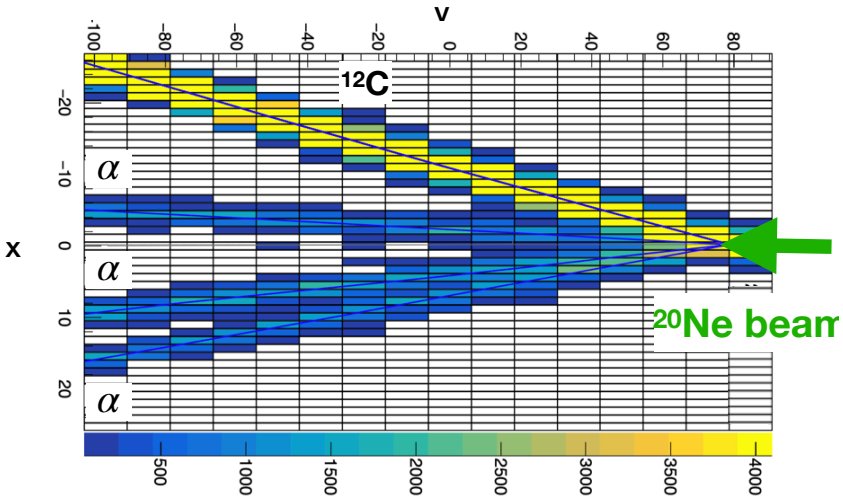


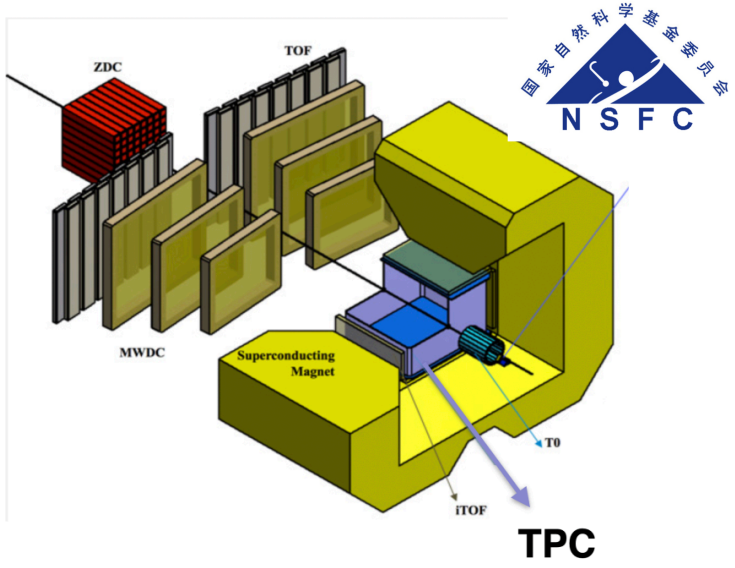
- Many rooms for collaboration
  - Development of new TPC electronics (upgrade or replacement of GET?)
  - Software and reconstruction algorithm for TPC
  - Measurement of same observables at two complementing energies at HIAF and RAON
- Hopefully, this can be a good example for larger Asian nuclear physics collaboration, extending the recent A3 effort.

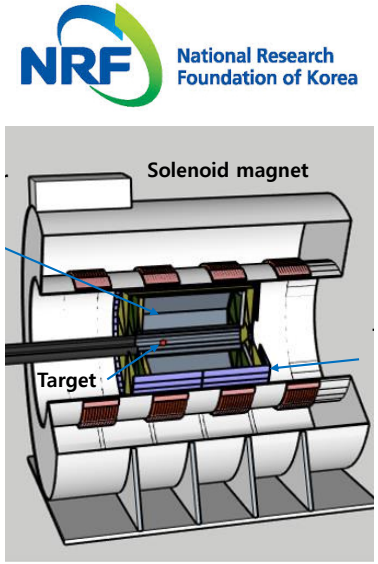
Summary

- With the goal of exploring exotic alpha-cluster structures, we aim to measure the direct decay of Hoyle states and the 4α decay of ^{16}O states, which are phenomena of increasing interest in the nuclear physics community.
- The TPC-Drum is ready for precision measurement
  - Good energy resolution of Si ⊗ Good angular resolution of TPC

- We have conducted a two-year bilateral program on nuclear physics collaboration between China and Korea
- I hope to continue and further expand this effort, creating synergy by combining the complementary strengths of HIAF and RAON.







NRF National Research Foundation of Korea

BACKUP