STUDIES OF FUSION REACTIONS WITH NEUTRON-RICH BEAMS

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On behalf of the MATE-TPC Collaboration

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MATE: Multi-purpose Active-target Time projection chamber for nuclear Experiments

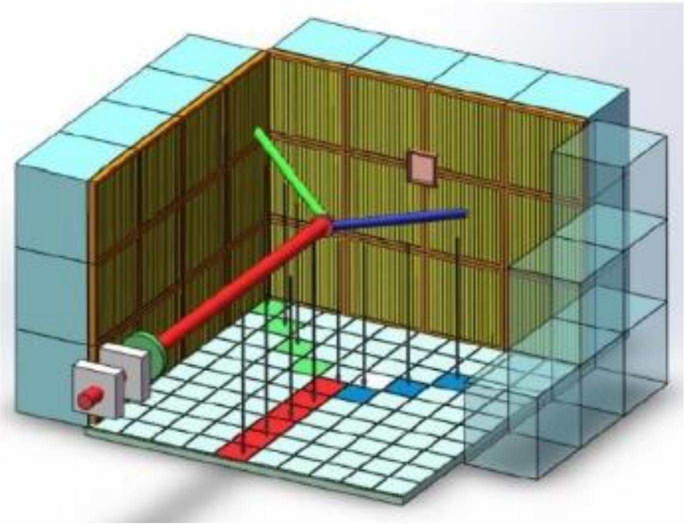
TPC： Chengui Lu、Tianlei Pu、Ningtao Zhang； Si array： Hooi-Jin Ong

MATE-TPC Team (IMP part in alphabetic order)

Bingshui Gao, Xiaobin Li, Bingfeng Lv, Junbing Ma, Longhui Ru, Fushuai Shi, Xiaodong Tang, Hooi-Jin Ong, Jinlong Zhang, Ningtao Zhang, Zhichao Zhang

Limin Duan, Rongjiang Hu, Chenggui Lu

Yi Qian, Tianlei Pu, Hongyu Zhao



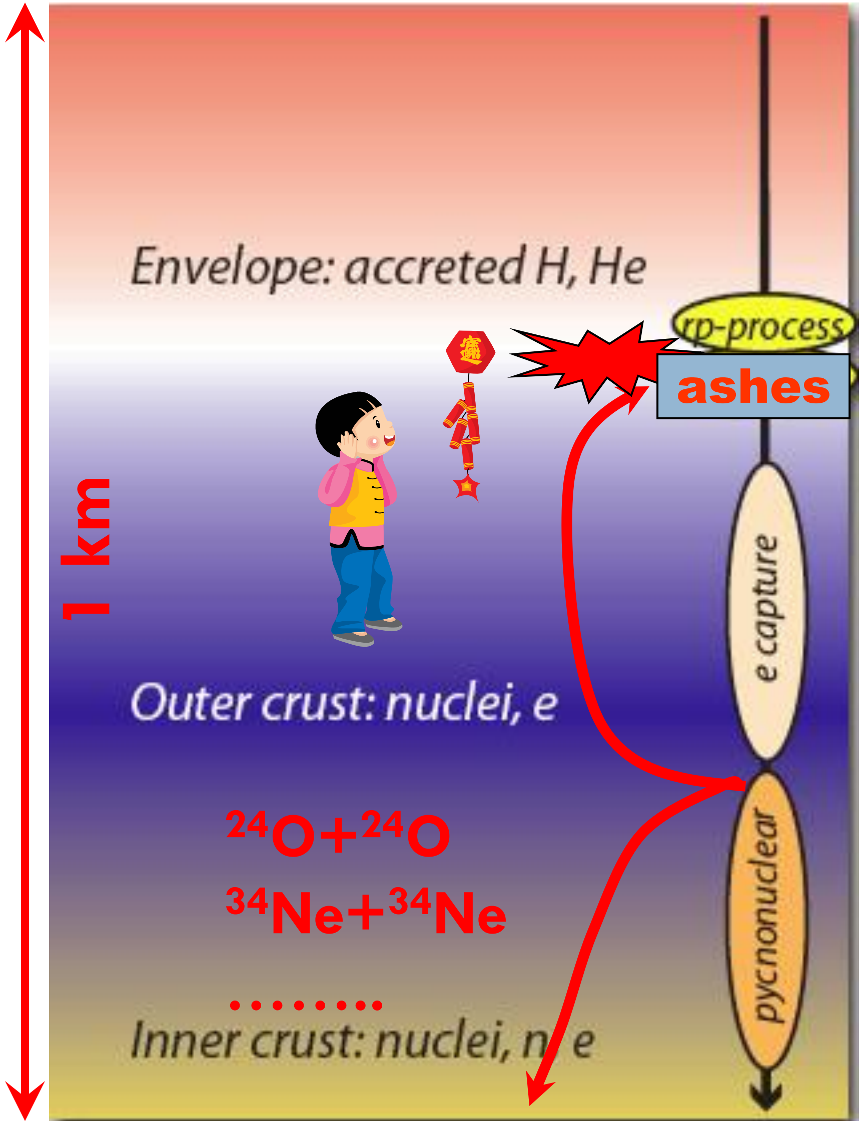
Collaborations outside of IMP

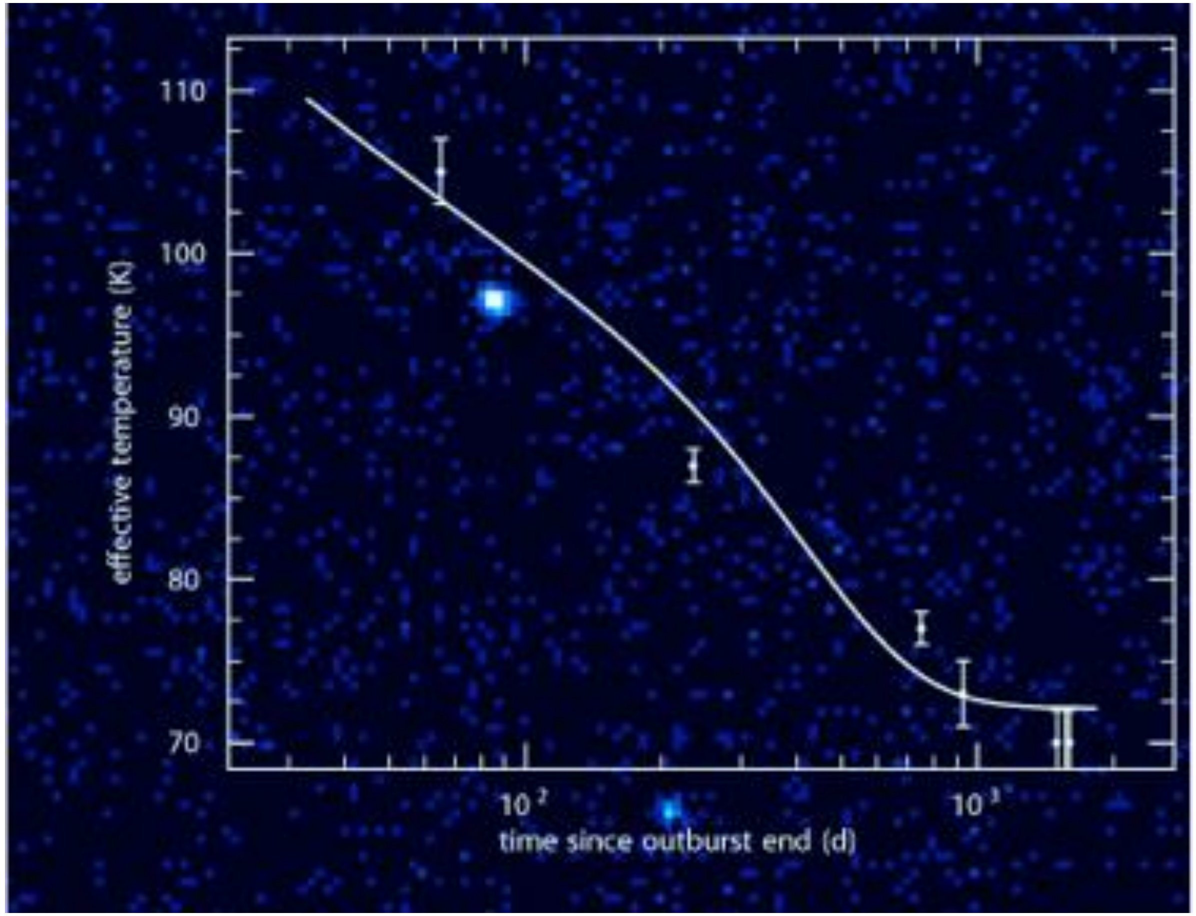
Jianjun He, Ziming Li (Beijing Normal U.)

Jian Gao, Qite Li, Jinyan Xu (Peiking U.)

Jie Cheng、Fenhua Lu、Xiaobin Li (Southern University of Science and TEchnology)

Heating source of Superburst: Fusion of Neutron-rich isotopes

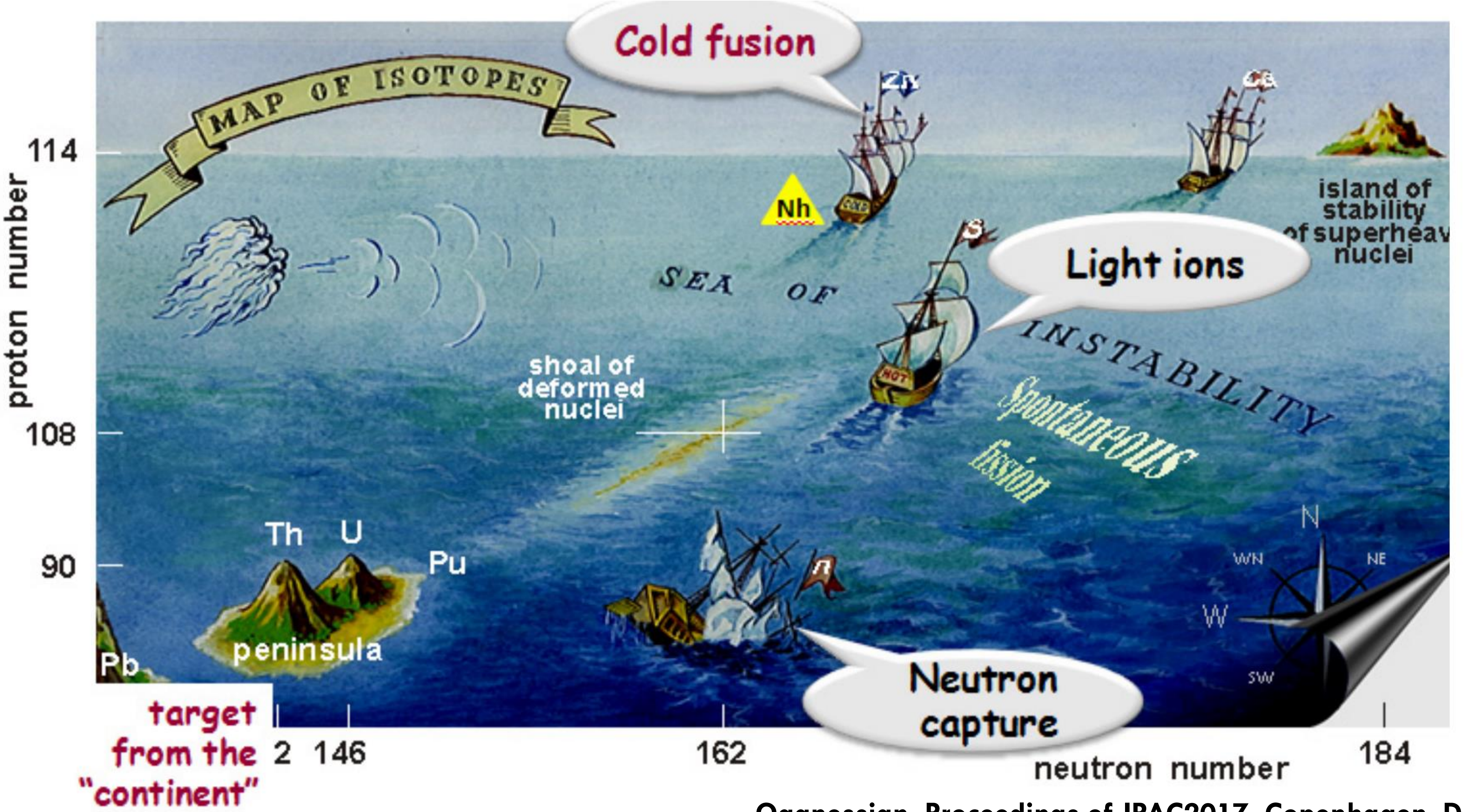




Pictures by E. Brown (MSU)

- Fusion reactions of neutron-rich isotopes: heating source in the crust
- Affects the superburst condition and the cooling curve after the accretion haled

Can we reach ISLAND of STABILITY using neutron-rich beams?



Oganessian, Proceedings of IPAC2017, Copenhagen, Denmark

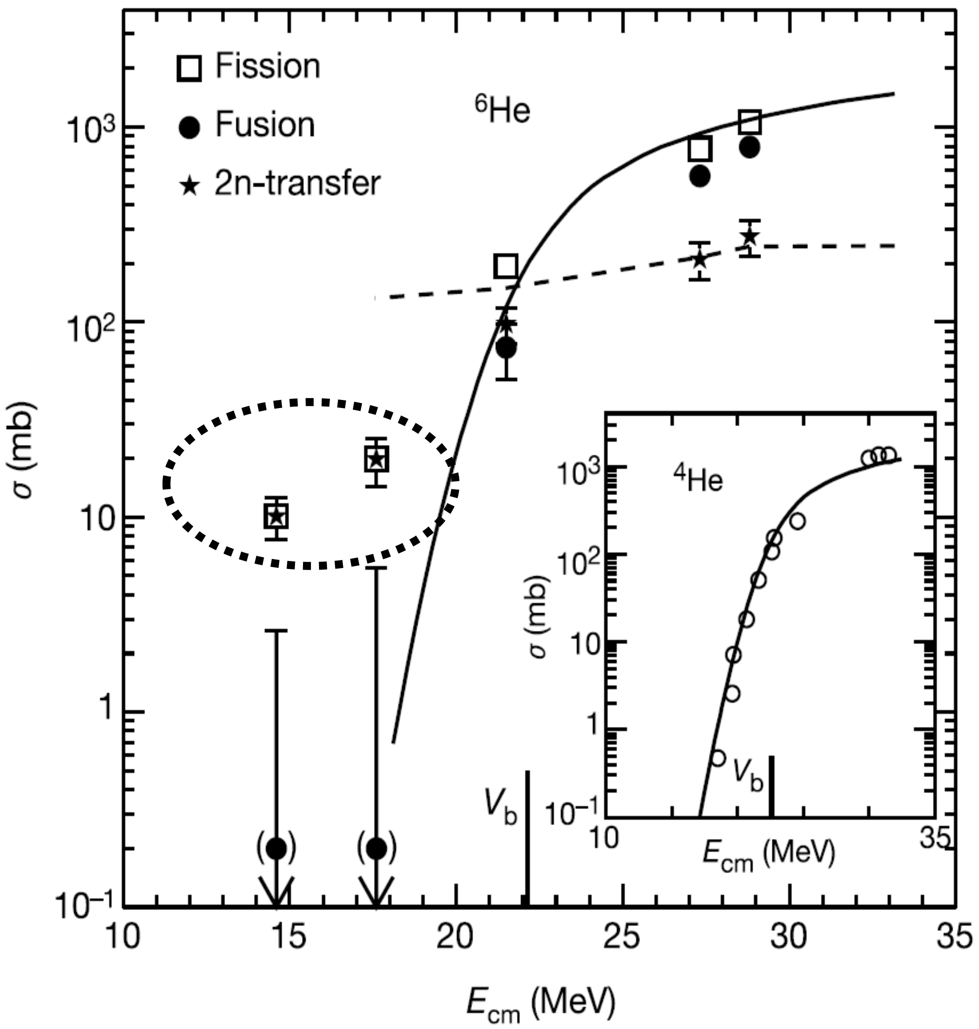
No enhancement of fusion probability by the neutron halo of ^6He

R. Raabe[1,2], J. L. Sida[1*], J. L. Charvet[1], N. Alamanos[1], C. Angulo[3], J. M. Casandjian[4], S. Courtin[5], A. Drouart[1], D. J. C. Durand[1], P. Figuera[6], A. Gillibert[1], S. Heinrich[1], C. Jouanne[1], V. Lapoux[1], A. Lepine-Szily[7], A. Musumarra[6], L. Nalpas[1], D. Pierroutsakou[8], M. Romoli[8], K. Rusek[9] & M. Trotta[8]

The extended neutron matter distribution
→ Enhance Fusion?
Weak binding energy of the nuclei
→ inhibit the process ?

At energies below the fusion barrier, we find **no evidence for a substantial enhancement** of fusion. Rather, the (large) fission yield is due to a two-neutron transfer reaction, with other direct processes possibly also involved.

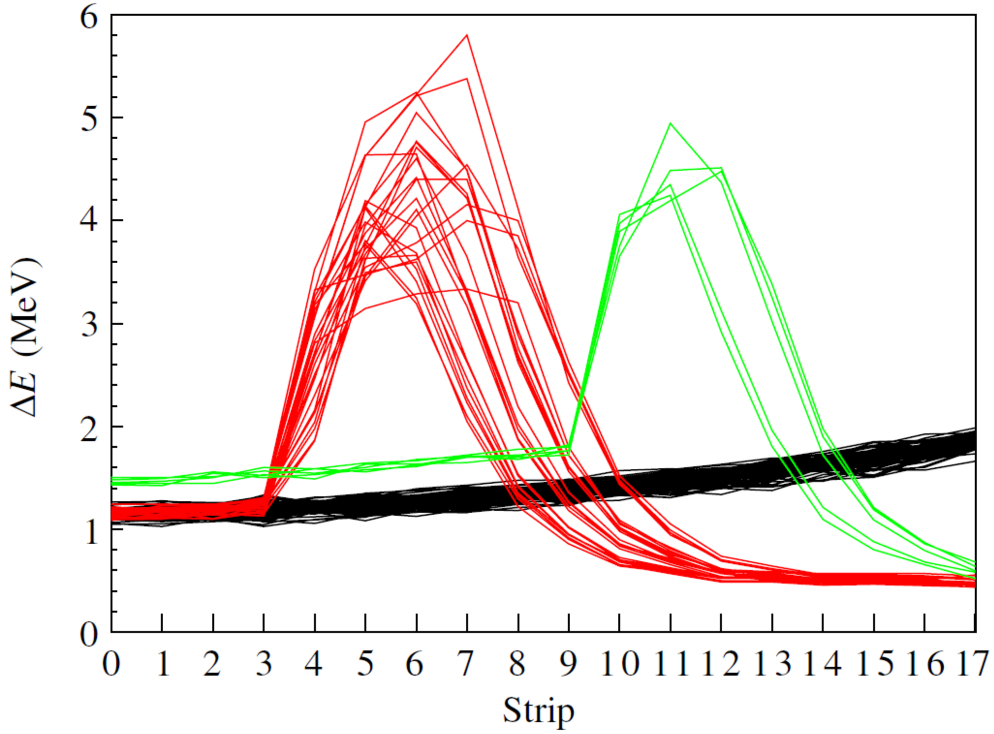
Nature (2004)

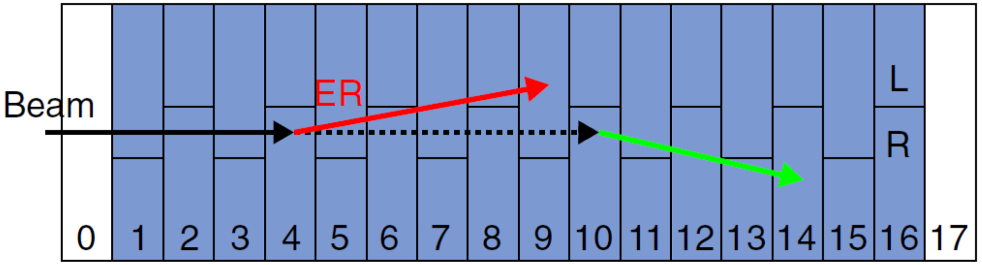


CYCLONE30+CYCLONE110

^6He intensity: $5x10^5$ pps

cross section: >10 mb



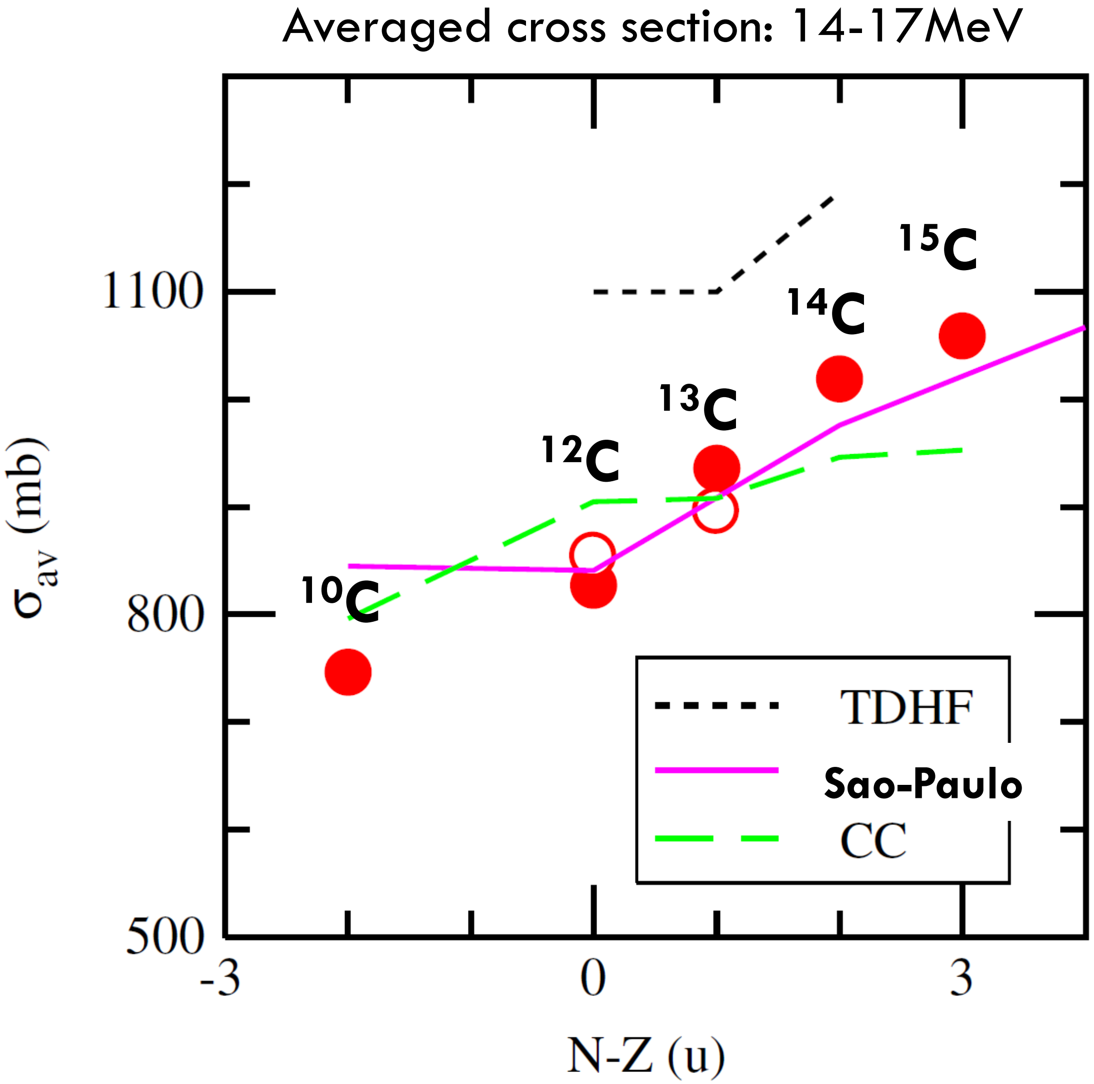


ATLAS@ANL in-flight beam

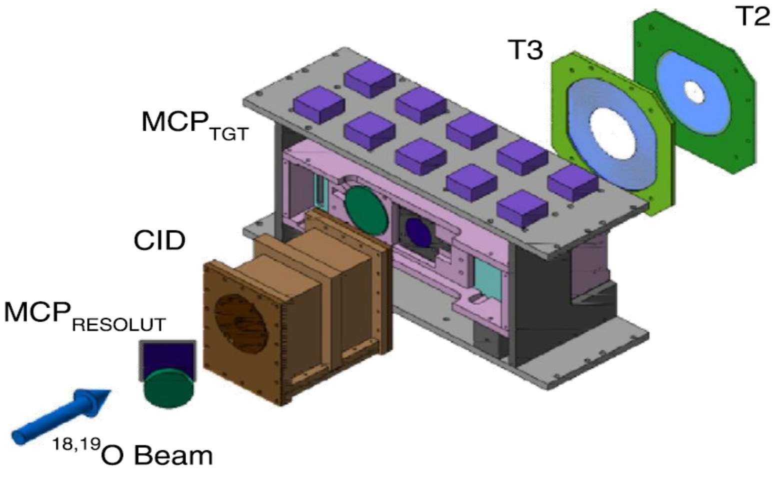
$^{10\text{-}15}$O intensity: $10^2 \sim 10^3$ pps

Cross section: >200 mb

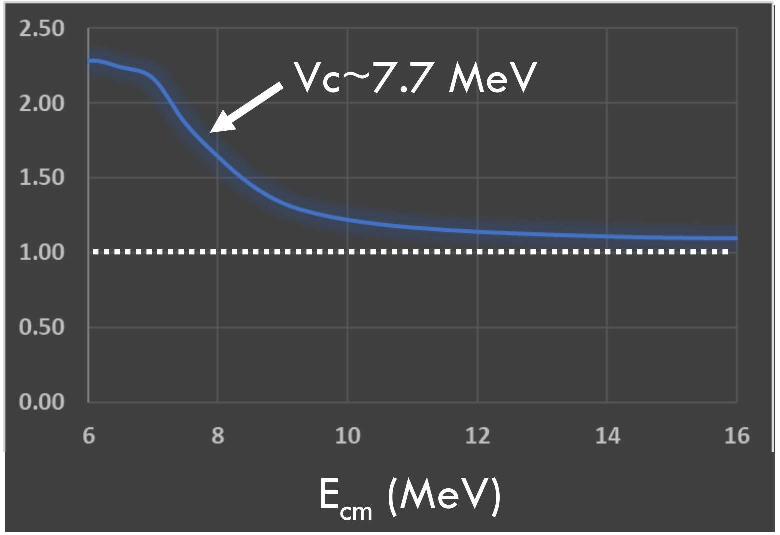
Carnelli et al., PRL 112 (2014) 192701



Confirms that **fusion of neutron-rich carbon isotopes behaves predictably**, without exotic enhancement.



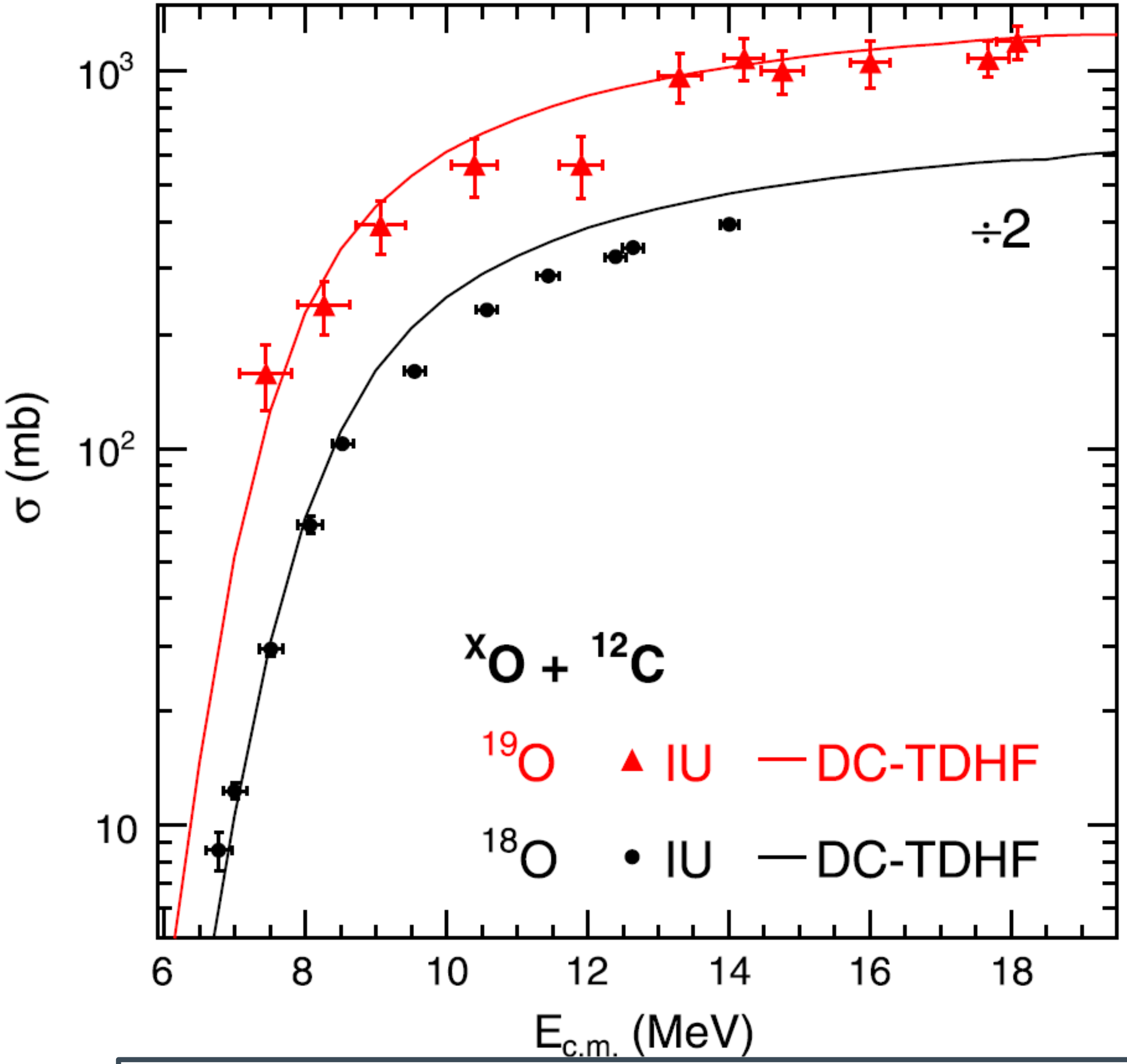
$^{19}O+^{12}C/^{18}O+^{12}C$ (DC-TDHF)



FSU in-flight beam

^{19}O intensity: 1.5~4x10^{3} pps

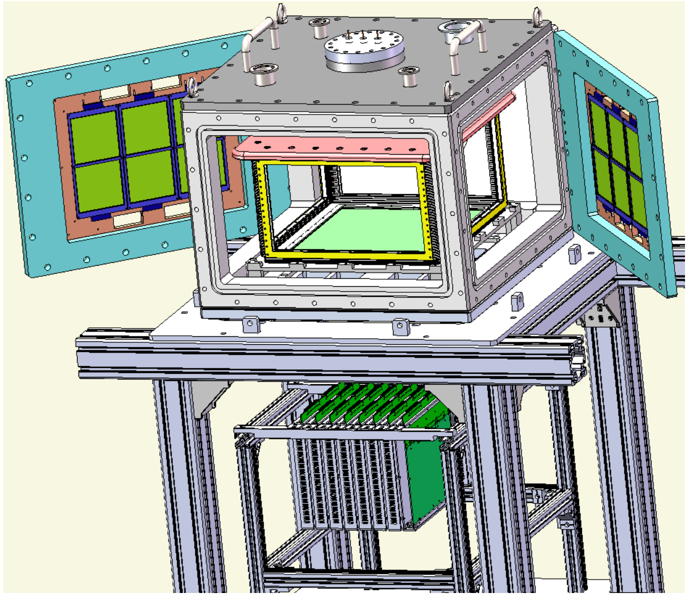
Cross section: >100 mb



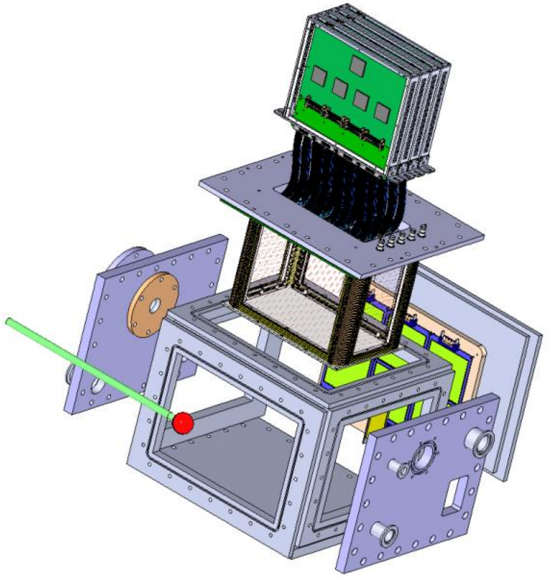
Supports hypothesis that **surface neutrons** and **asymmetric density tails** enhance tunneling probability.

V. Singh et al. , Physics Letters B 765 (2017) 99–103

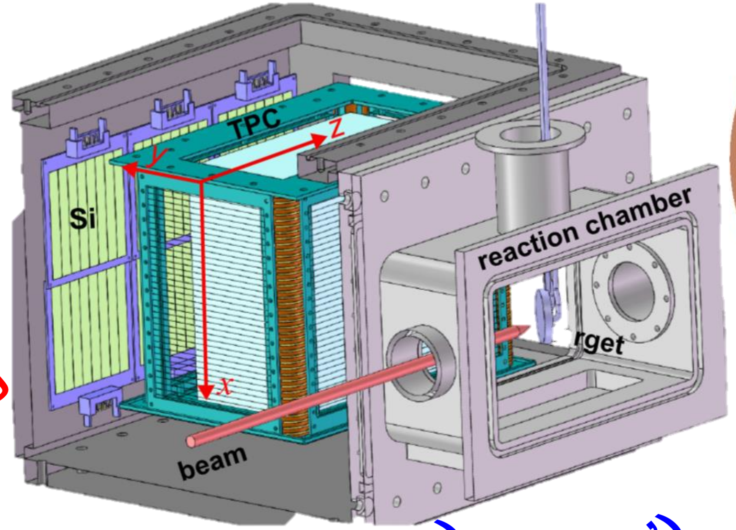
MATE TPC
3800ch THGEM



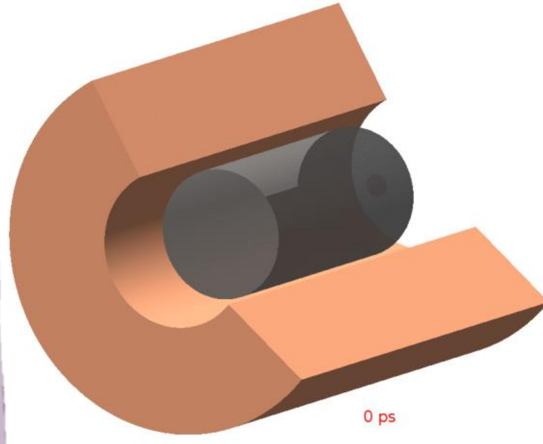
pMATE TPC
1024ch THGEM



mMATE TPC
684-ch micromegas



cMATE TPC
Cylindrical TPC
+Solenoid



2015 — pMATE R&D

2019

2019/10 — $^{12}C+^{12}C$

2020/1 — Commissioning, $^{19}O+^{12}C$

MATE R&D

2021

2021/7 — $^{14}O(\alpha,p)$

2022/7 — $^{11}C(\alpha,\alpha')$

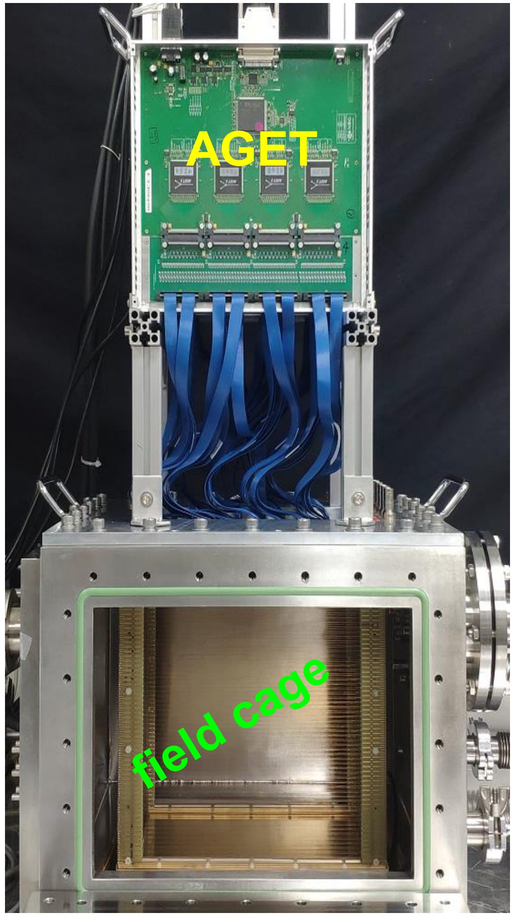
mMATE R&D

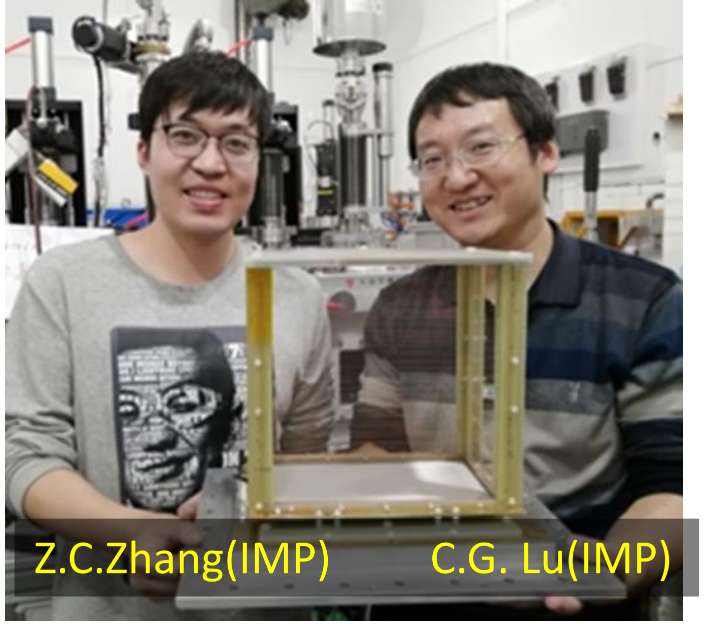
2023/7 — $^{12}C+^{12}C$

cMATE R&D

HIAF — (α,α'), $(d,{}^{2}He)$

Prototype MATE TPC



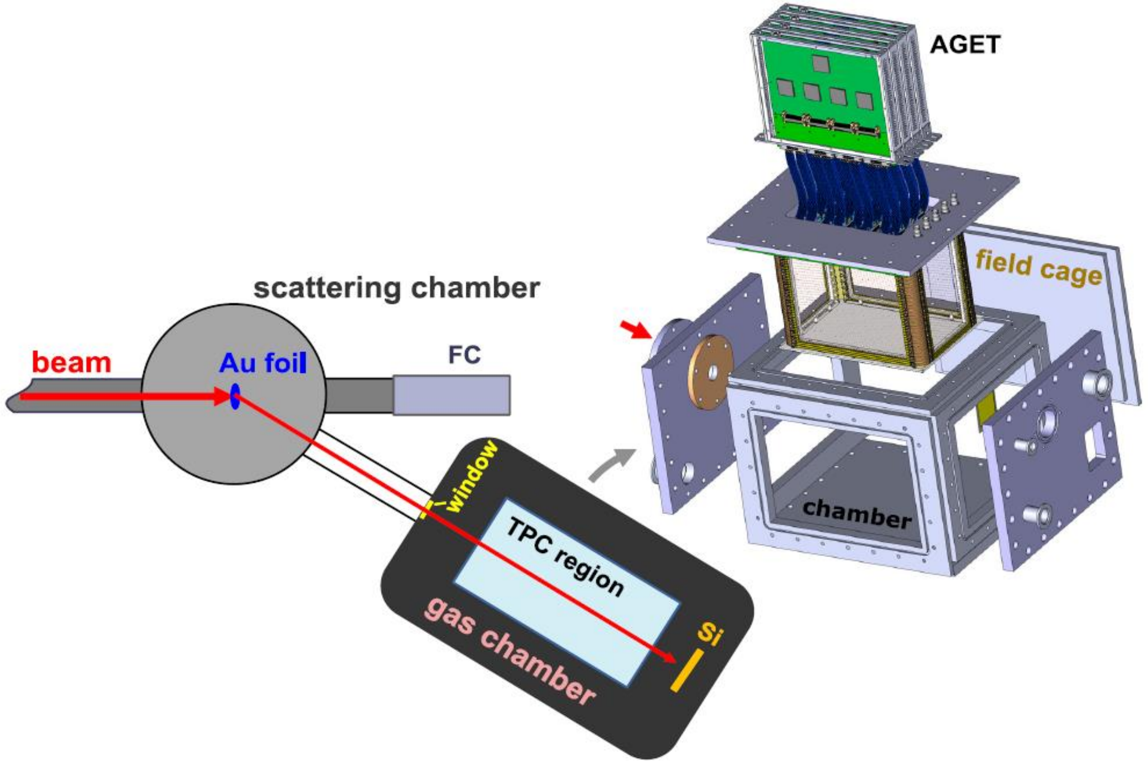


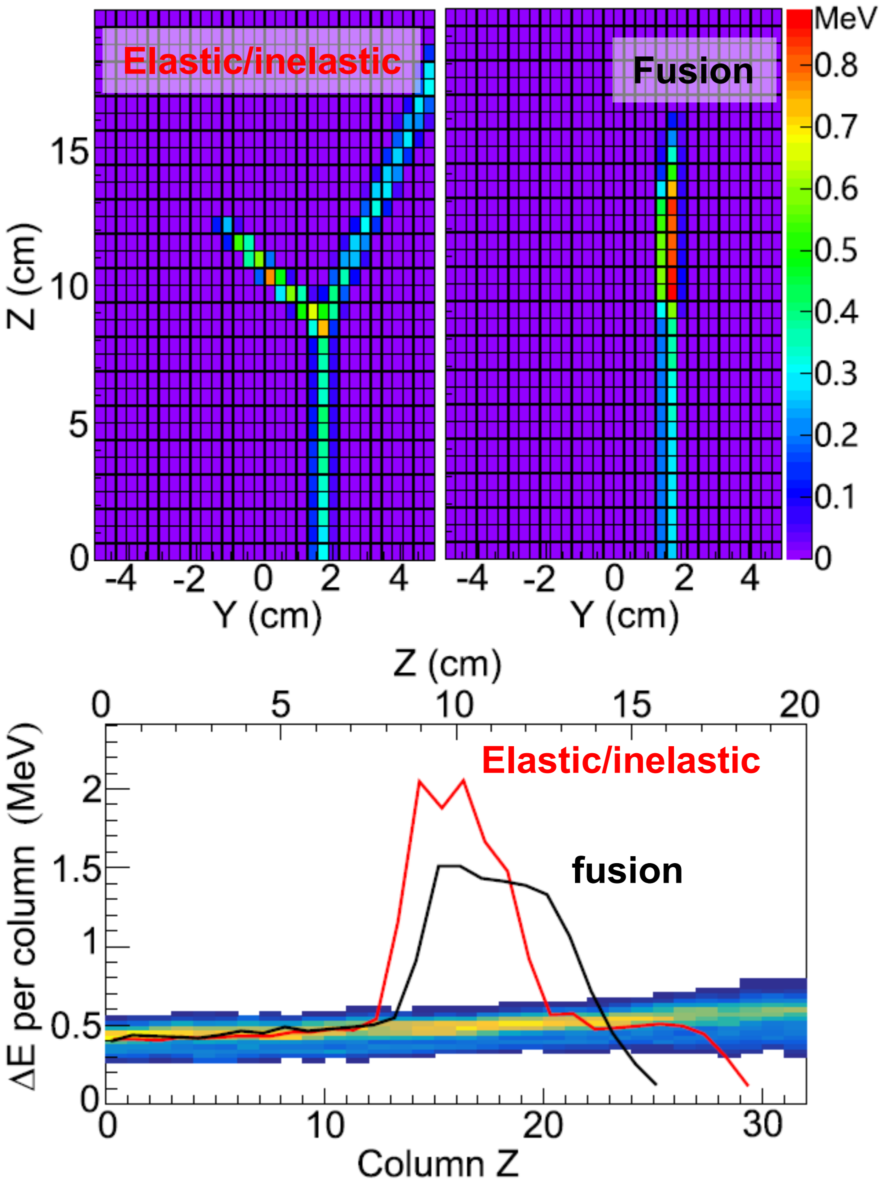
- **Active volume: 10cm(W)×20cm(L)×25cm(H)**
- **Field cage: 3 layers of Be-Cu wires（Φ0.1mm）**
- **Double THGEMs: thickness 0.3mm**
- **Rectangular pad: 3mm×6mm, 1024 pads**

"*Studying the heavy-ion fusion reactions at stellar energies using Time Projection Chamber*", Z. C. Zhang et al., Nuclear Inst. and Methods in Physics Research, A 1016, 165740 (2021).

$^{12}C+^{12}C$ Active Target Experiment

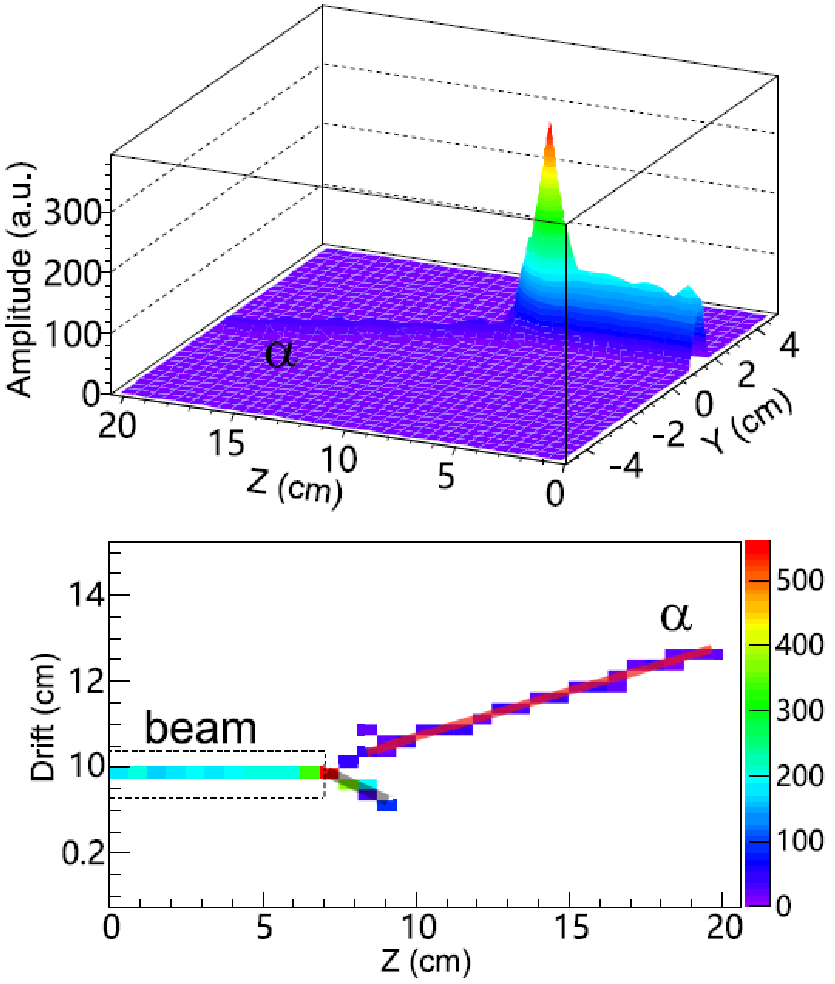
- $^{12}C^{4+}$ **beam:** 4.9 AMeV (HIRFL, IMP)
- **TPC gas:** C_4H_{10} at 50, 100 mbar
- **Injection rate:** 200-400 cps
- **Beam time:** 31.2 hours



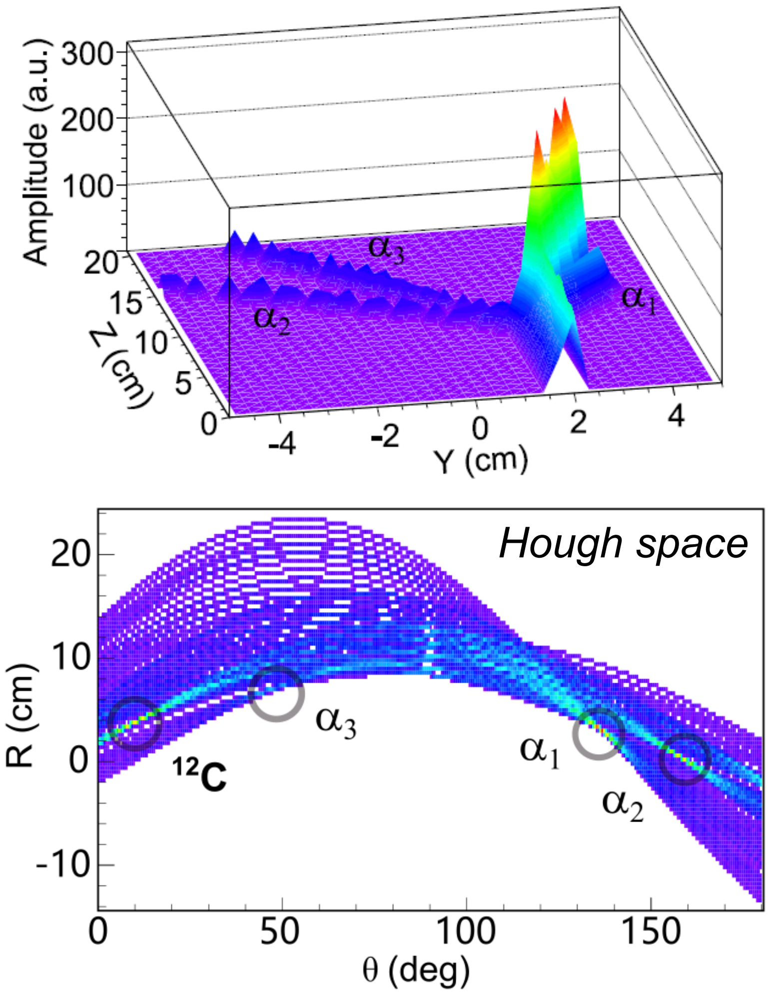


X. Y. Wang, N. T. Zhang, Z. C. Zhang *et al.*, *Chin. Phys. C 46, 104001 (2022)*

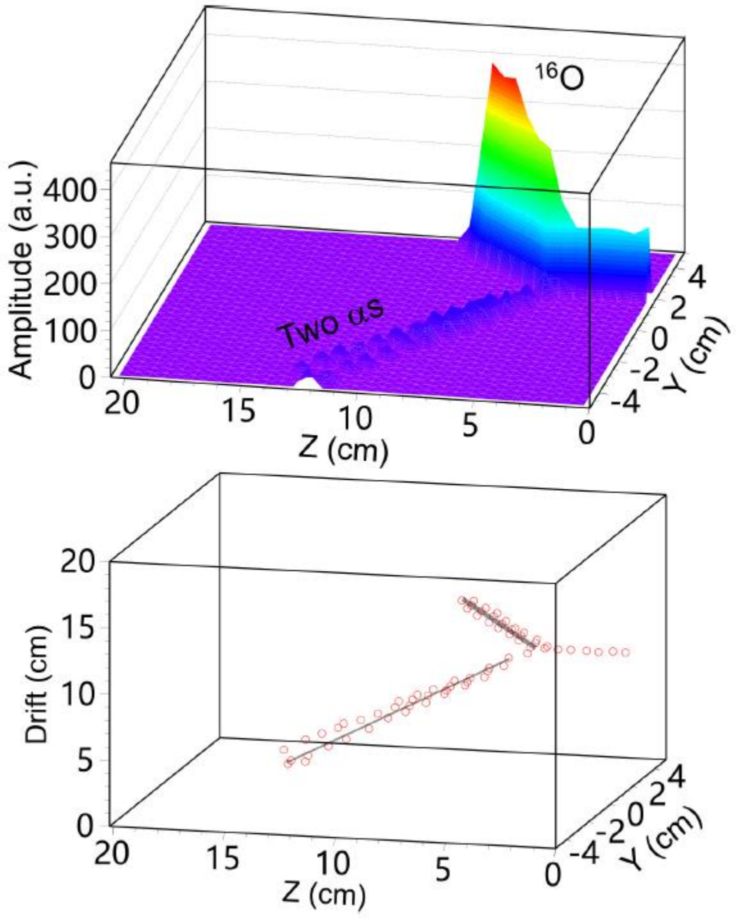
$^{12}C+^{12}C \rightarrow ^{20}Ne+\alpha$



$^{12}C+^{12}C \rightarrow ^{12}C+3\alpha$



$^{12}C+^{12}C \rightarrow ^{16}C+^{8}Be(2\alpha)$



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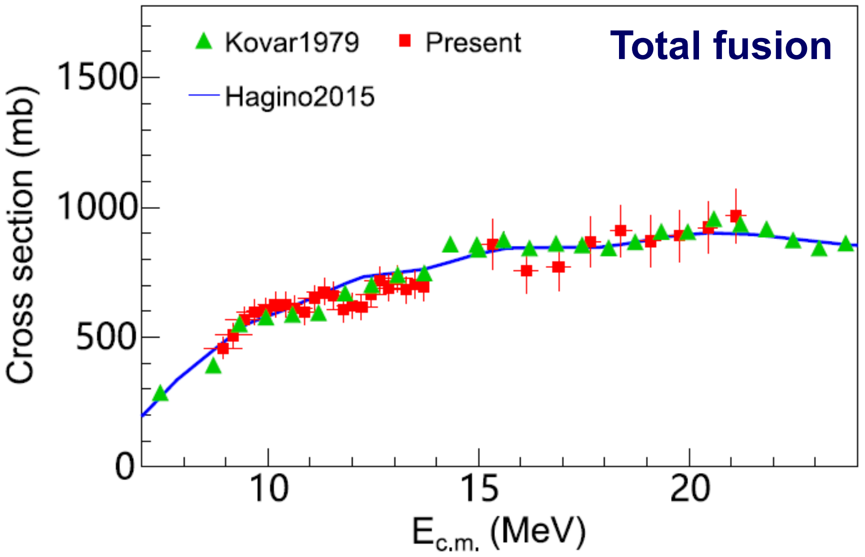
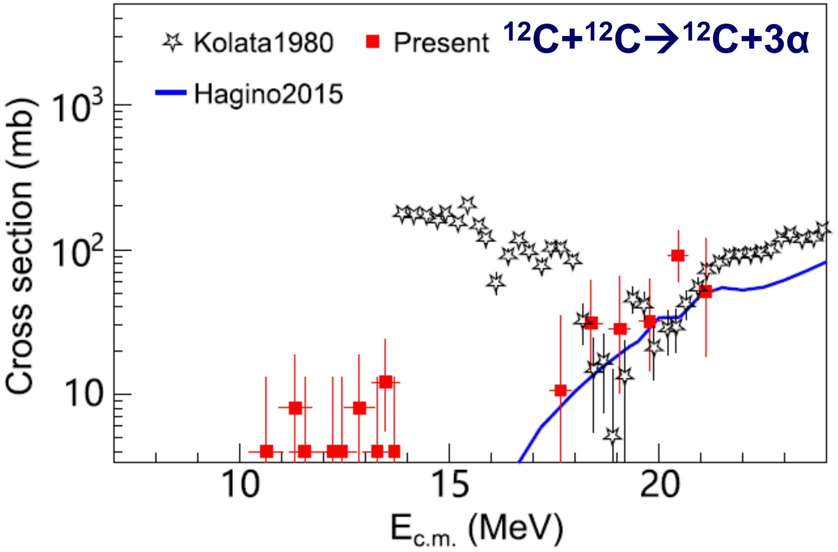
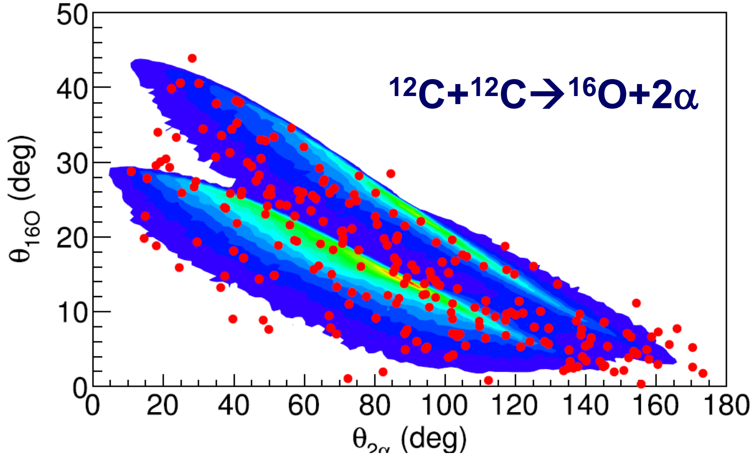
Experimental results

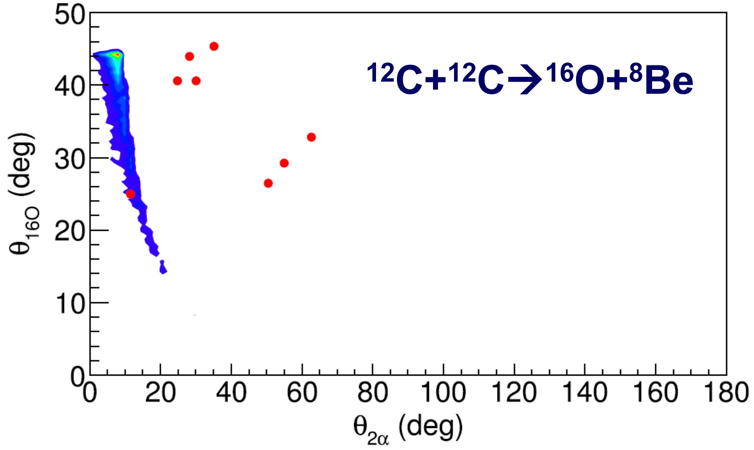




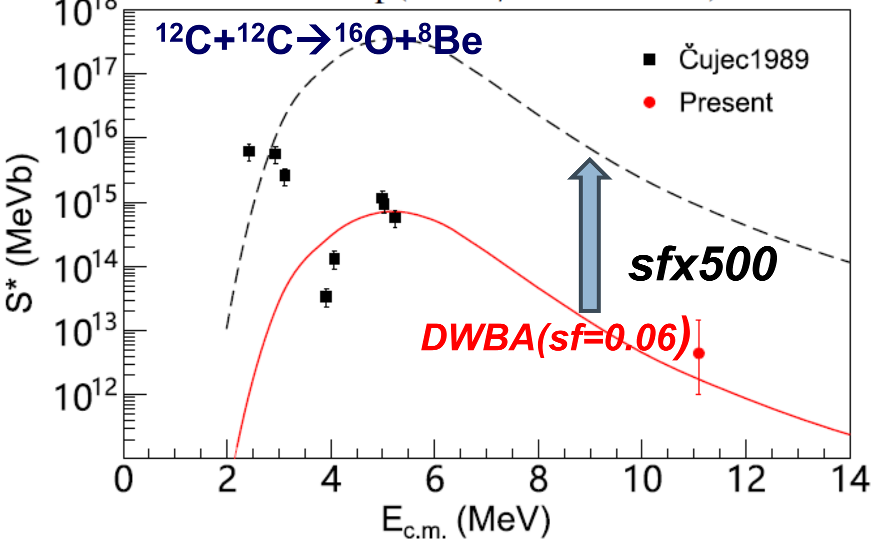
$^{12}C+^{12}C \rightarrow ^{12}O+3a$

- ✓ No peaks in the Q values
- ✓ Consistent with statistical calculations at E_{cm}>15 MeV
- ✓ At E_{cm}<15 MeV, other mechanisms are needed





$$S^* = \sigma \cdot E \cdot \exp(87.21/\sqrt{E} + 0.46E)$$



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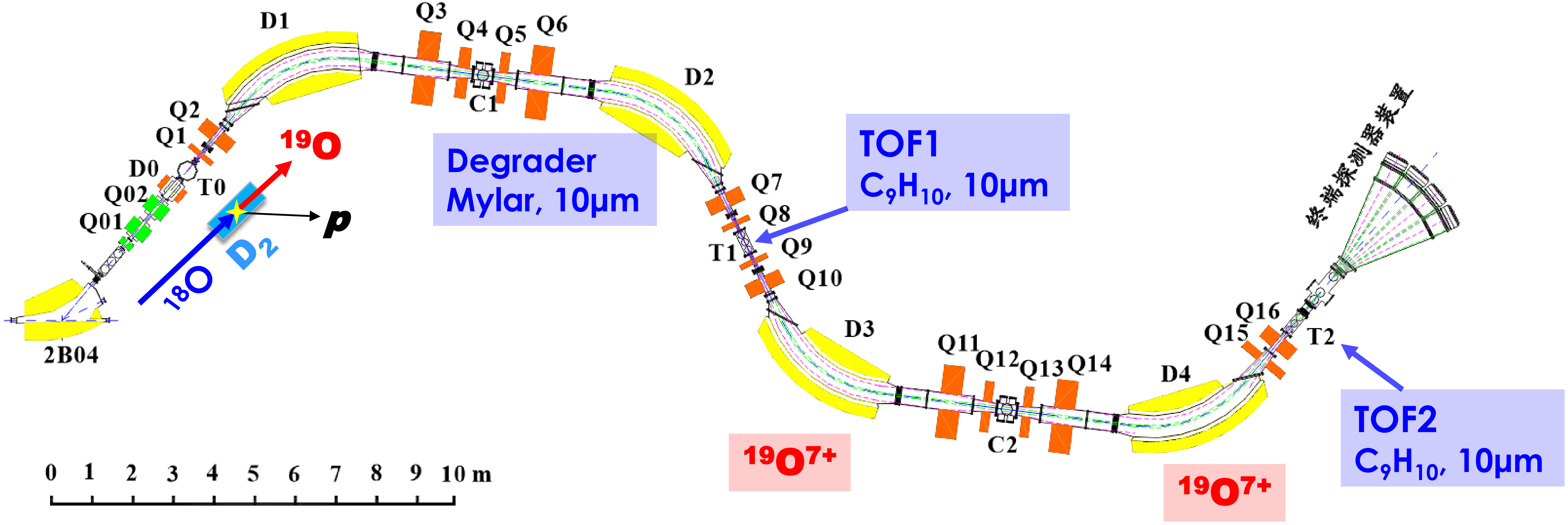
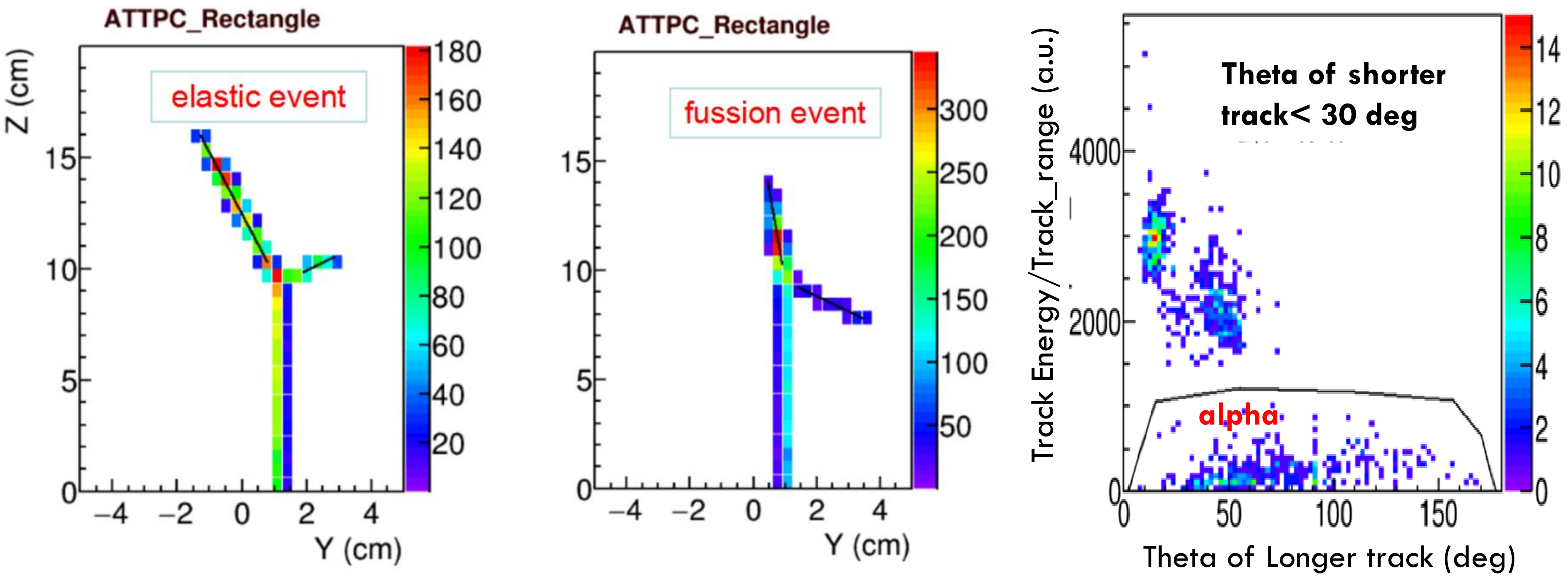
$^{19}O+^{12}C$ Fusion Experiment



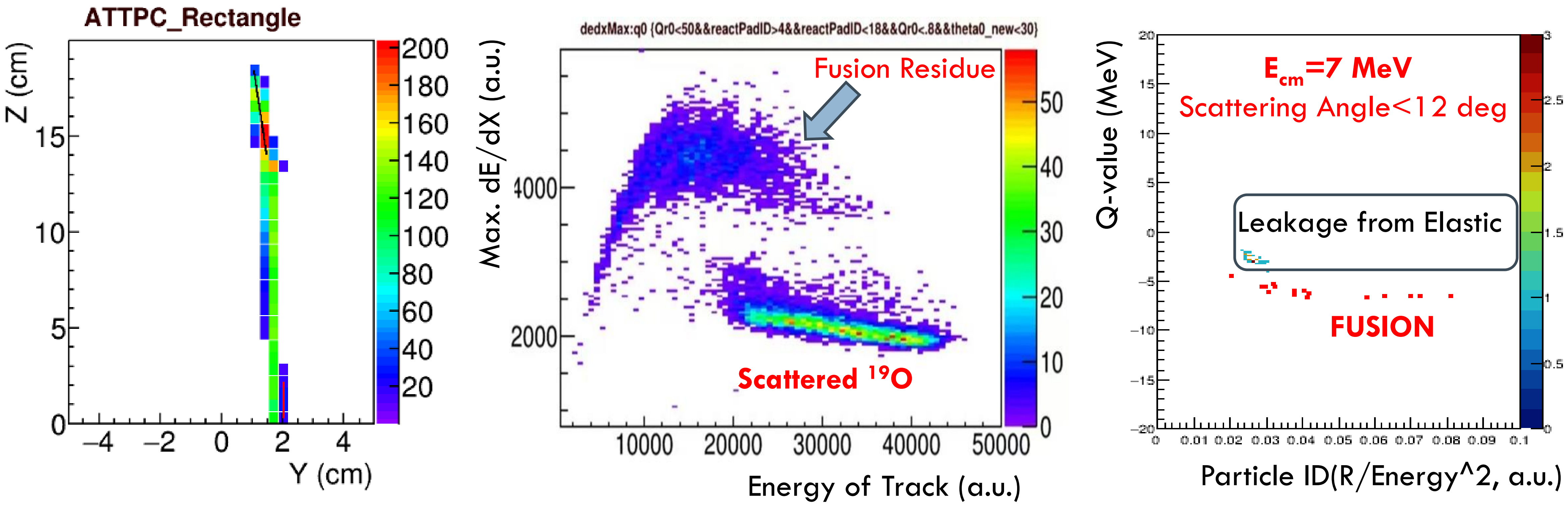
- **Primary beam: $^{18}O^{8+}$, 6.17MeV/u, 260enA (HIRFL)**
- **Primary target: D_2 gas cooled by LN_2 at 150mbar, 500mbar**
- **Second beam: $^{19}O^{7+}$, 10^3-10^4 pps (reduced to ~800 pps in measurement)**
  - **$^{18}O(d,p)^{19}O$ reaction**
  - **Purity: ~75%**

Data Analysis



- **TPC is capable of capturing alpha particles emitted from fusion reaction.**
- **Events with signature of light particles can be effectively distinguished from elastic scattering events.**

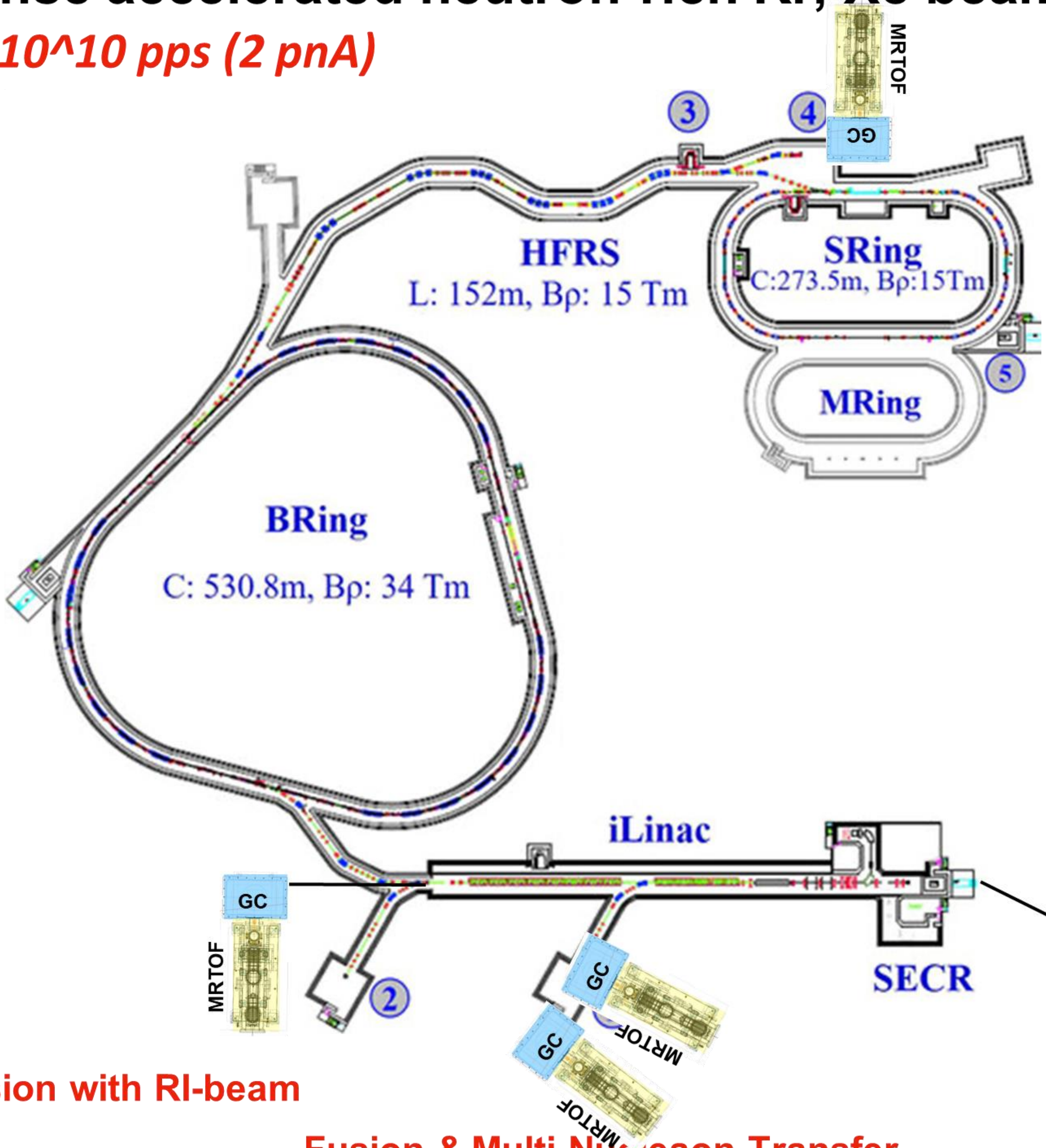
Data Analysis



- **TPC is capable of identifying the heavy residue based on the Energy and maximum dE/dx; But not sensitive to protons and neutrons**
- **Fusion events are further identified with Q-value (reconstructed using measured track length and angle) and Particle identification using Range/Energy^2**

Intense accelerated neutron-rich Kr, Xe beams with CiADS

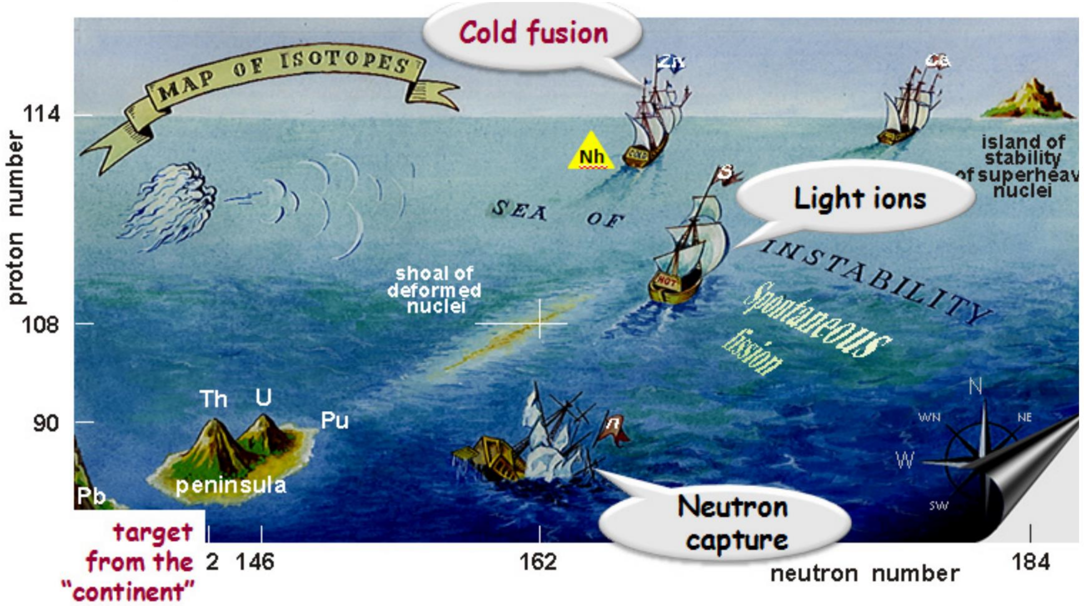
>10^10 pps (2 pnA)



Fusion with RI-beam

Fusion & Multi-Nucleaon-Transfer

Xsec~1nb, det. Eff. 10%
1 event/4 day



>100m LEBT with FODO Lattice

n-rich Kr-Xe production station at CiADS

CiADS Phase 1:
500MeV*10mA=5 MW

Courtesy of M. Wada (IMP)

Summary

- The new measurement of $^{19}O+^{12}C$ supports DC-TDHF which includes the dynamic effect (neck formation, nucleon transfer, and excitations..) are important
- The Enhancement of fusion reaction cross section by unpaired neutron is confirmed; Future studies with $^{20,21}O$ are interesting
- The particle-nA Neutron-rich beams ($^{140\text{-}142}Xe$, $^{90\text{-}93}Kr$) from CiADS+HIAF may open a new way to reach the ISLAND of STABILITY