中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

NSD 2019

Reactions with Exotic Nuclei at Near and Sub-barrier Energies

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Outline

1. Potentials of Exotic Nuclear Systems

2. Recent RIB experiments

3. Summary

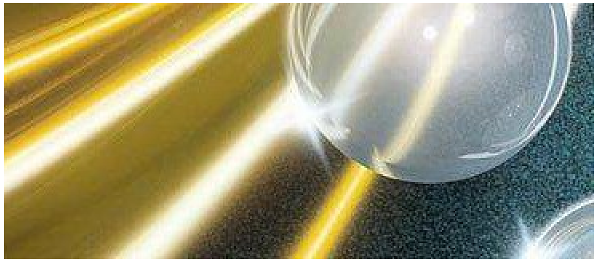
Optical Model Potential

♠ Optical Model is a successful model to explain the nuclear scattering and reaction, which resembles the case of light scattered by an opaque glass sphere.

Optical Model Potential (OMP):

$$\boxed{U = V(r) + iW(r)}$$

attractive **absorptive**



★phenomenological potential, independent on energy.

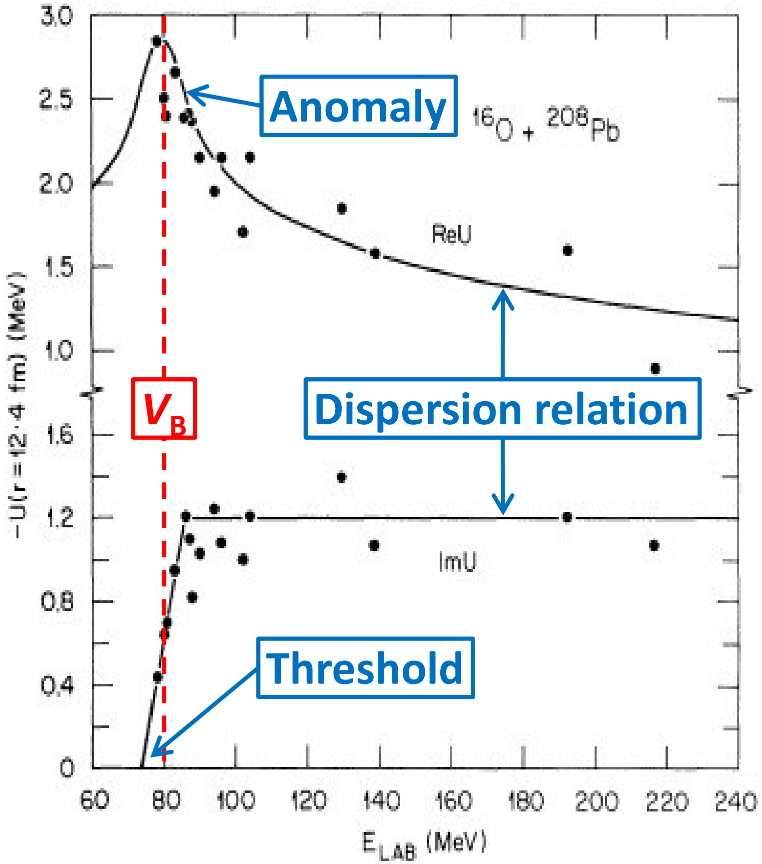
♠ A basic task in nuclear reaction study is to understand the nuclear interaction potential.

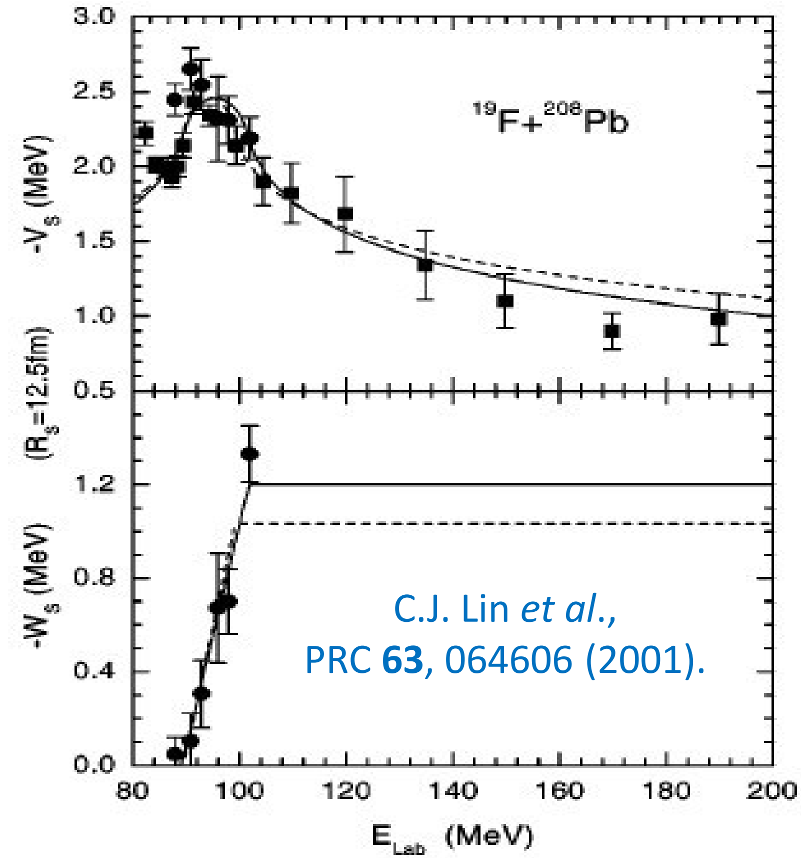
Cf: 1) S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. **73**, 1352 (1949).
2) H. Feshbach, “The optical model and its justification”, Ann. Rev. Nucl. Sci. **8**, 49 (1958).

Tightly-bound Nuclei

Threshold Anomaly

A universal phenomenon at energies around the Coulomb barrier



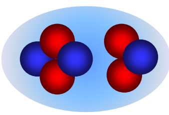


Cf: 1) M. A. Nagarajan, C. C. Mahaux, and G. R. Satchler, Phys. Rev. Lett. **54**, 1136 (1985).
2) C. Mahaux, H. Ngo, and G. R. Satchler, Nucl. Phys. **A449**, 354 (1986).
3) G. R. Satchler, Phys. Rep. **199**, 147 (1991).

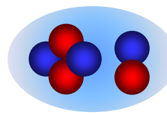
Weakly-bound Stable Nuclei

Threshold Anomaly

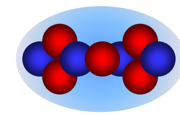
Abnormal Threshold Anomaly



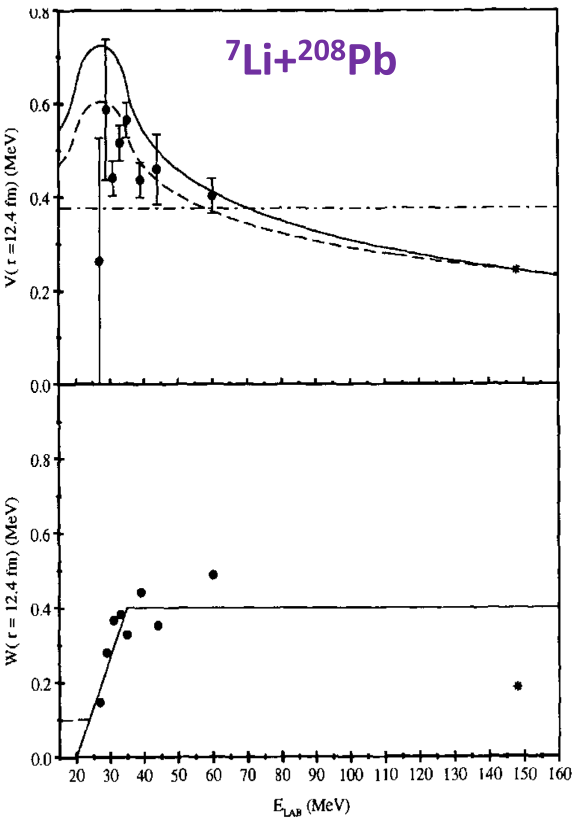
^{7}Li (α+t)
S_{α} = 2.47 MeV

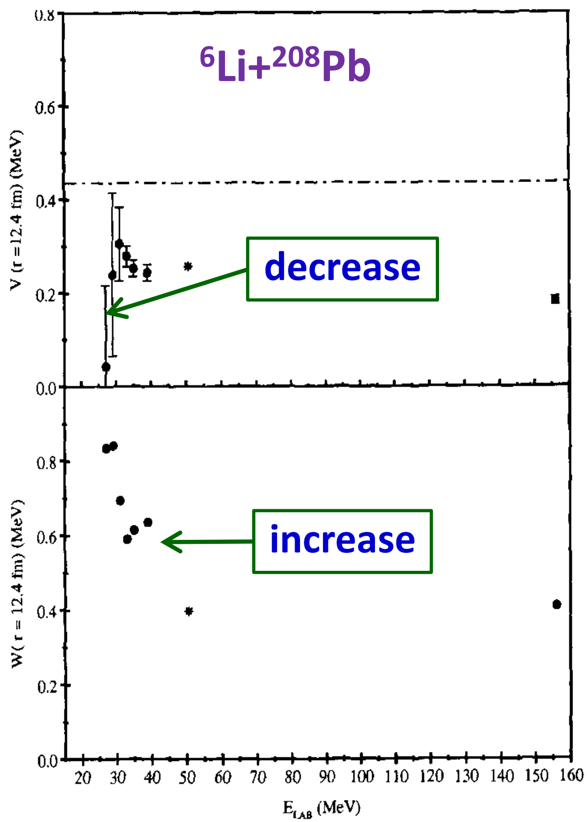


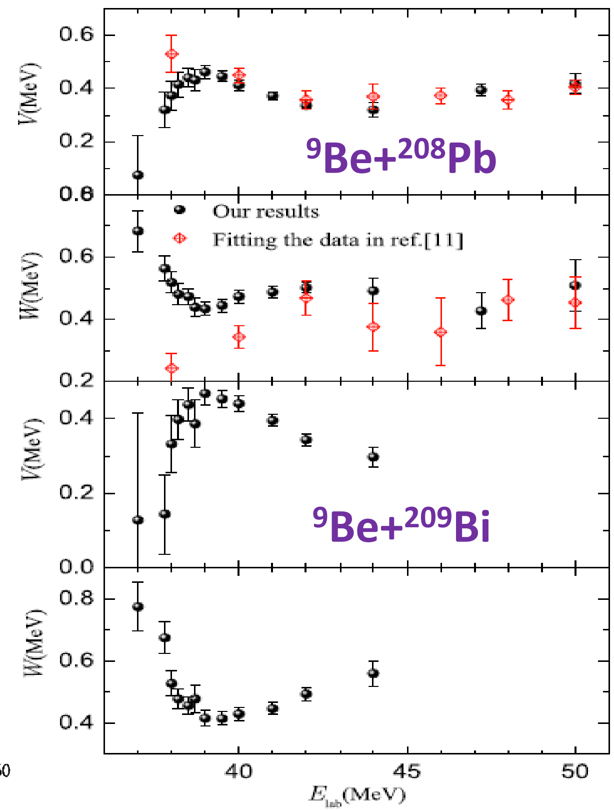
^{6}Li (α+d)
S_{α} = 1.47 MeV



^{9}Be (α+n+α)
S_{n} = 1.66 MeV



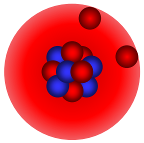




N. Keeley et al., Nucl. Phys. A **571**, 326 (1994).

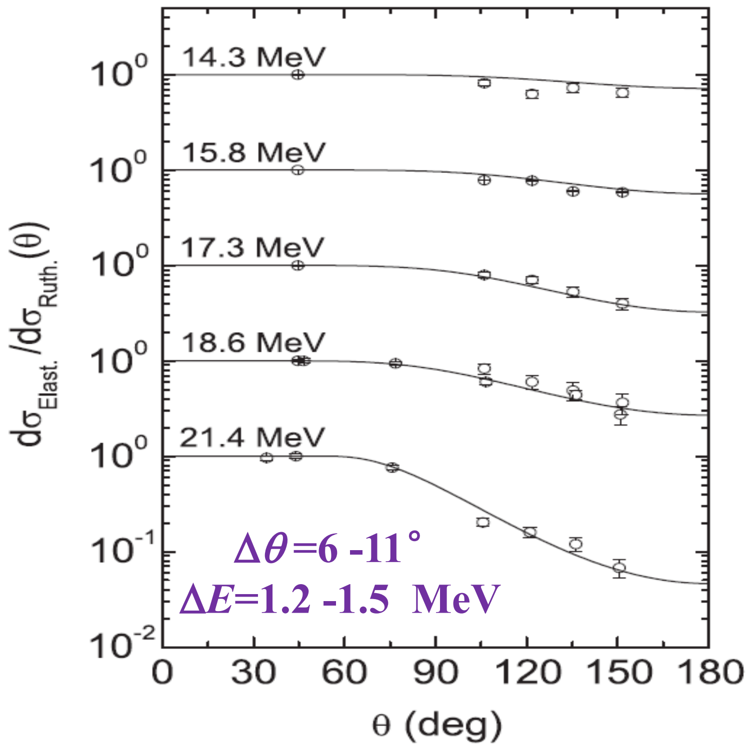
N. Yu et al., JPG **371**, 075108 (2010).

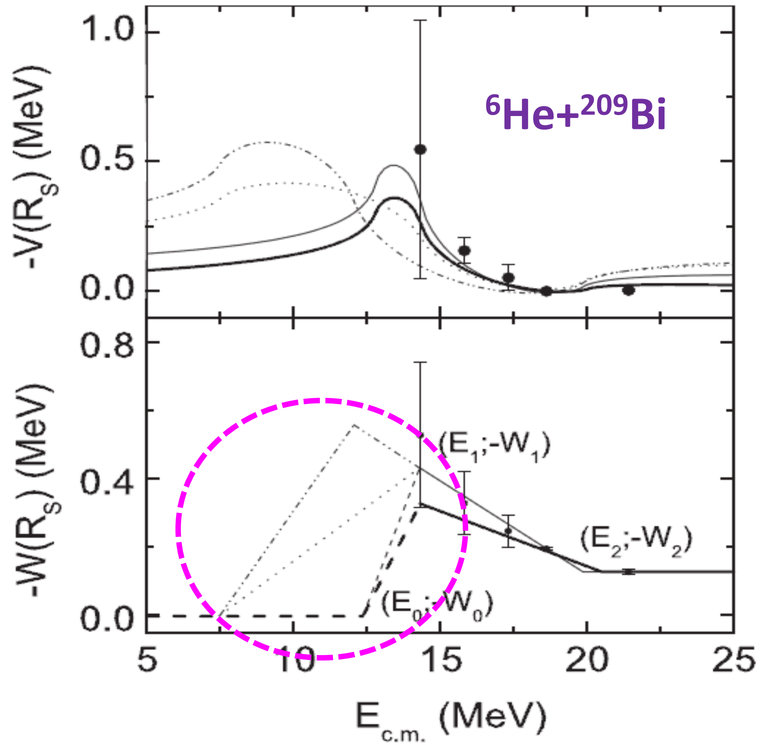
Exotic Nuclei



^{6}He (α+2n)
S_{2n} = 0.98 MeV

Abnormal Threshold Anomaly



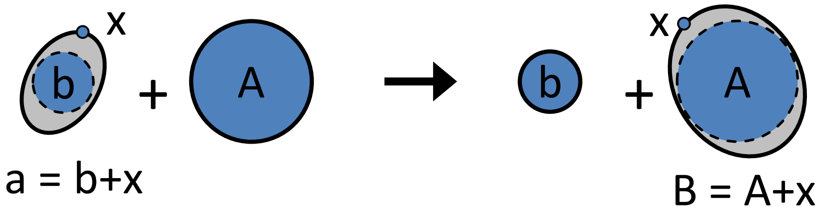


OMPs are usually extracted from elastic scattering.

★ Impossible to extract effective OMPs at energy far below the barrier.

Cf: 1) E.F. Aguilera *et al*., PRL **84**, 5058 (2000); PRC **63**, 061603R (2001).
2) A. R. Garcia *et al*., Phys. Rev. C **76**, 067603 (2007).

Transfer Method



$$\left(\frac{d\sigma}{d\Omega}\right)_{if} = P_{if}\left(\left(\frac{d\sigma}{d\Omega}\right)_{ii}\cdot\left(\frac{d\sigma}{d\Omega}\right)_{ff}\right)^{1/2}$$

Transfer reaction A(a,b)B

elastic scatting cross sections

Transition amplitude: $T = J\int d^3r_b\int d^3r_a\chi^{(-)}(\vec{k}_f,\vec{r}_b)^*\,\langle bB|V|aA\rangle\,\chi^{(+)}(\vec{k}_i,\vec{r}_a),$

4 wave functions are needed,

♣ two bound states: b+x & A+x (single-particle potential model)

♣ two scattering states: incoming & outgoing (optical potentials)

First presented at the FUSION06, Venice; C. J. Lin et al., AIP Conf. Proc. **853**, 81 (2006).

^{16}O(^{14}N,^{13}C)^{17}F: Chin. Phys. Lett. **25**, 4237 (2008).

^{11}B(^{7}Li,^{6}He)^{12}C: Chin. Phys. Lett. **26**, 022503 (2009). Phys. Rev. C **87**, 047601 (2013).

^{208}Pb(^{7}Li,^{6}He)^{209}Bi: Phys. Rev. C **89**, 044615 (2014), Il Nuovo Cimento C **39**, 367 (2016), Chin. Phys. Lett. **31**, 092401 (2014), Phys. Rev. C **96**, 044615 (2017), Phys. Rev. Lett. **119**, 042503 (2017).

^{63}Cu(^{7}Li,^{6}He)^{64}Zn: Phys. Rev. C **95**, 034616 (2017).

Experiments: $^{208}Pb(^7Li,^6He)^{209}Bi$

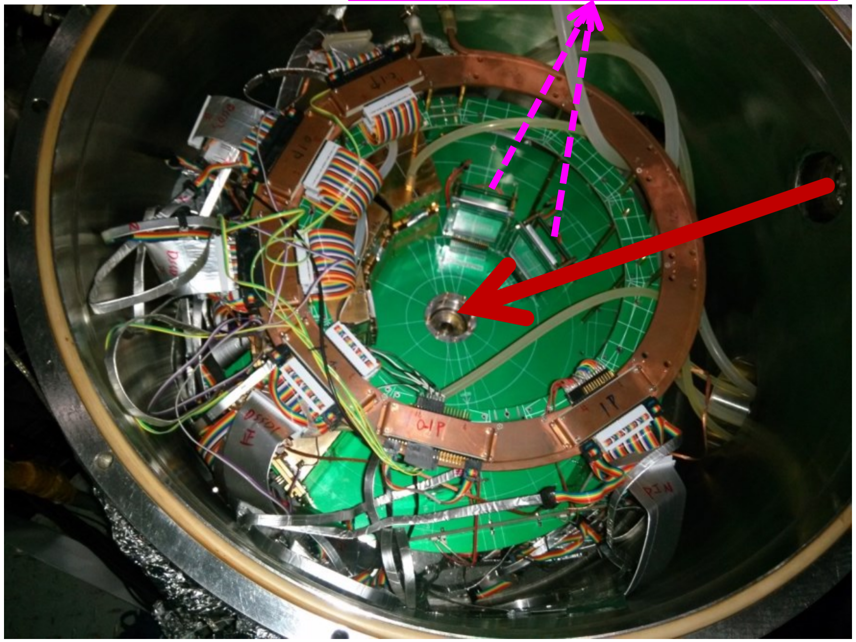
Two experiments have been done at HI-13 tandem accelerator @ CIAE

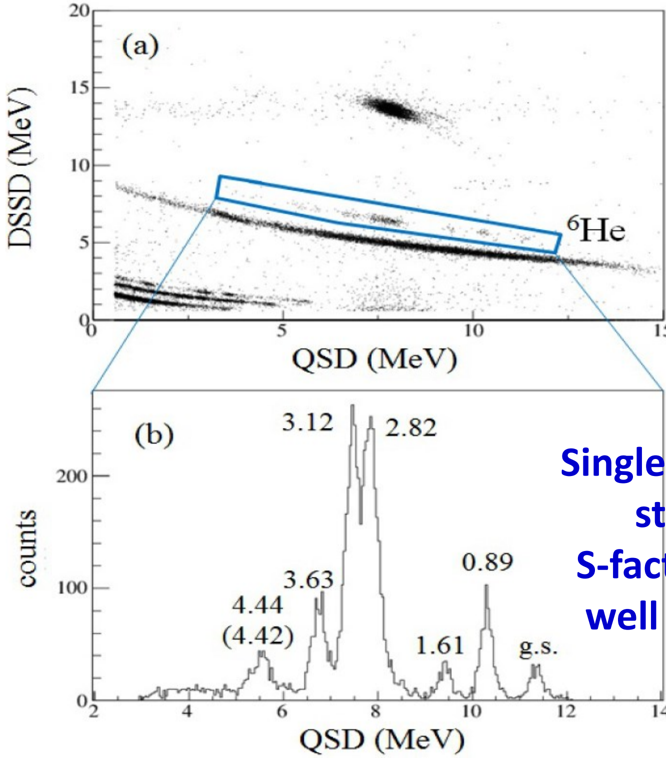
Exp1: E_{beam} = 42.55, 37.55, 32.55, **28.55**, 25.67 MeV – high energies 【2004.8】

Exp2: E_{beam} = **28.55**, 25.67, 24.3, 21.2 MeV -- low energies 【2016.4】

★Angular distributions of both **elastic** scattering and **transfer** were measured.

2 Telescopes: SSSD(20μm) + DSSD(60μm) + QSD(100μm)

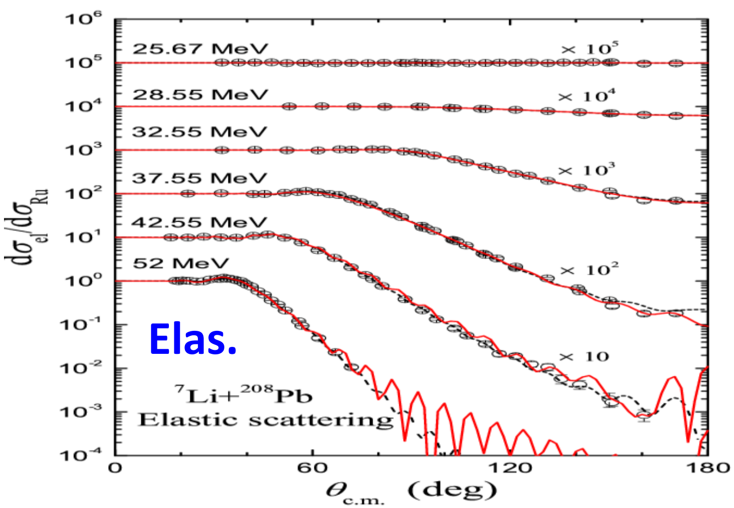


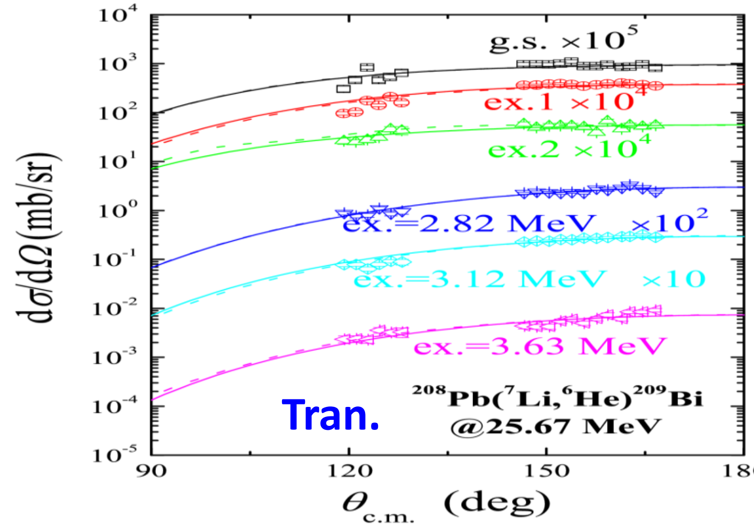


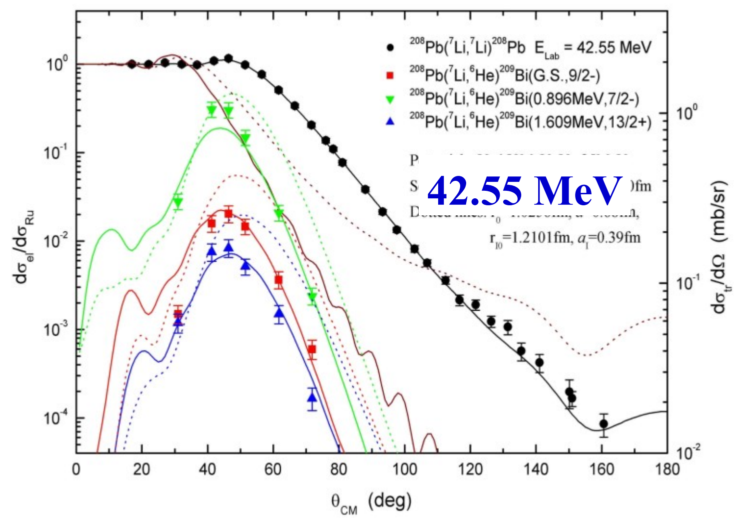
Single-particle states
S-factors are well known

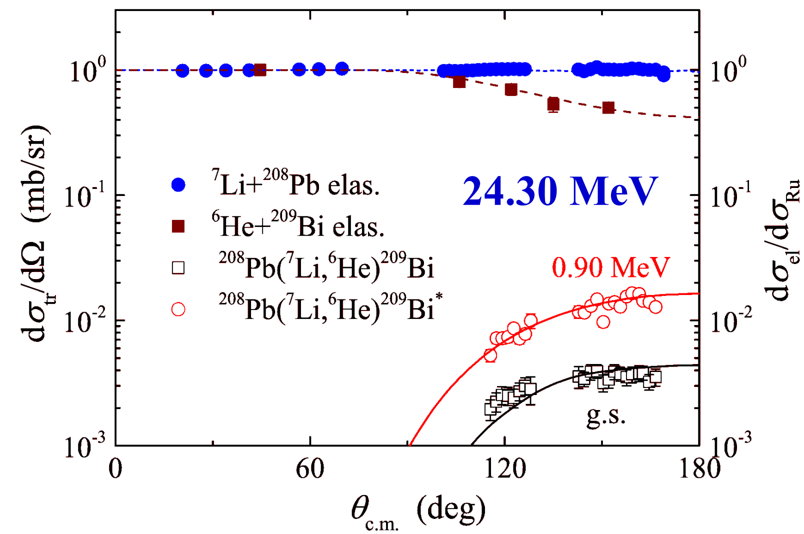
Analyses: ^{208}Pb(^{7}Li,^{6}He)^{209}Bi

DWBA & CRC analyses

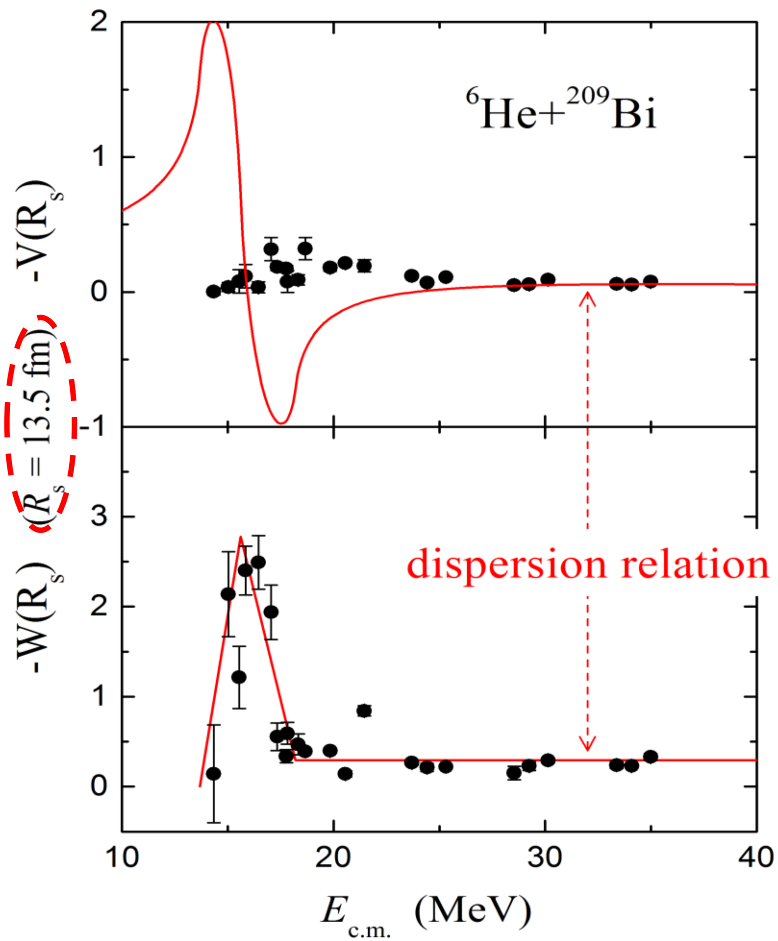








Results: $^{208}Pb(^{7}Li,^{6}He)^{209}Bi$



★ OMPs of the $^{6}He+^{209}Bi$ system are determined precisely;

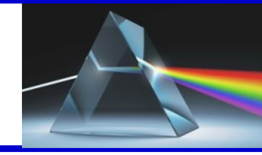
★ The decreasing trend in the imaginary part is observed, and the threshold energy is about 13.73 MeV (~0.68V_B);

★ The real part looks normal, i.e. like a bell shape around the barrier;

★ The dispersion relation cannot describe the behavior between the real and imaginary part.

L. Yang, C.J. Lin*, H.M. Jia et al., Phys. Rev. Lett. **119**, 042503 (2017);
Phys. Rev. C **96**, 044615 (2017).

Dispersion Relation

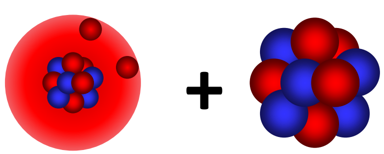


★ Dispersion relation results from causality, connecting real and imaginary part;
★ Any wave/particle should follow this rule when it passes through a media;
★ The classical dispersion relation is not applicable for exotic nuclear systems.

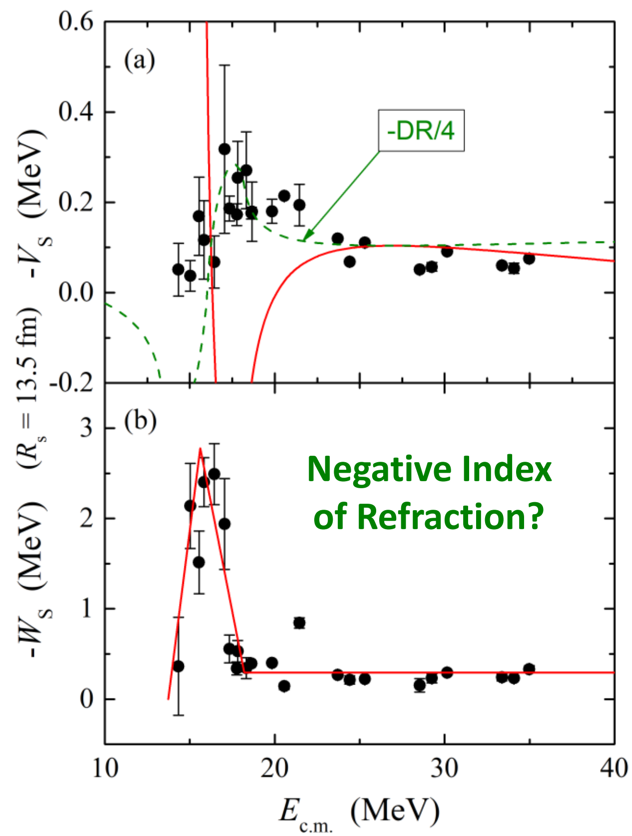
Possible reasons:

- **Causality → dispersion relation**
  stable systems: causality ↔ analyticity
- **Cauchy integration**
  infinity poles (breakup) & off-axis (multi-process)
- **Negative Index of Refraction**
  causality based criteria must be used with care
  [Phys. Rev. Lett. **101**, 167401 (2008).]
- **Locality vs. non-locality**
  equivalent local potential in Schrödinger equation

Metamaterials?



four-body



Outline

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Reactions with RIBs

♠ **Elastic scattering**

3-body, 4-body

CDCC …

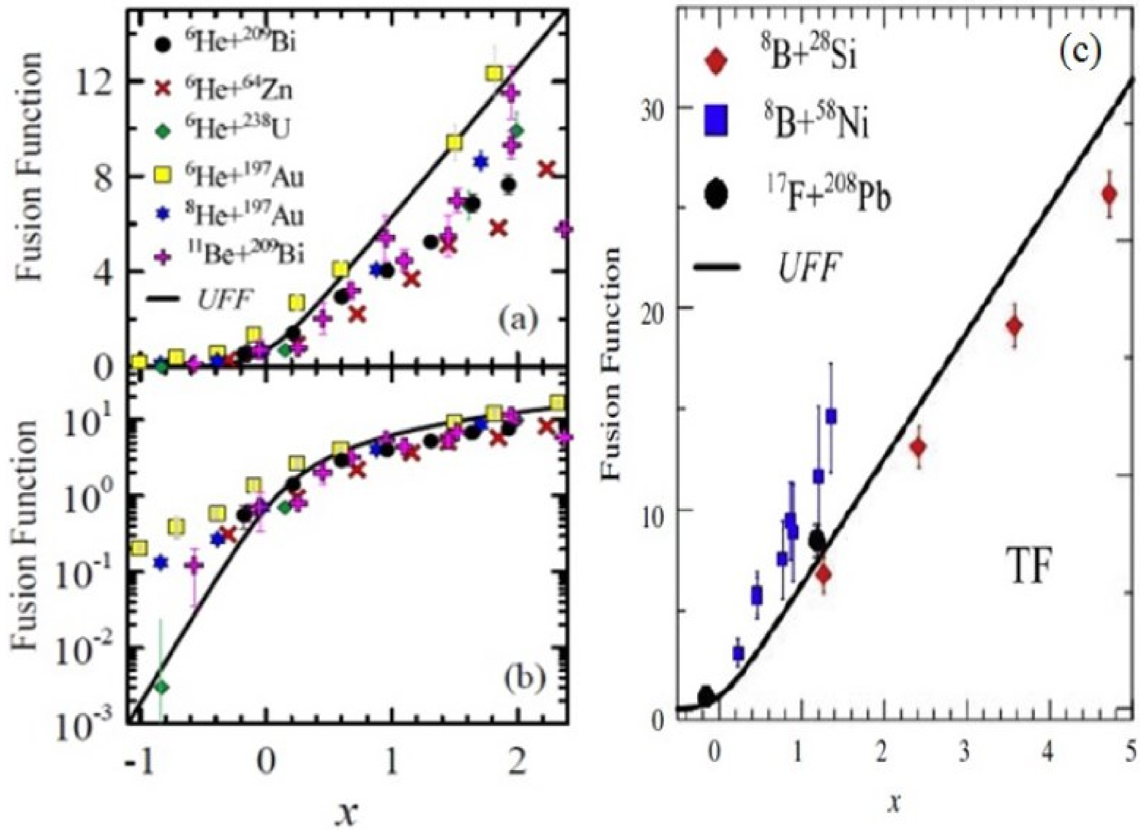
♠ **Fusion**

TF, ICF, CF …

♠ **Breakup/transfer**

Effects & mechanisms

neutron-rich **proton-rich**

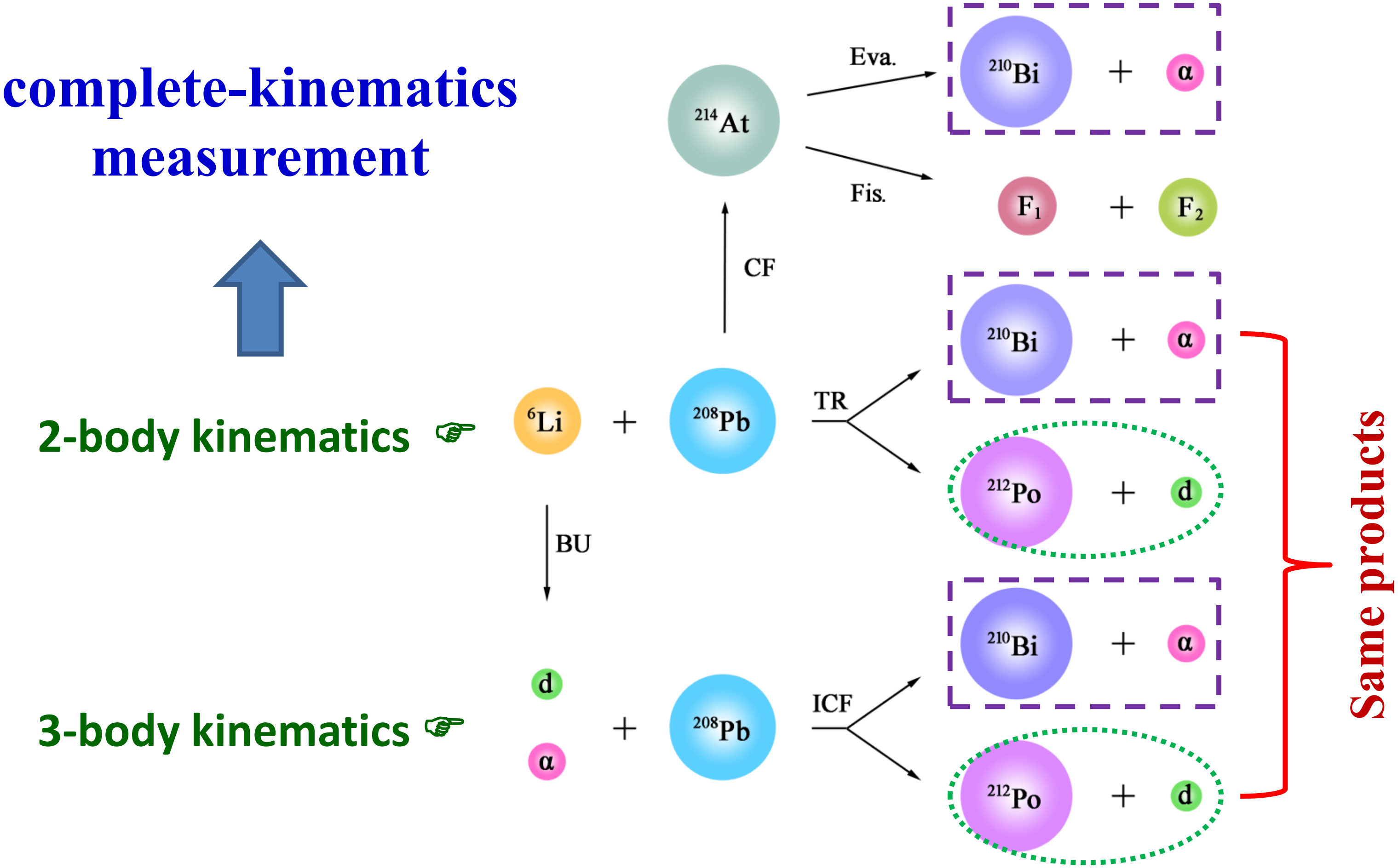


[1] L. F. Canto, P. R. S. Gomes, R. Donangelo et al., Phys. Rep. 424, 1 (2006).
[2] L. F. Canto, P. R. S. Gomes, R. Donangelo et al., Phys. Rep. 596, 1 (2015).
[3] B. B. Back, H. Esbensen, C. L. Jiang and K. E. Rehm, Rev. Mod. Phys. 86, 317 (2014).

BK/TR Processes

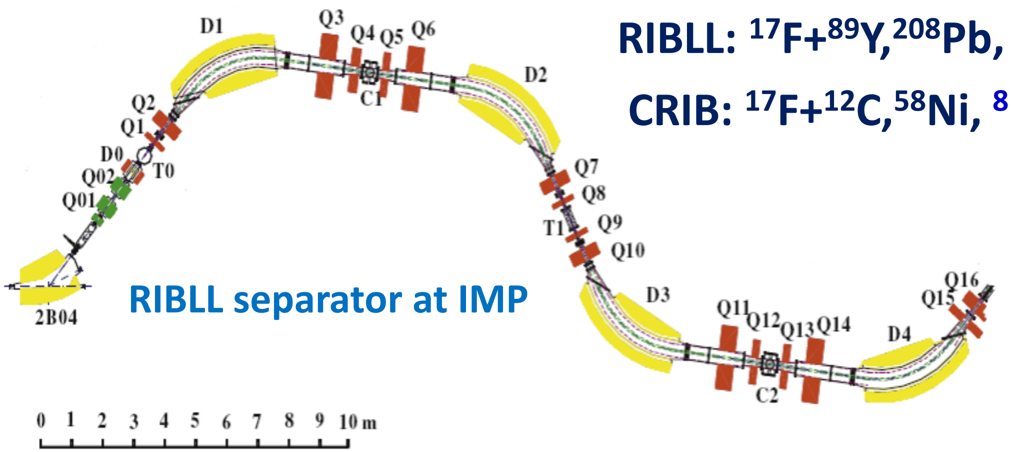
★ How to identify the different reaction process?

complete-kinematics measurement



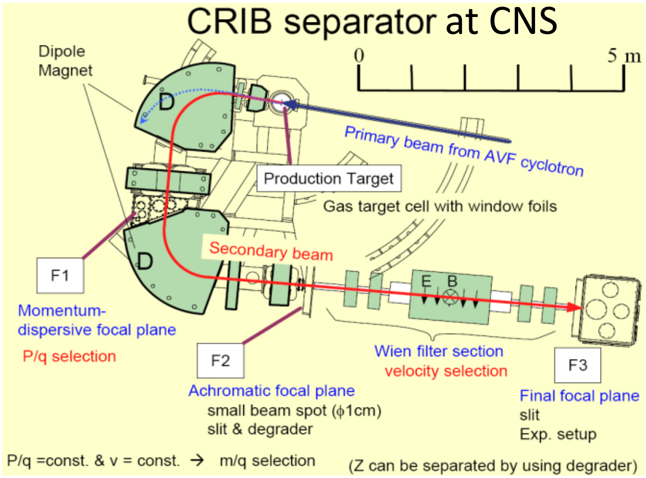
Recent Experiments

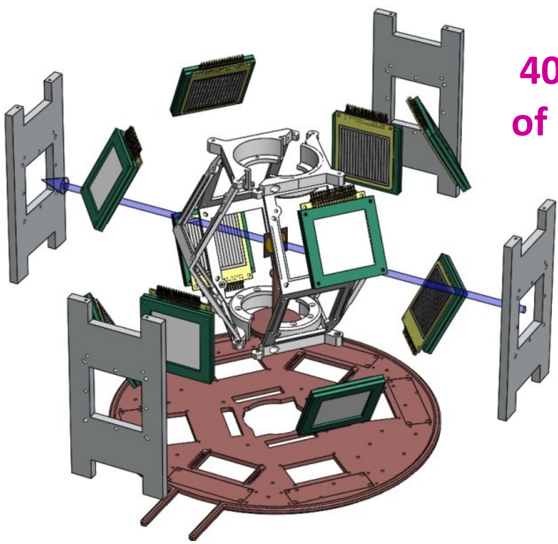
★ **Complete-kinematics measurement ;** ★ **Reactions induced by ^{7}Be, ^{8}B, ^{17}F …**



RIBLL: ^{17}F+^{89}Y,^{208}Pb, ^{7}Be+^{209}Bi

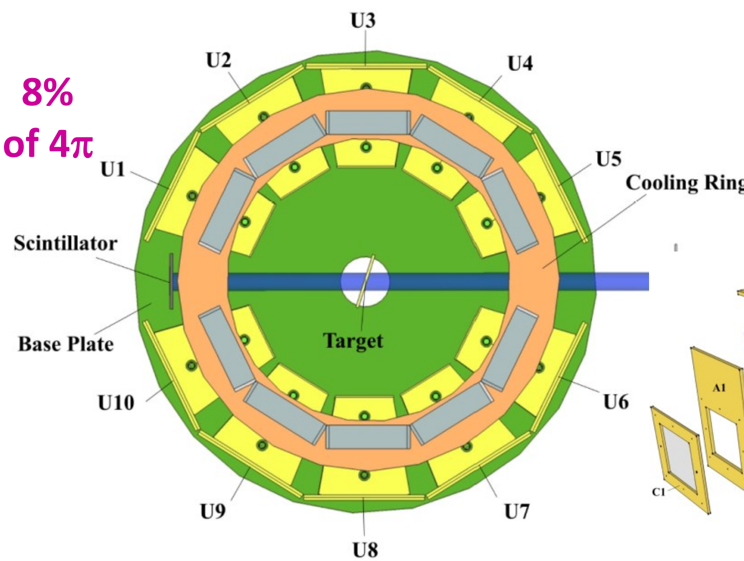
CRIB: ^{17}F+^{12}C,^{58}Ni, ^{8}B+^{120}Sn



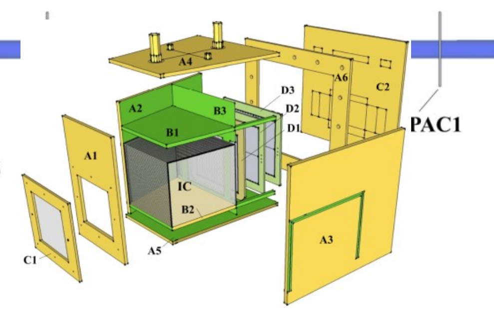


40% of 4π

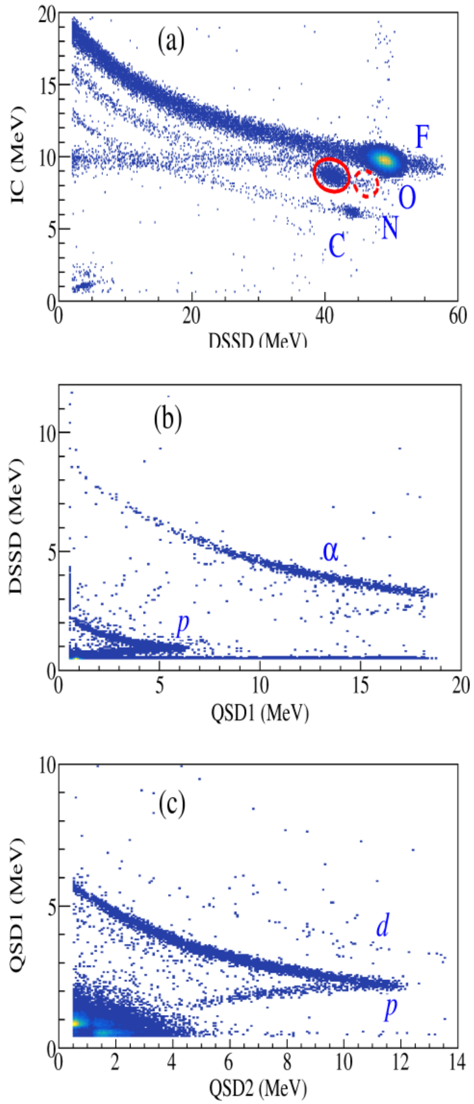
8% of 4π

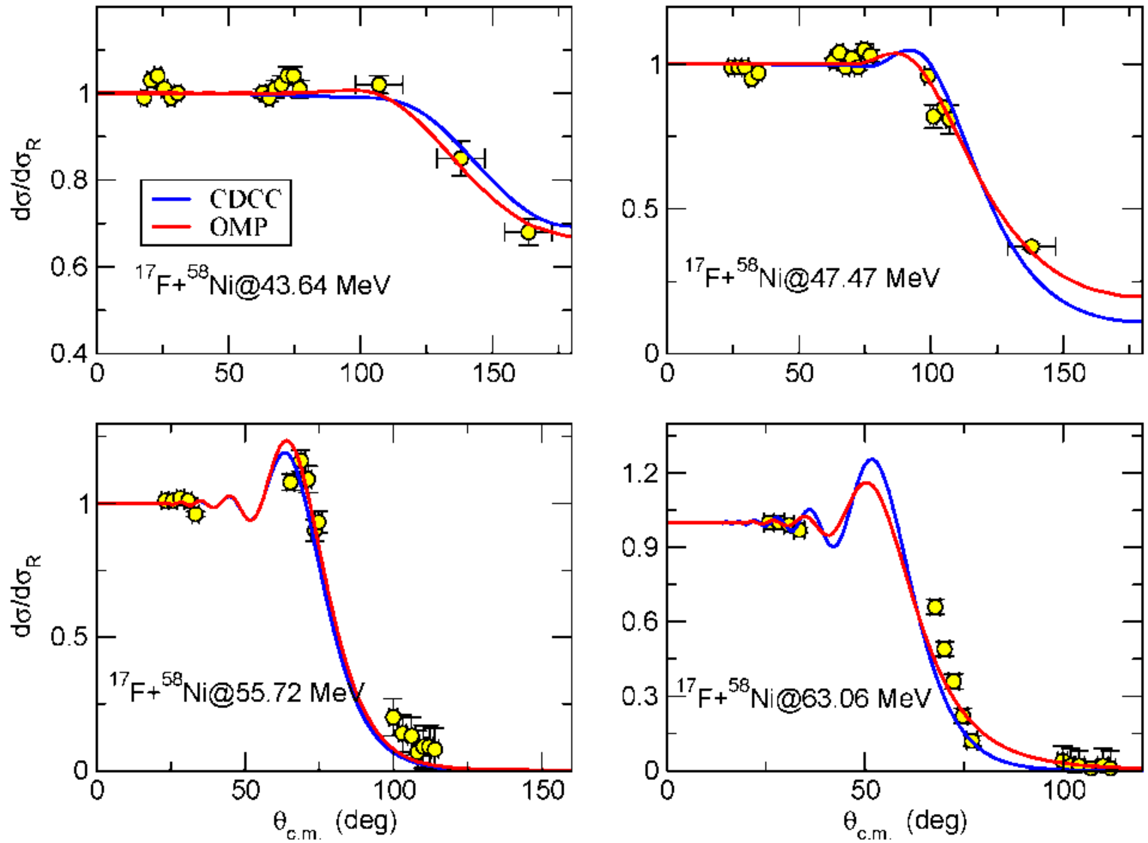


40/60 μm DSSD
300 μm QSD
1-1.5 mm QSD



Preliminary Results: $^{17}F+^{58}Ni$

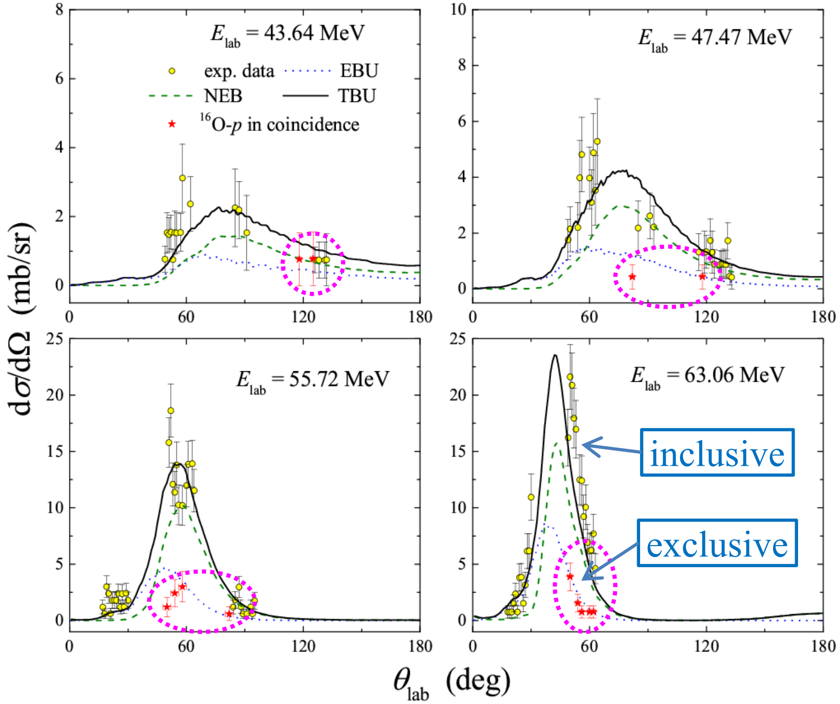




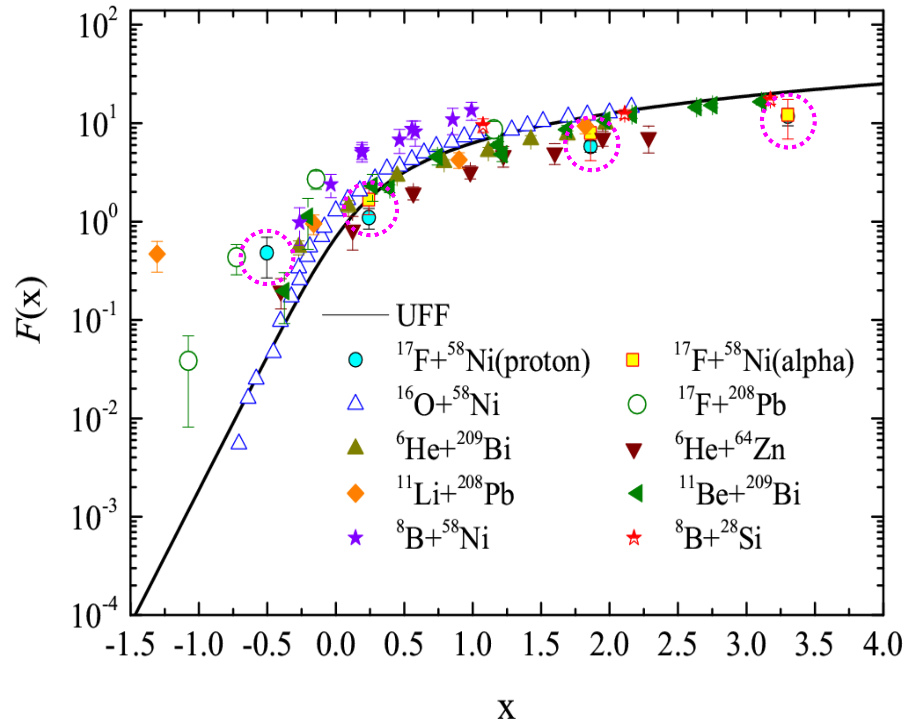
Angular distributions of **quasi-elastic scattering**.

[OMP & CDCC calculated by Lei Jin]

Preliminary Results: $^{17}F+^{58}Ni$



Angular distributions of **breakups/transfer**
[theoretical calculated by Lei Jin]



Fusion excitation functions of
$^{17}F+^{58}Ni$ and other systems

Preliminary conclusions:

- The non-elastic breakups are dominant at energies around the barrier;
- Fusions are suppressed (enhanced) at energies above (below) the barrier.

Exclusive Breakup

★ **Exclusive breakup** (^{17}F $\rightarrow$ ^{16}O + p, S_p = 0.6 MeV)

Our result: **σ ~ 1.2 mb @ 63 MeV**; Liang's result: **σ ~ 15.6 mb @ 170 MeV**.

[J.F. Liang et al., PLB 681, 22 (2009).]

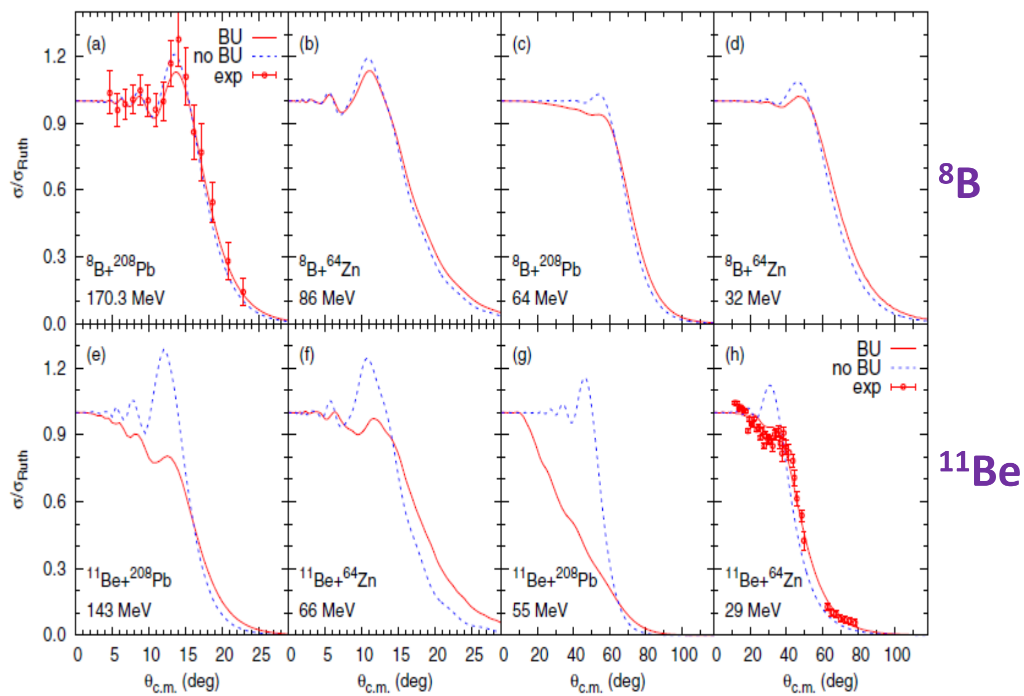
Others (^{7}Be, ^{8}B …) also show very low cross sections of exclusive breakup.

★ **Why is it so low?**

Possible reasons:

- **Constraint by the Coulomb barrier, (need to penetrate the barrier)**
- **Screen effects due to the Coulomb repulsion (dynamic polarization)**

Coulomb rainbow



Y.Y. Yang et al., Phys. Rev. C94, 034614

Summary

★ **Optical potentials** of exotic nuclear systems have been extracted by the **transfer method**. The complete picture of abnormal "threshold anomaly" for the ^{6}He+^{209}Bi system has been obtained. The classical **dispersion relation** cannot descript the behavior between the imaginary potential and real potential.

★ Reactions of **^{17}F+^{12}C, ^{58}Ni, ^{89}Y, ^{208}Pb, ^{7}Be+^{209}Bi, and ^{8}B+^{120}Sn** systems have been systematically measured by the **complete-kinematics measurement** method with large solid-angle covered detector array. The **exclusive breakup cross sections** (in coincidence) were found to be very low, which needs further understand.

Collaborators

Affiliations

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7. Department of Physics, Sungkyunkwan University, Suwon 16419, Korea
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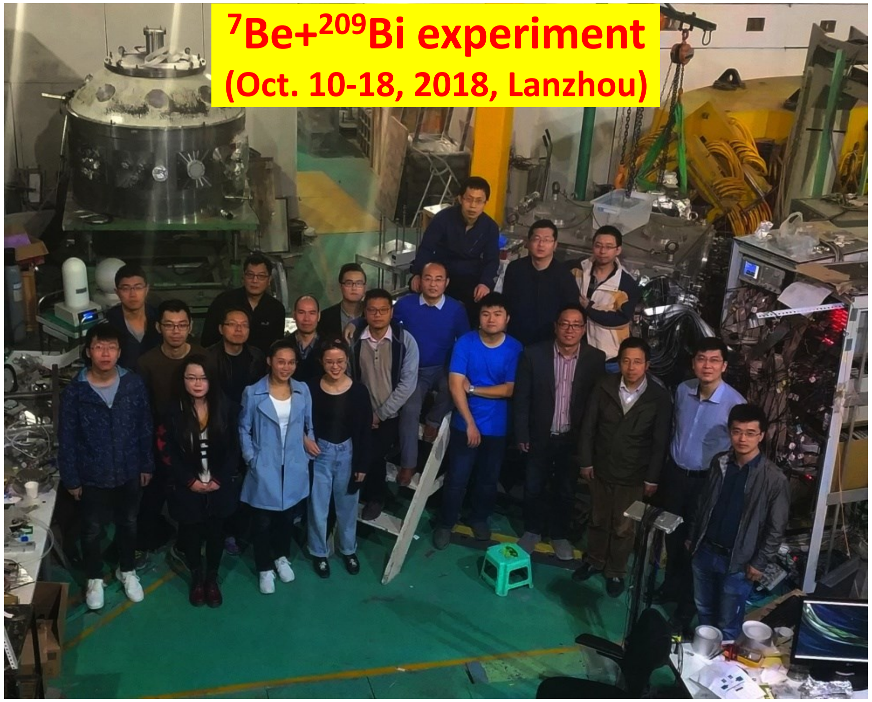
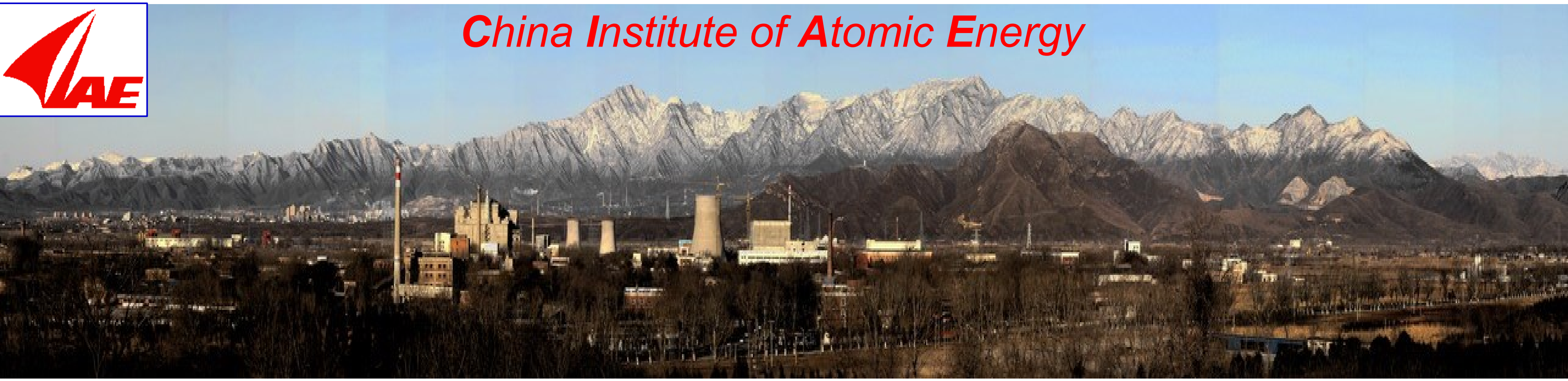
9. Istituto Nazionale di Fisica Nucleare-Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy
10. Department of Physics, Guangxi Normal University, Guilin 541004, China
11. National Innovation Center of Radiation Application, Beijing 102413, China

… …



$^{7}Be+^{209}Bi$ experiment
(Oct. 10-18, 2018, Lanzhou)

Thank you for your attention!



Exotic Nuclei

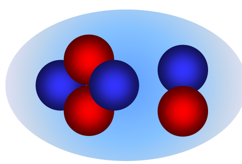
- **Exotic nuclei:**

  weakly-bound & having unusual structures (cluster, halo/skin …)

- **Reactions with exotic nuclei:**

  easily breakup, strongly couplings to continuum state …

cluster



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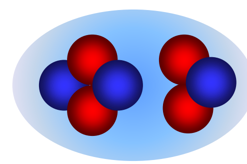
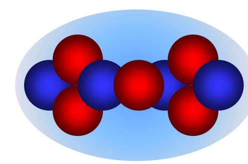
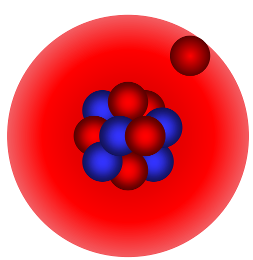


^{7}Li (α+t)
$S_{\alpha} = 2.47$ MeV

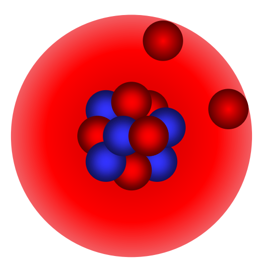


^{9}Be (α+n+α)
$S_{n} = 1.66$ MeV

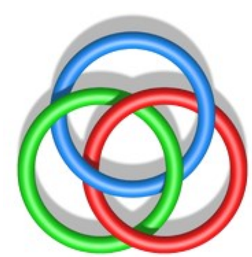
halo



^{11}Be (^{10}Be+n)
$S_{n} = 0.50$ MeV

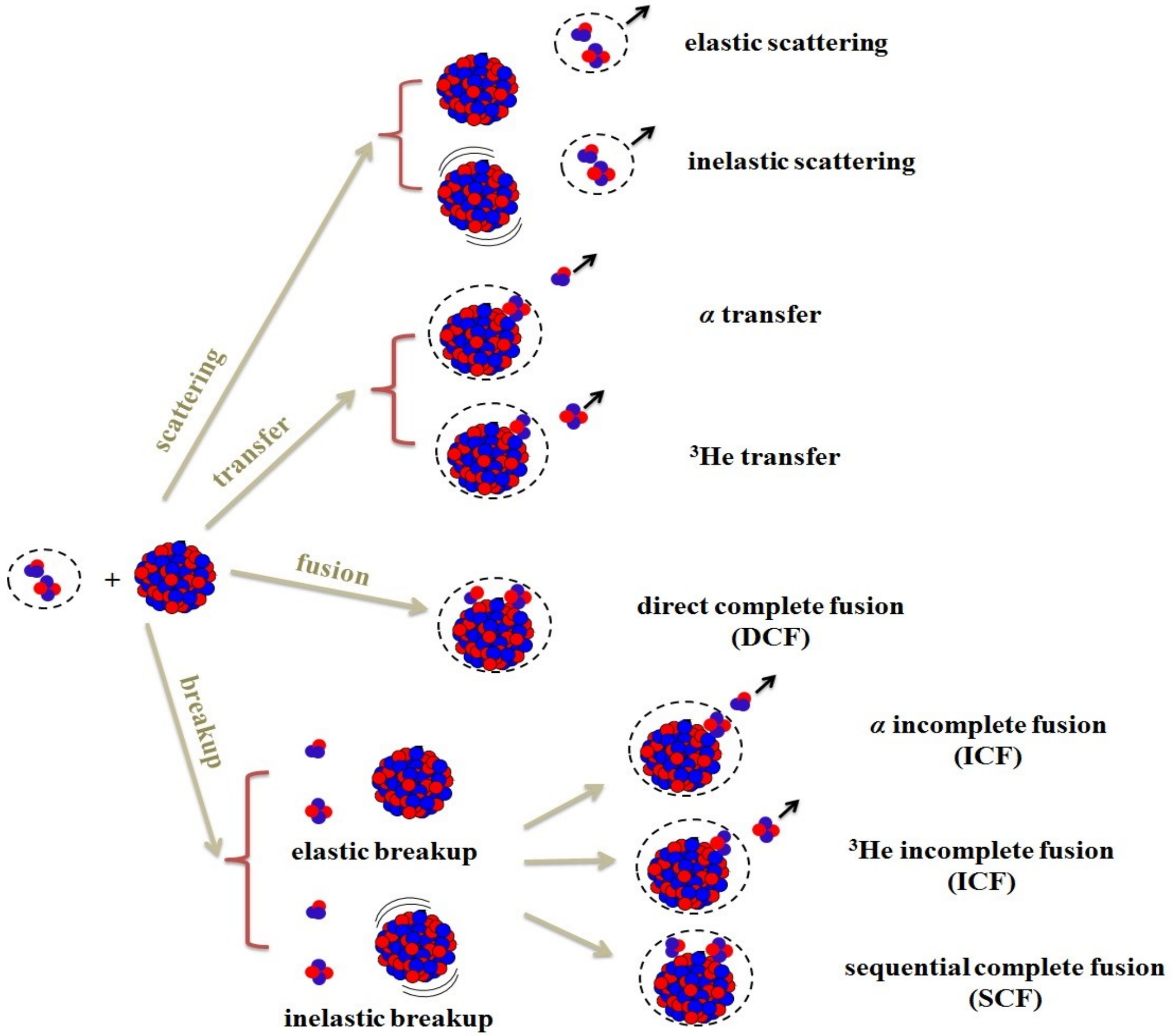


^{6}He (α+2n)
$S_{2n} = 0.98$ MeV



Borromean

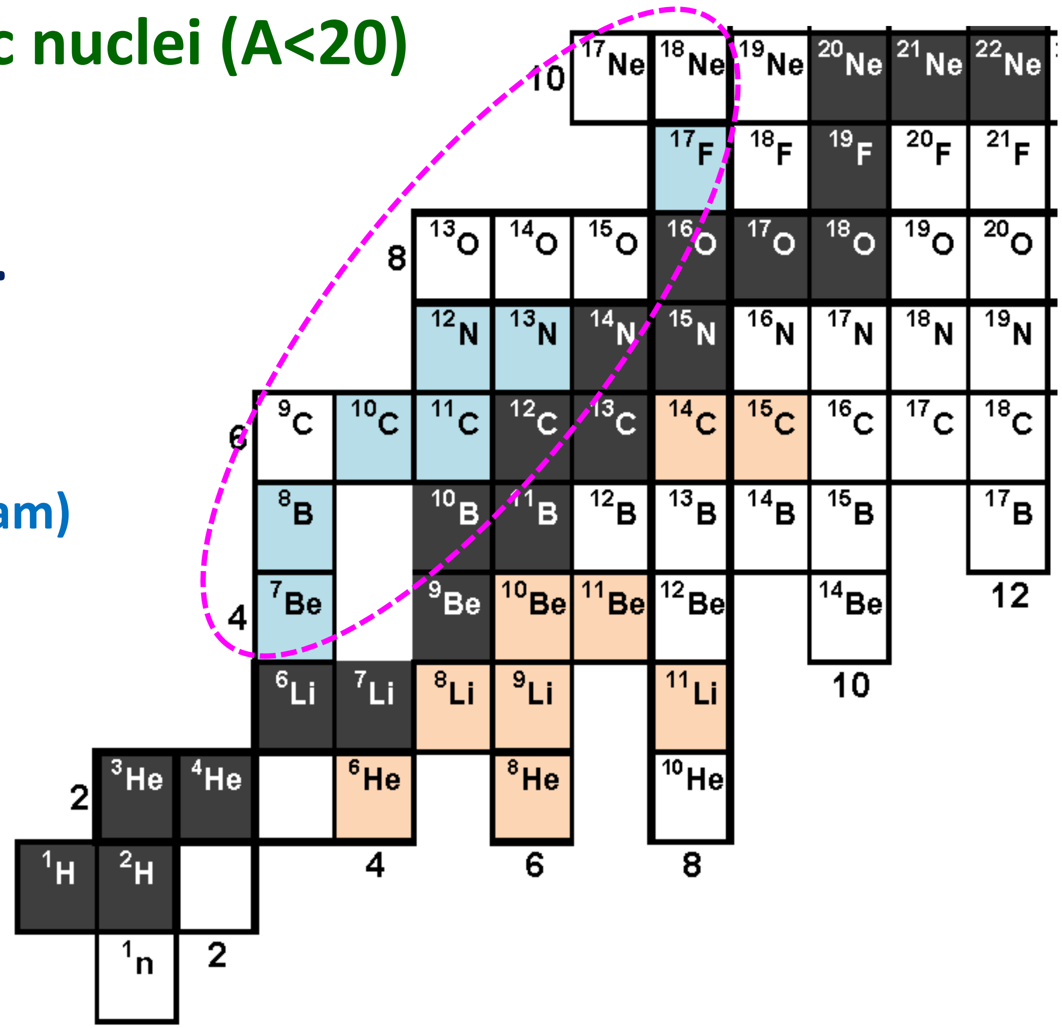
Reactions with Exotic Nuclei



Light Exotic Nuclei

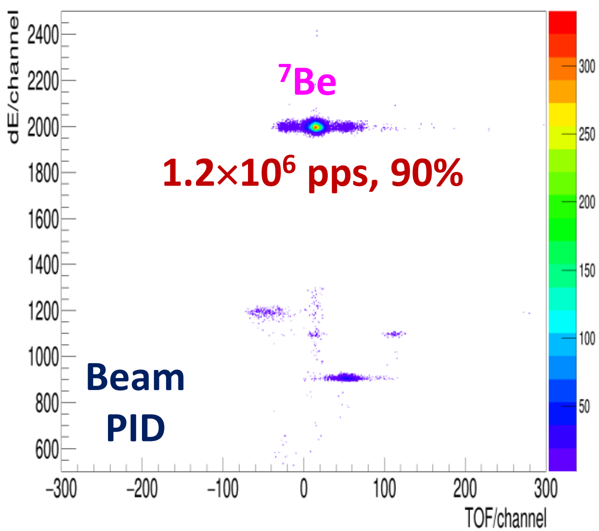
Reactions with light exotic nuclei (A<20)

- Elastic, fusion, breakup …
- Proton-rich nuclei
- ^{7}Be, ^{8}B, ^{17}F (Key R&D Program)
  ^{12}N, ^{17,18}Ne …
- Complete-kinematics measurement
  (particle identification & large solid-angle covered)



J.J. Kolata *et al.*, Eur. Phys. J. A 52, 123 (2016).

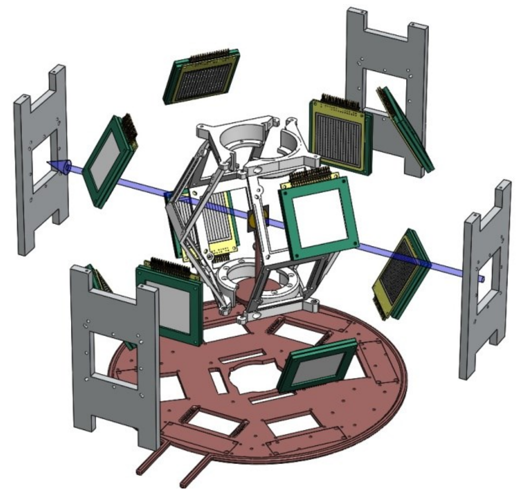
The ^{7}Be+^{209}Bi Experiment



p(^{7}Li, ^{7}Be)n

^{7}Li: 8.8 MeV/u, 1.5 euA

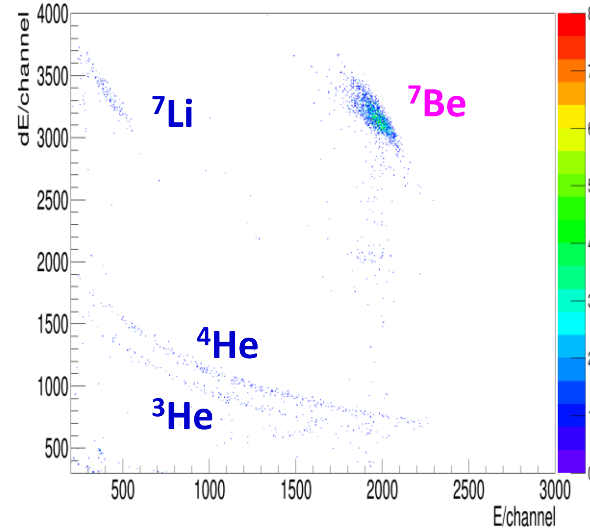
H_2 gas: 1000 mbar, 8 cm, 90 K



20/40μm SSD + 300μm QSD + 1.5mm QSD

10 group of ΔE-ΔE-E telescopes

40% of 4π



ΔE-ΔE spectrum

by 40μm DSSD & 300μm QSD

(1 strip, 1 run, 2 hours)

1. Exclusive breakup: ^{7}Be → ^{3}He+^{4}He (coin. Eff. ~10% by MC simulations);
2. ^{4}He stripping: ^{7}Be+^{209}Bi → ^{3}He+^{213}At;
3. ^{3}He stripping: ^{7}Be+^{209}Bi → ^{4}He+^{212}At;
4. 1*n* stripping: ^{7}Be+^{209}Bi → ^{6}Be(→^{4}He+*p*+*p*)+^{210}Bi;
5. 1*n* pickup: ^{7}Be+^{209}Bi → ^{8}Be(→^{4}He+^{4}He)+^{208}Bi;
6. 1*p* striping: ^{7}Be+^{209}Bi → ^{6}Li(→^{4}He+*d*)+^{210}Po;
8. 1*p* pickup: ^{7}Be+^{209}Bi → ^{8}B(→???)+^{208}Pb;
9. Fusion: ^{7}Be+^{209}Bi → ^{216}Fr → *α*, *p*, *n* eva. & decay (energy & angular distri.)

$\left.\begin{array}{l}2.\\3.\\4.\\5.\\6.\\8.\end{array}\right\}$ **ICF** (Ene-Ang corr.)