Reactions of weakly-bound nuclei at near-barrier energies

Chengjian Lin (cjlin@ciae.ac.cn)

China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413

7th International Workshop of the Hellenic Institute of Nuclear Physics under the auspices of HNPS on Nuclear Structure, Astrophysics and Reaction Dynamics

31 May – 1 June 2024, Ioannina, Greece

Contents

1. OMPs of weakly-bound nuclear systems

   ^{6}He+^{209}Bi, ^{6}Li+^{208}Pb

2. Breakups of weakly-bound nuclei

   - stable nuclei: ^{6,7}Li+^{209}Bi
   - proton-rich nuclei: ^{17}F+^{58}Ni, ^{8}B+^{120}Sn

3. Summary and outlook

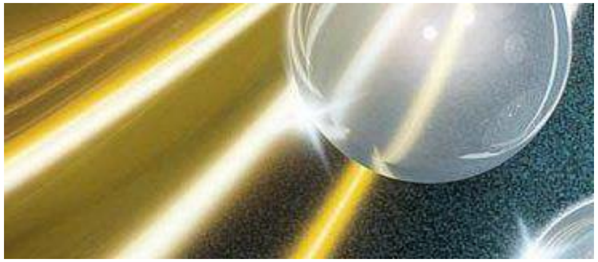
Optical Model Potential

- ♠ 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**



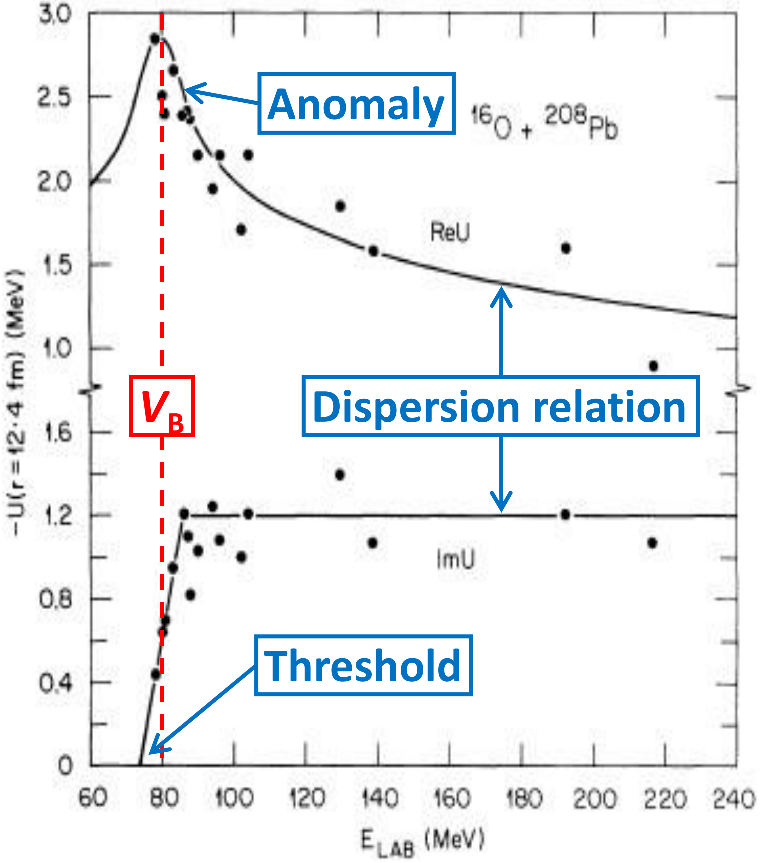
★phenomenological potential, independent on energy.

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

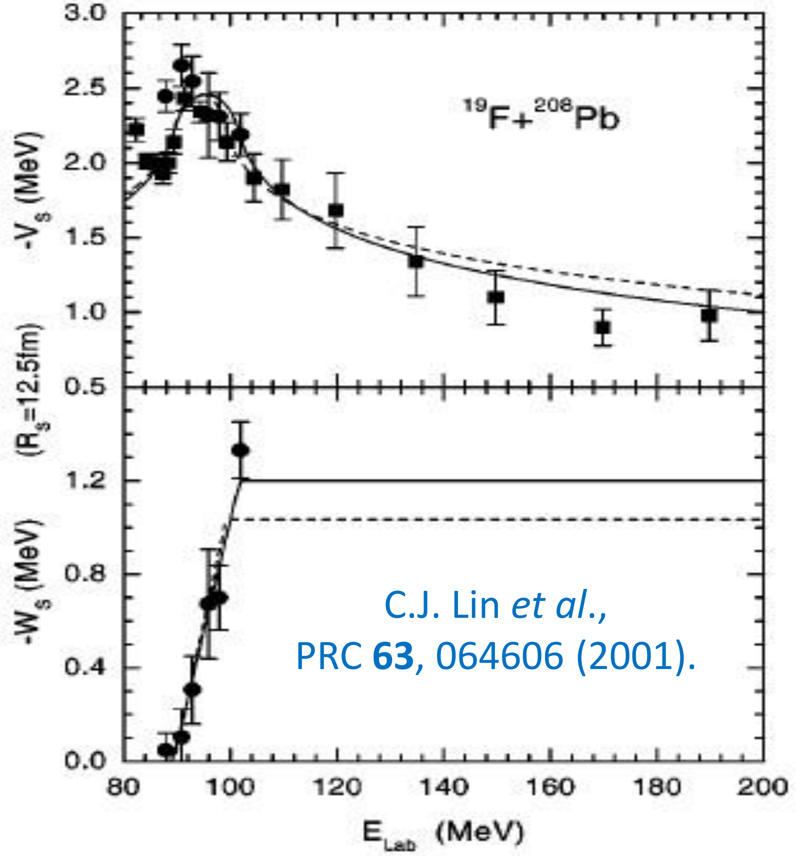
Cf: 1) S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. **73**, 1352 (1949).
2) H. Feshbach, "The optical model and its justification", Ann. Rev. Nucl. Sci. **8**, 49 (1958).

Tightly-bound Nuclei

Threshold Anomaly



A universal phenomenon
at energies around the Coulomb barrier



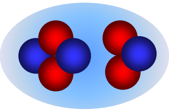
C.J. Lin *et al.*,
PRC **63**, 064606 (2001).

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).

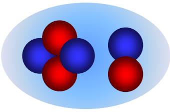
Weakly-bound Stable Nuclei

Threshold Anomaly

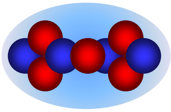
Abnormal Threshold Anomaly



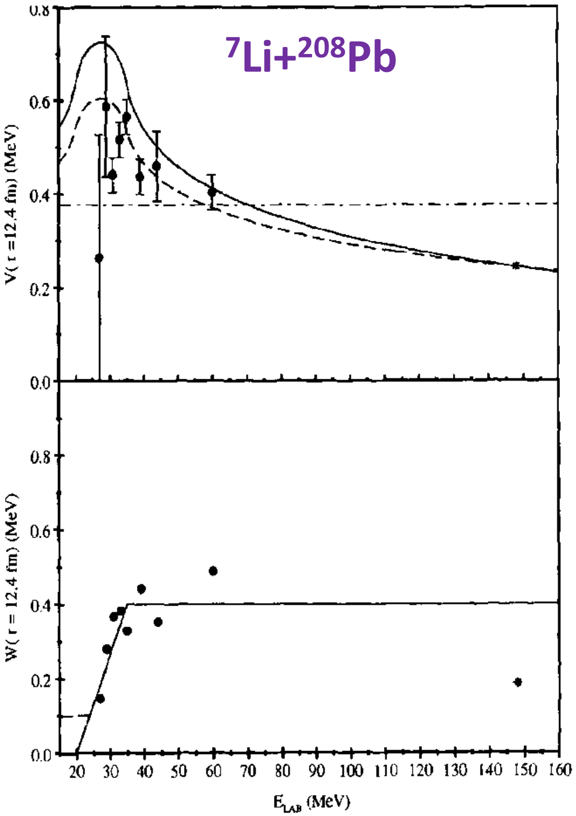
^{7}Li (α+t)
S_α = 2.47 MeV

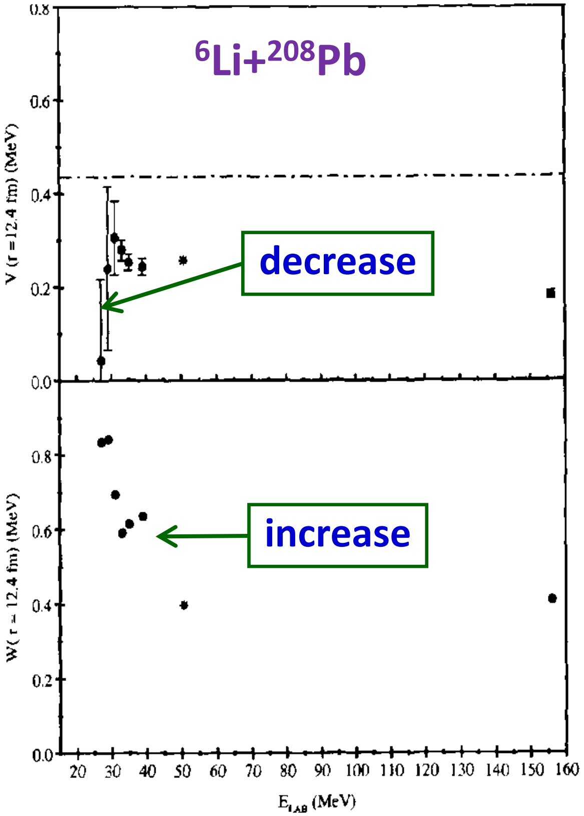


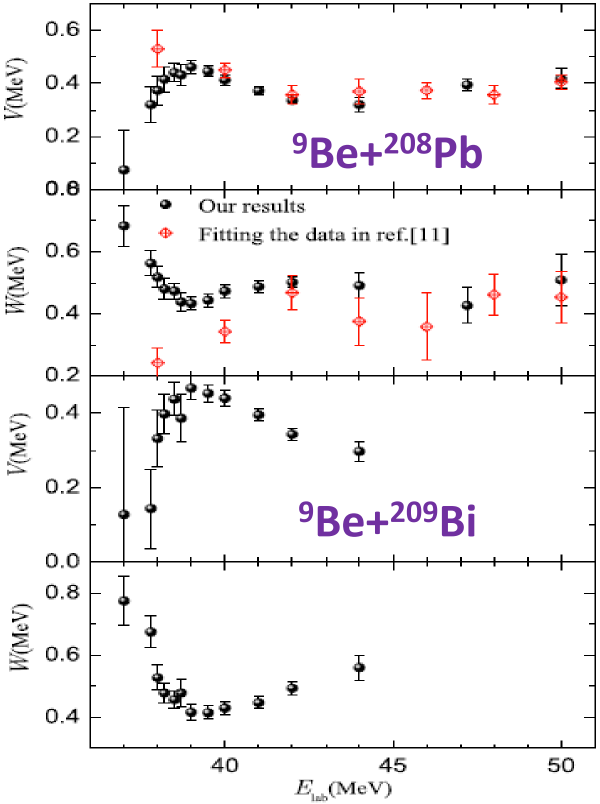
^{6}Li (α+d)
S_α = 1.47 MeV



^{9}Be (α+n+α)
S_n = 1.66 MeV



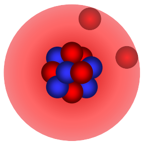




N. Keeley et al., Nucl. Phys. A **571**, 326 (1994).

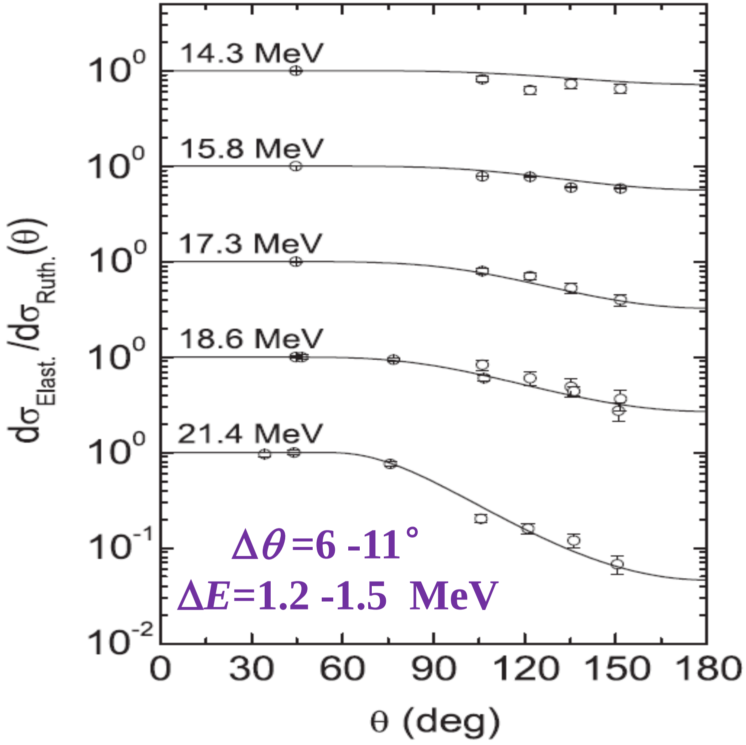
N. Yu et al., JPG **371**, 075108 (2010).

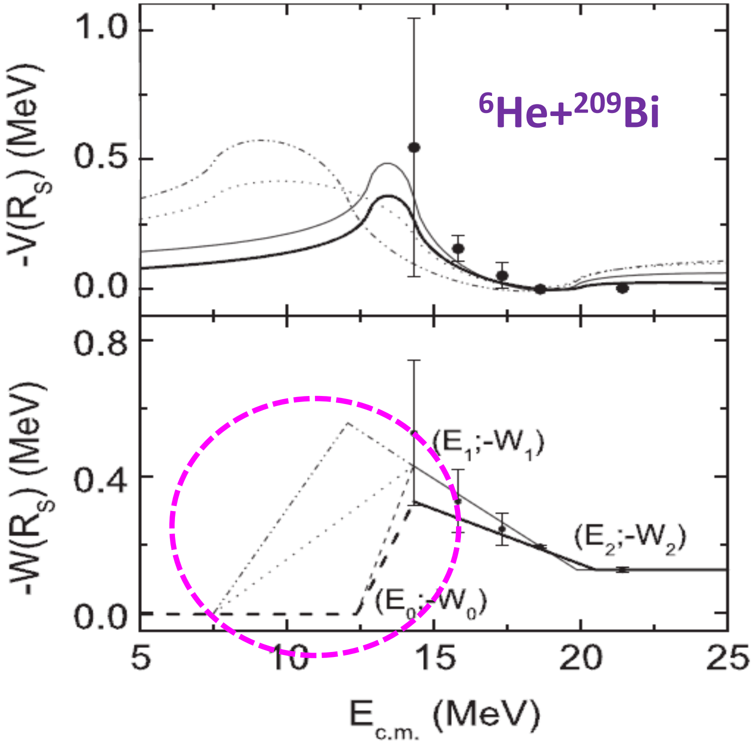
Halo Nuclei



^{6}He (α+2n)
S_{2n} = 0.98 MeV

Abnormal Threshold Anomaly



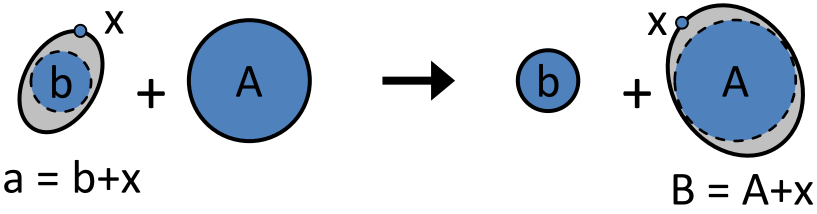


OMPs are usually extracted from elastic scattering.

★ 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
2) A. R. Garcia *et al*., Phys. Rev. C **76**, 067603 (2007).

OMPs from Transfers



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

Transfer reaction A(a,b)B

elastic scatting cross sections

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

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).

Experiment of ^{208}Pb(^{7}Li,^{6}He)^{209}Bi

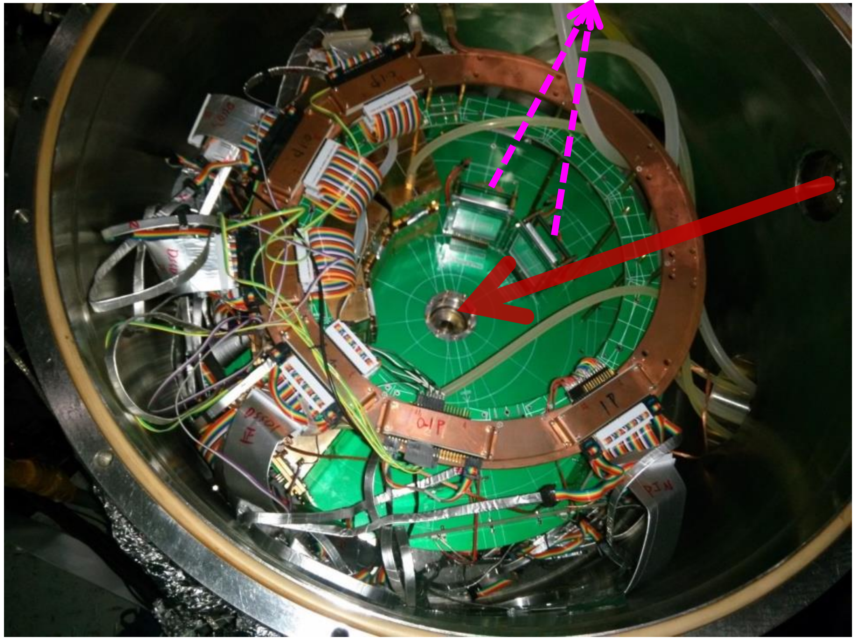
Two experiments have been done at HI-13 tandem accelerator @ CIAE

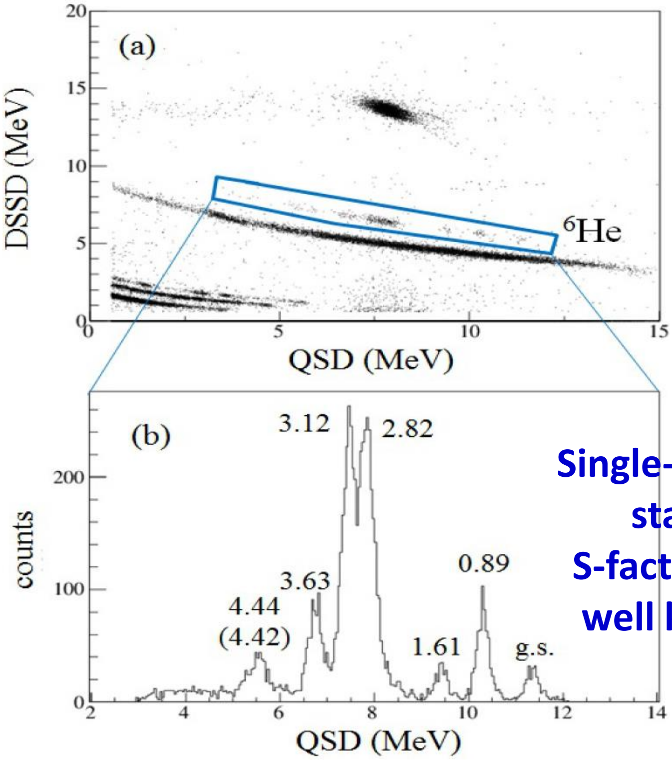
Exp1: E_{beam} = 42.55, 37.55, 32.55, **28.55**, 25.67 MeV – high energies **【2004.8】**

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)

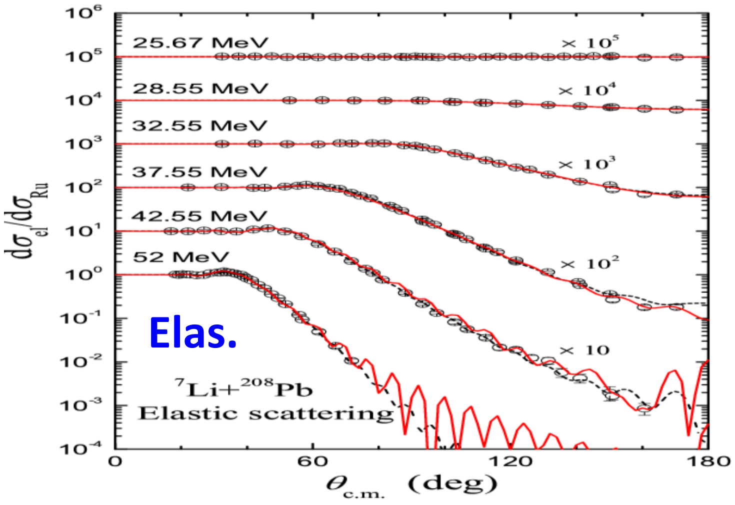


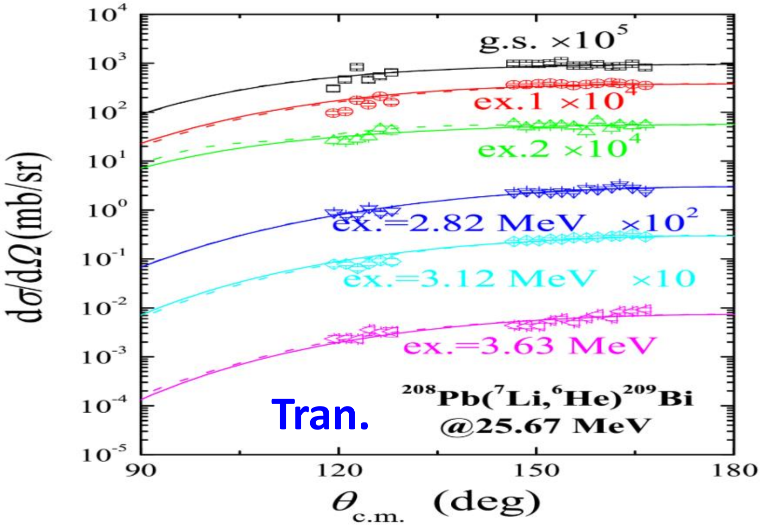


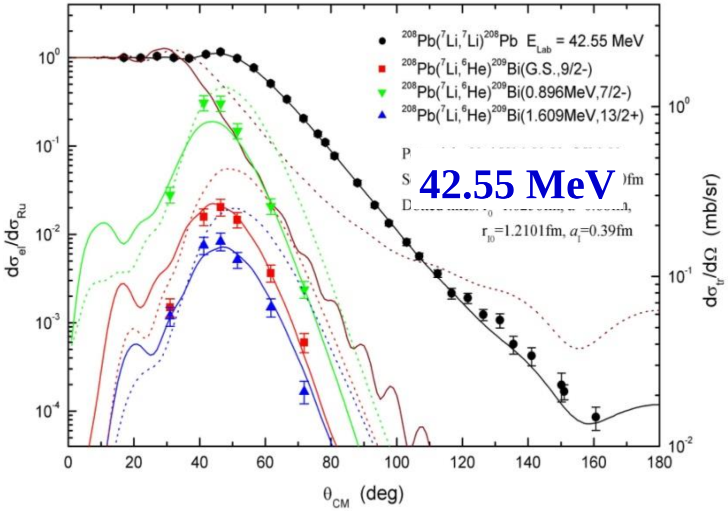
Single-particle states
S-factors are well known

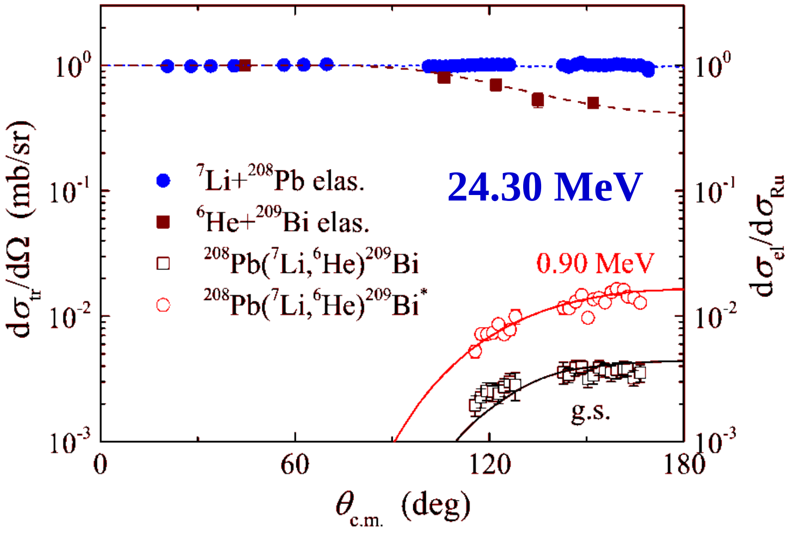
Data Analysis of $^{208}Pb(^{7}Li,^{6}He)^{209}Bi$

DWBA & CRC analyses

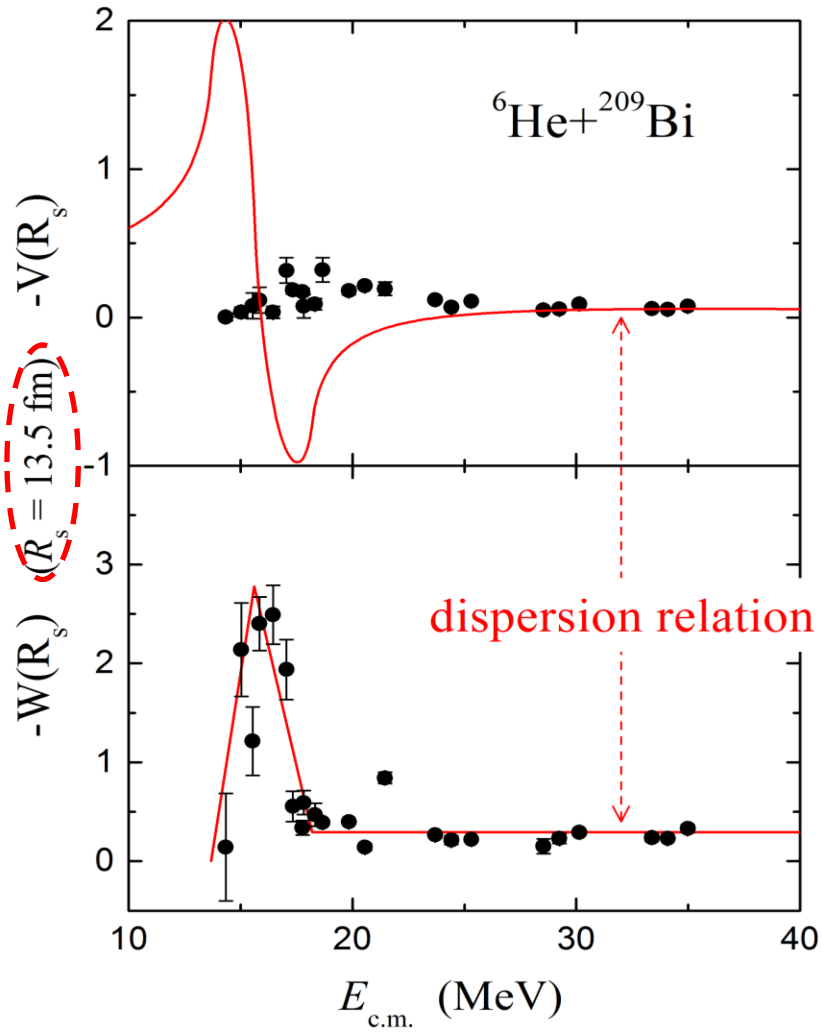








OMPs of ^{6}He+^{209}Bi



★ 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 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).

Experiment of ^{6}Li+ ^{208}Pb

Motivation: to extract the OMPs of ^{6}Li+^{208}Pb with high precisions, especially at sub-barrier energies.

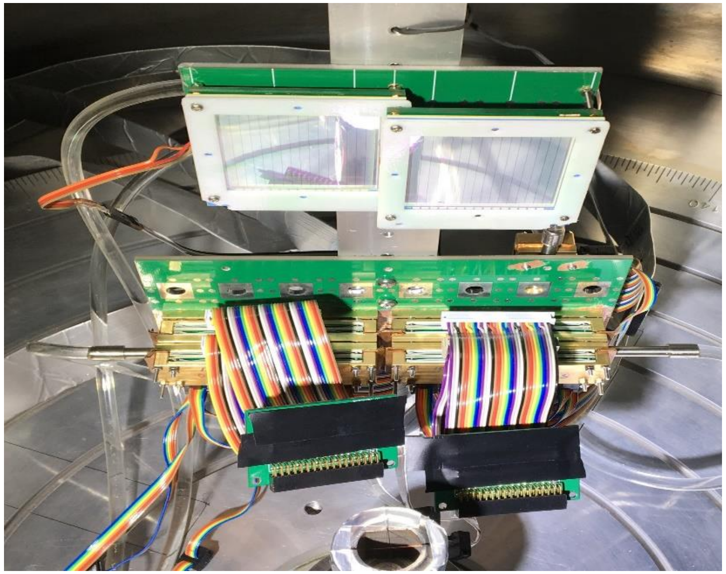
Tow experiments have been done by the HI-13 tandem accelerator at CIAE.

1. ^{6}Li+^{208}Pb elastic scattering

64 Si-PIN detectors have been installed around the target, covering 20°-175° in step of 5°.

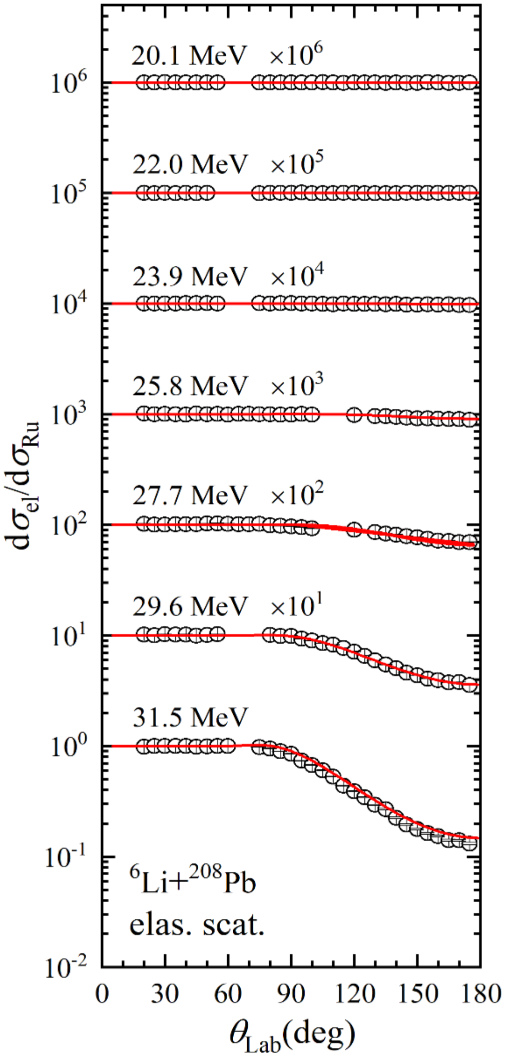
2. ^{207}Pb(^{7}Li,^{6}Li)^{208}Pb transfers

2 ΔE-E$_1$-E$_2$ telescopes have been installed, consisting of 40 μm DSSD, 300 μm and 1500 μm QSD.

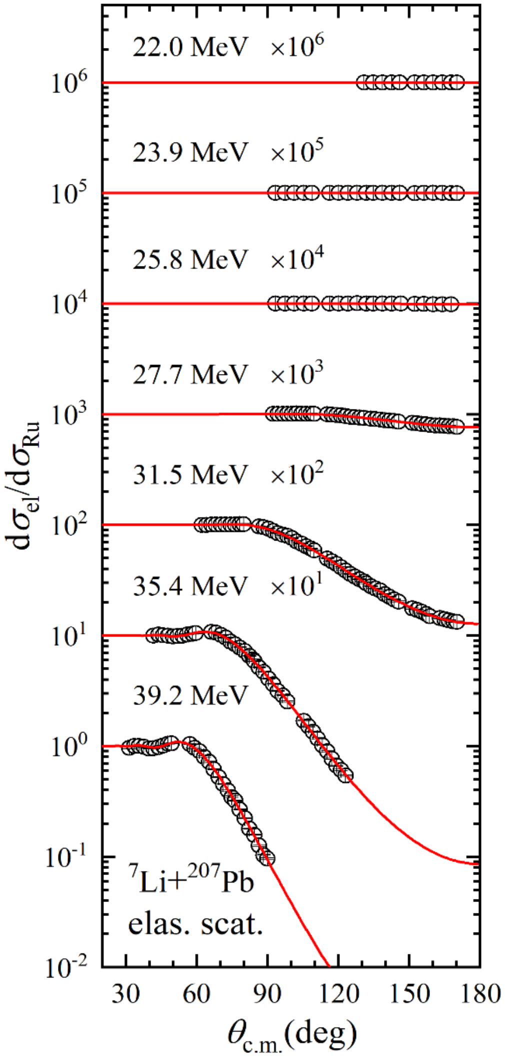


Angular Distributions

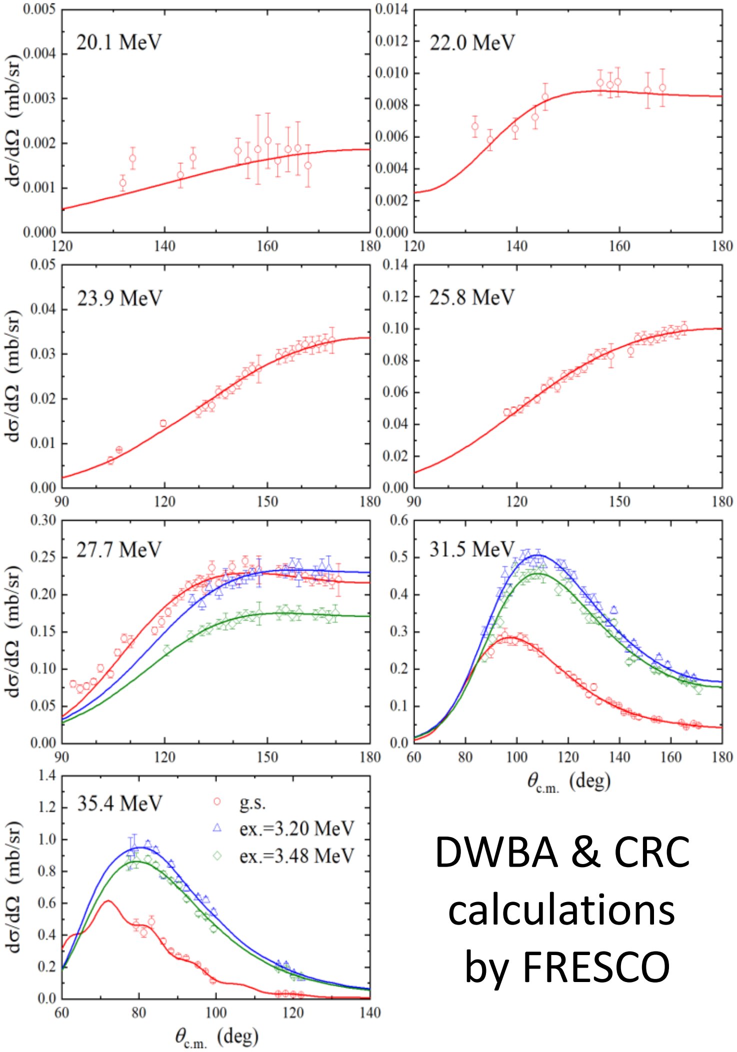
^{6}Li+^{208}Pb elas.



^{7}Li+^{207}Pb elas.



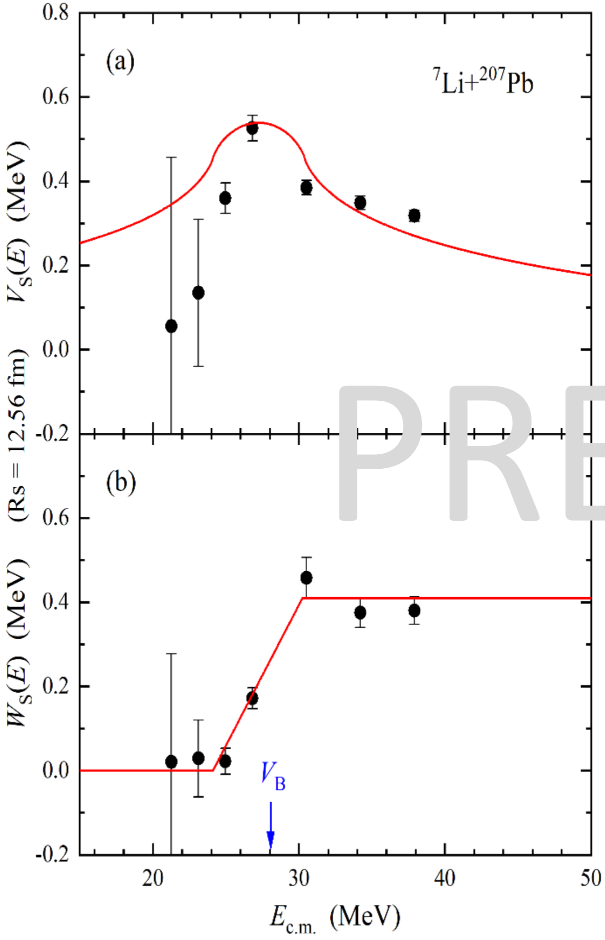
^{207}Pb(^{7}Li,^{6}Li)^{208}Pb tran.



DWBA & CRC calculations by FRESCO

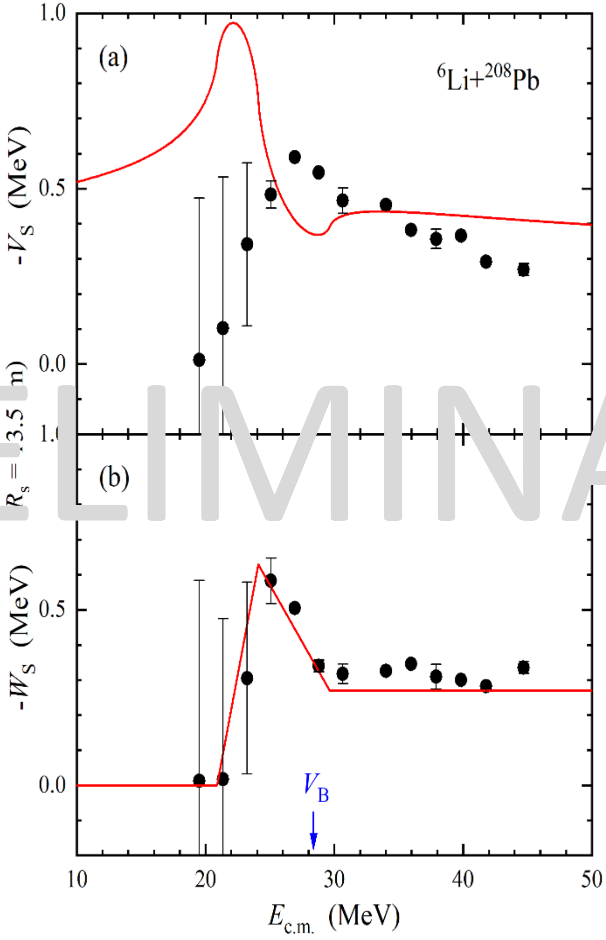
OMPs

^{7}Li+^{207}Pb
from elastic



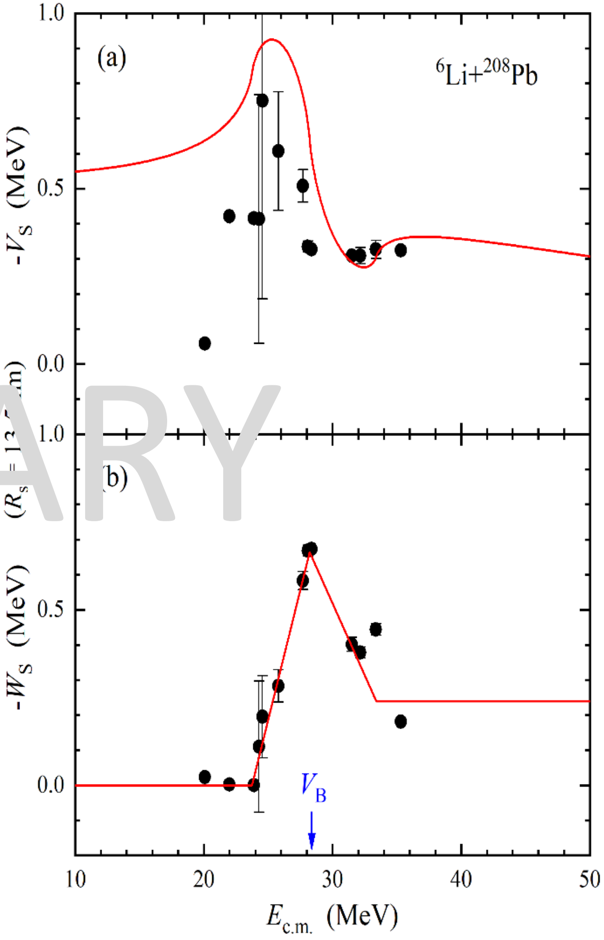
normal

^{6}Li+^{208}Pb
from elastic



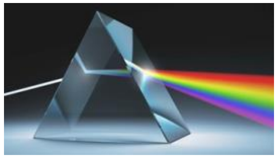
abnormal

^{6}Li+^{208}Pb
from transfer



abnormal

Dispersion Relation



★ Dispersion relation results from causality, connecting real and imaginary part;

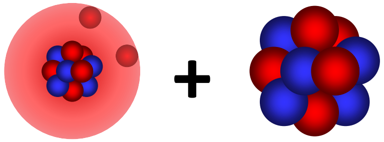
★ Any wave/particle should follow this rule when it passes through a media;

★ The classical dispersion relation is **not** applicable for ^{6}He+^{209}B and ^{6}Li+^{208}Pb.

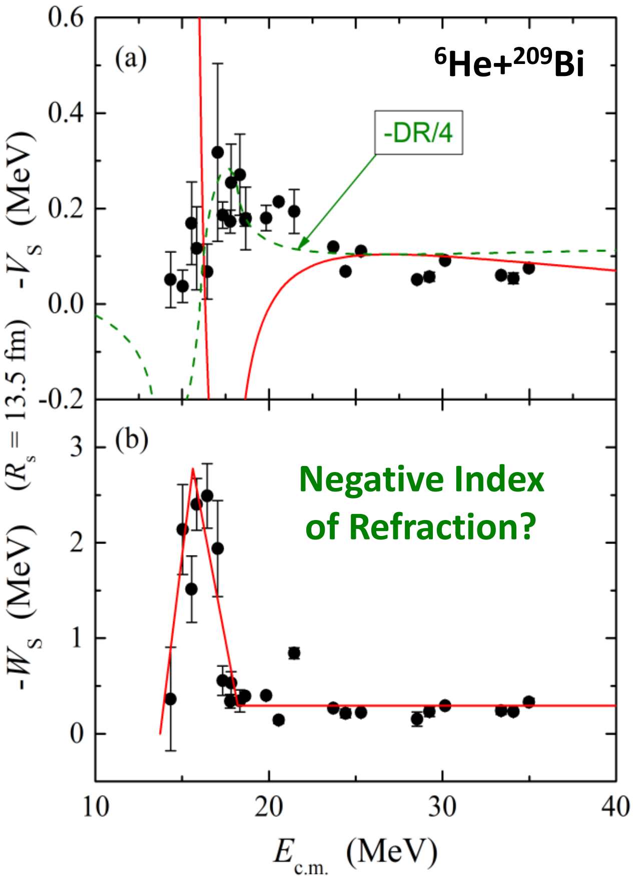
Possible reasons:

- 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?



3/4-body



Contents

1. OMPs of weakly-bound nuclear systems

   ^{6}He+^{209}Bi, ^{6}Li+^{208}Pb

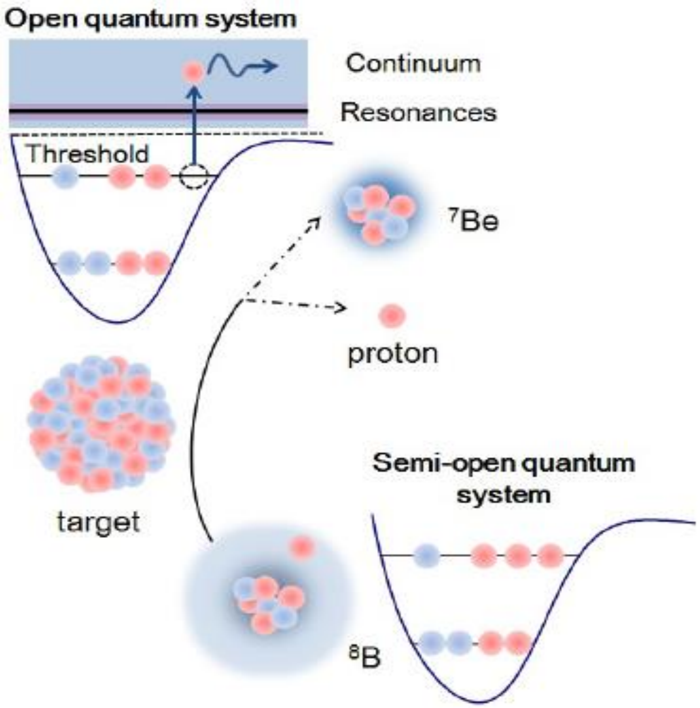
2. **Breakups of weakly-bound nuclei**
   - stable nuclei: ^{6,7}Li+^{209}Bi
   - proton-rich nuclei: ^{17}F+^{58}Ni, ^{8}B+^{120}Sn

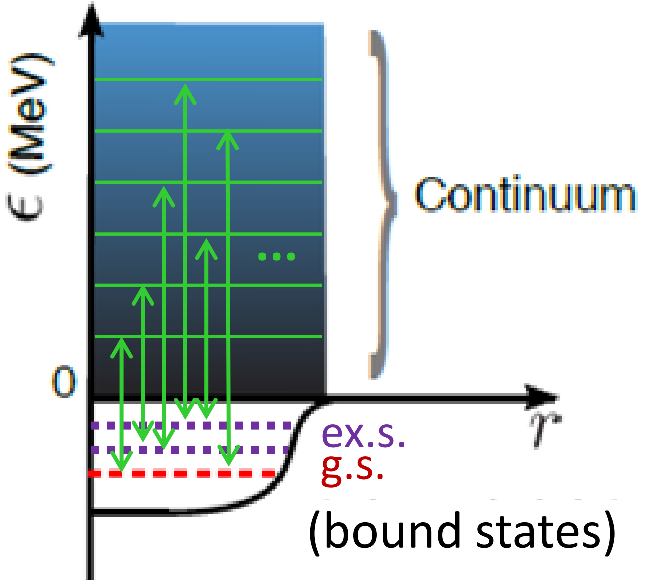
3. **Summary and outlook**

Breakup → Open Quantum System

★ **Reactions with weakly-bound nuclei:**

easily breakup, and leading to continuum state





CDCC

Continuum Discretized Coupled Channels

From sei-open quantum system
to open quantum system

Strongly couplings of low-lying states
to continuum states

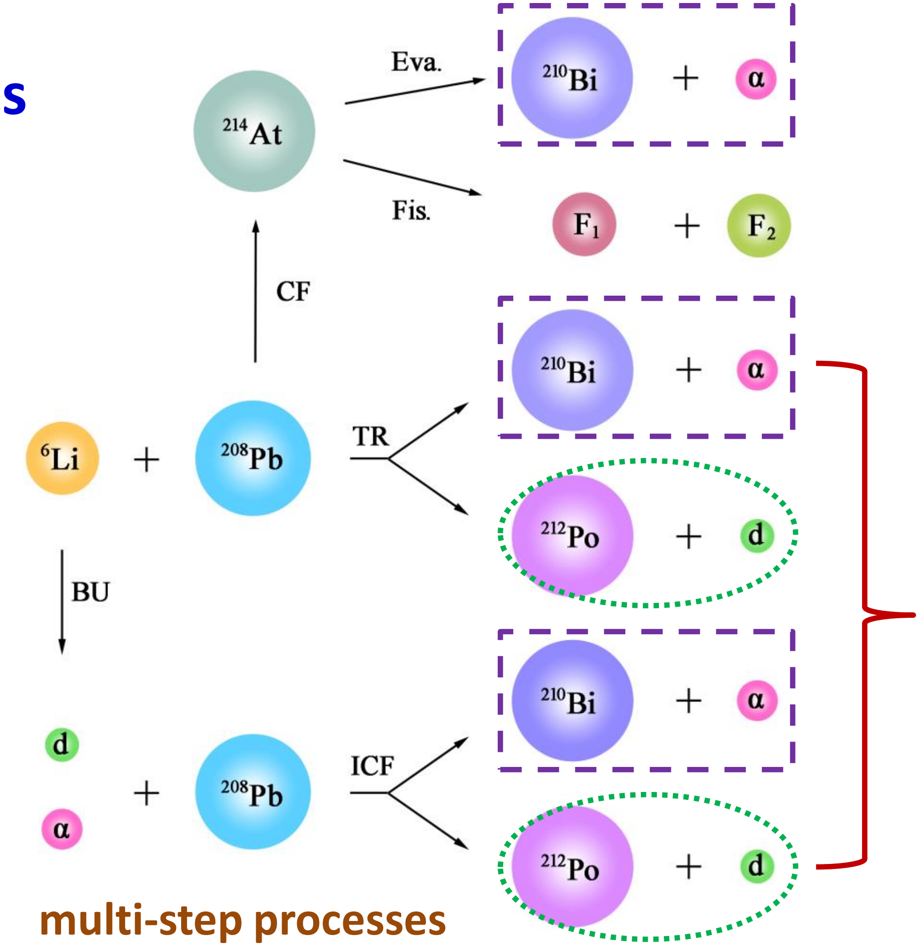
Complex Processes

★ **How to identify different reaction processes in a experiment?**

complete-kinematics measurement

2-body kinematics ☞

3-body kinematics ☞



multi-step processes

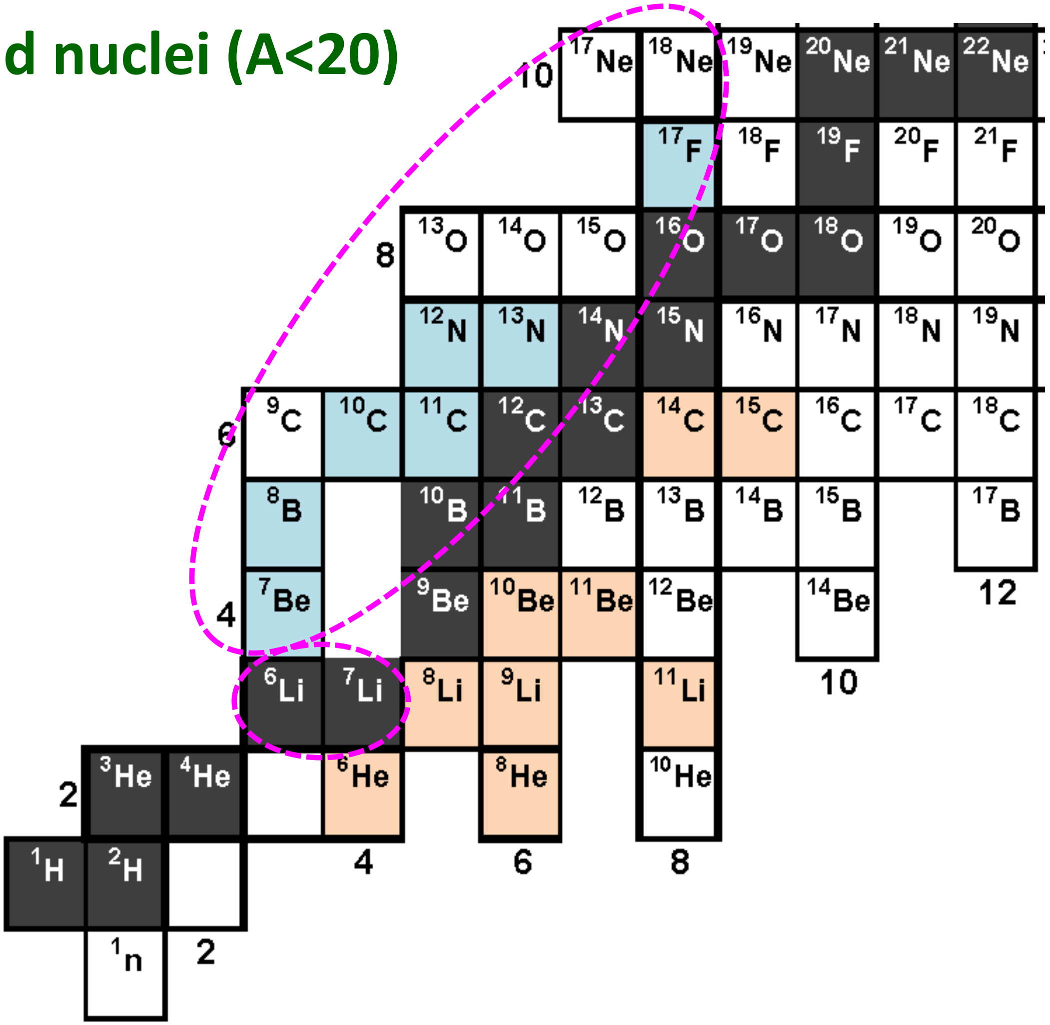
Same products

Researches in NRG@CIAE

Reactions with weakly-bound nuclei (A<20)

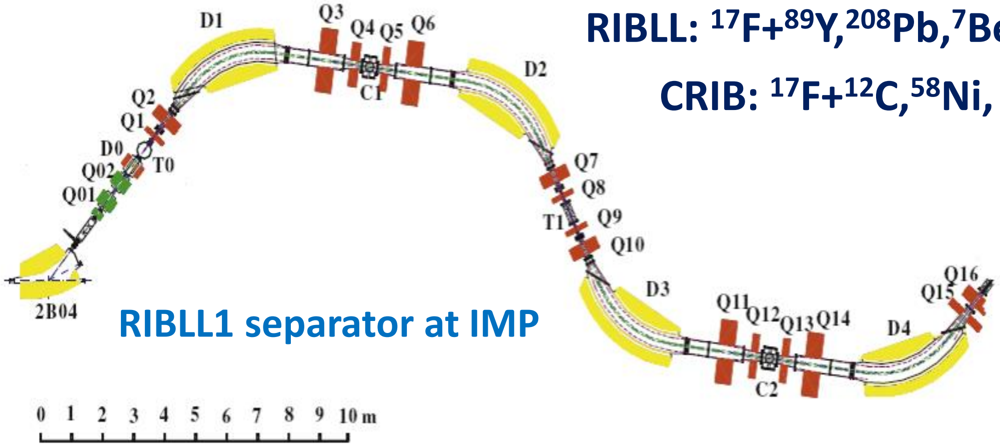
- Elastic, fusion, breakup …
- Stable: ^{6,7}Li, ^{9}Be
- p-rich: ^{7}Be, ^{8}B, ^{17}F, ^{10}C, ^{12}N, ^{17,18}Ne …
- Complete-kinematics measurement

  (particle identification & large solid-angle covered)



Overview of RIB Experiments

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

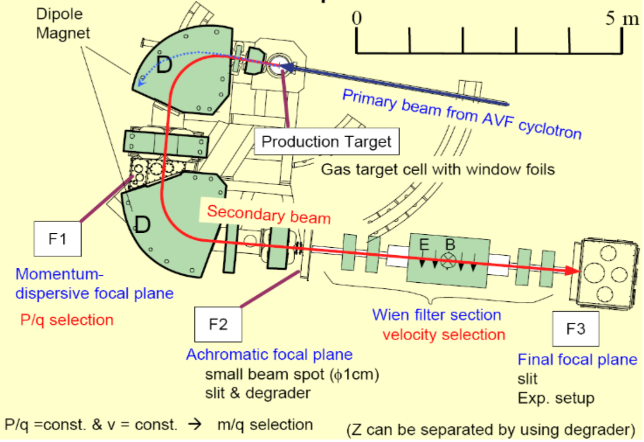


RIBLL1 separator at IMP

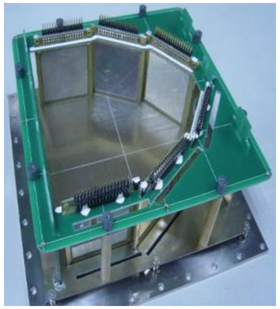
RIBLL: ^{17}F+^{89}Y,^{208}Pb,^{7}Be+^{209}Bi,^{120}Sn

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

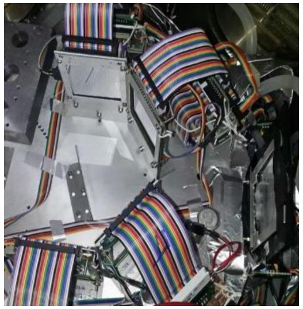
CRIB separator at CNS



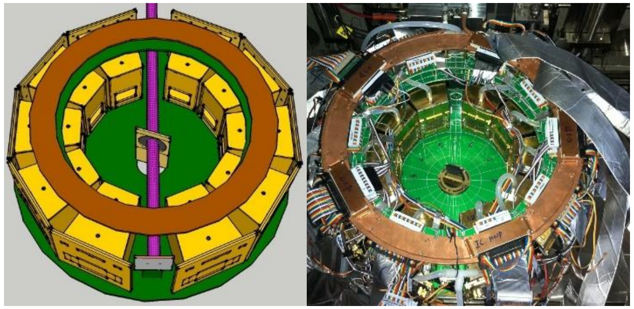
^{17}F+^{12}C
2007@CRIB



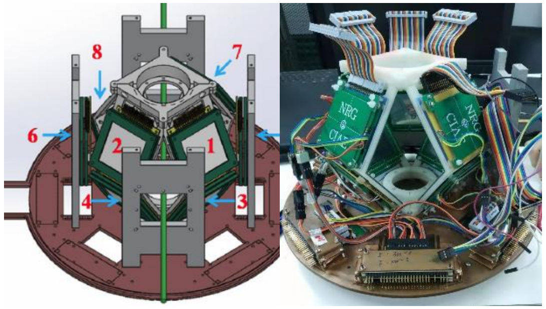
^{17}F+^{89}Y
2015@RIBLL1



^{17}F+^{208}Pb, 2015@RIBLL1
^{17}F+^{58}Pb, 2015@CRIB



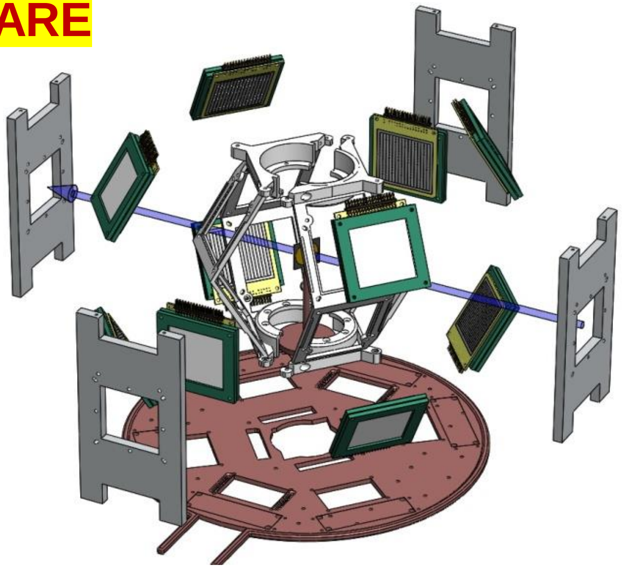
^{7}Be+^{209}Bi, 2018@RIBLL1
^{8}B+^{120}Sn, 2019@CRIB
^{7}Be+^{120}Sn, 2021@RIBLL1



EPJA **48**, 65 (2012); PRC **97**, 044618 (2018); EPJA **57**, 143 (2021); PLB **813**, 136045 (2021); NC **13**, 7193 (2022) …

Detector Arrays

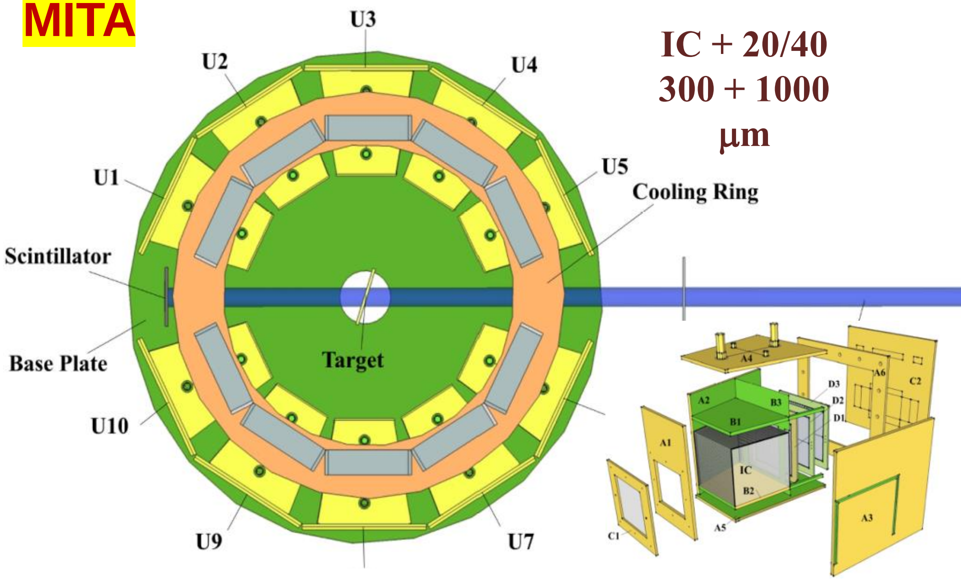
STARE



20/40
+
300
+
1000
μm

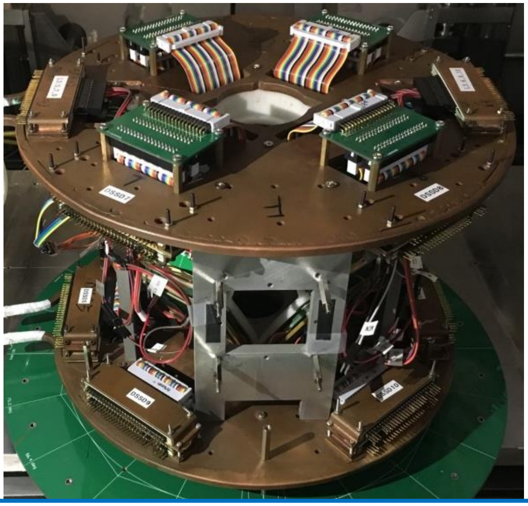
10 sets, 3 layers, 40% 4π

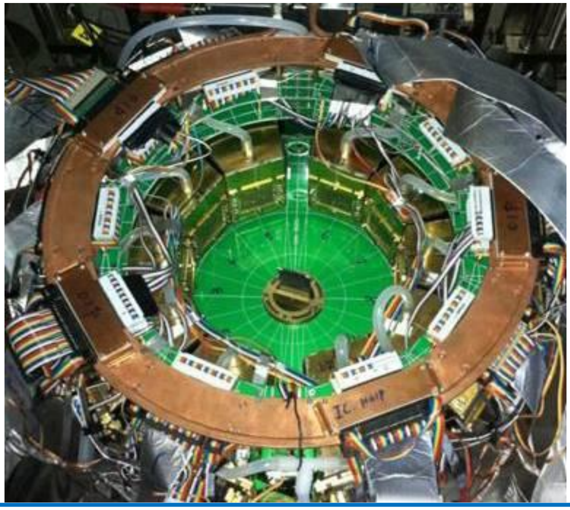
MITA



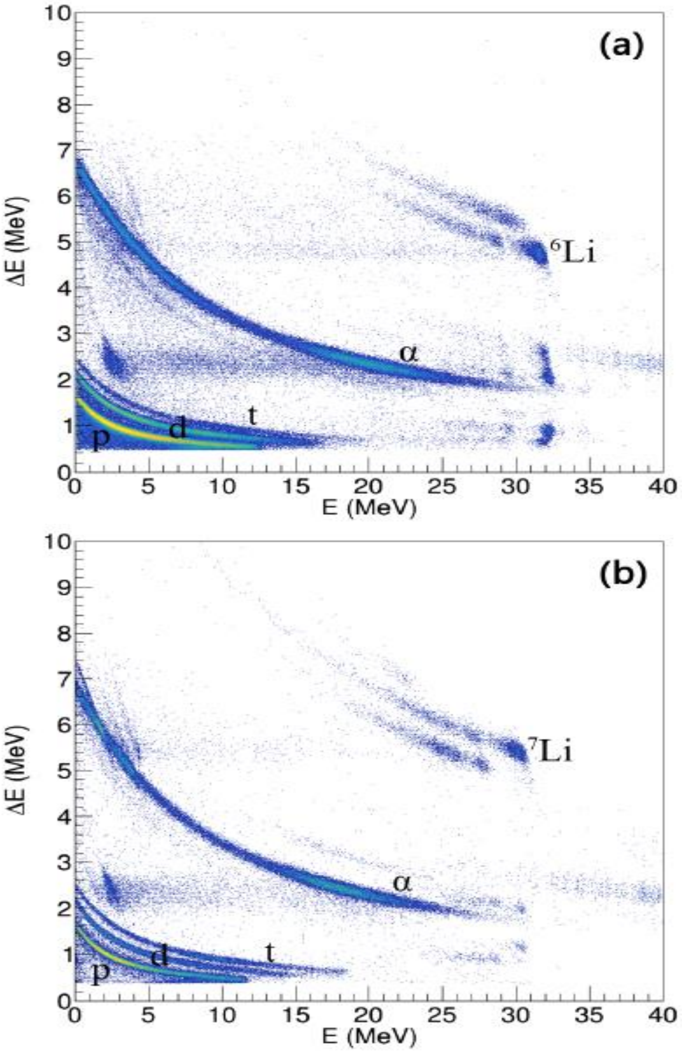
IC + 20/40
300 + 1000
μm

10 sets, 4 layers, 8% 4π

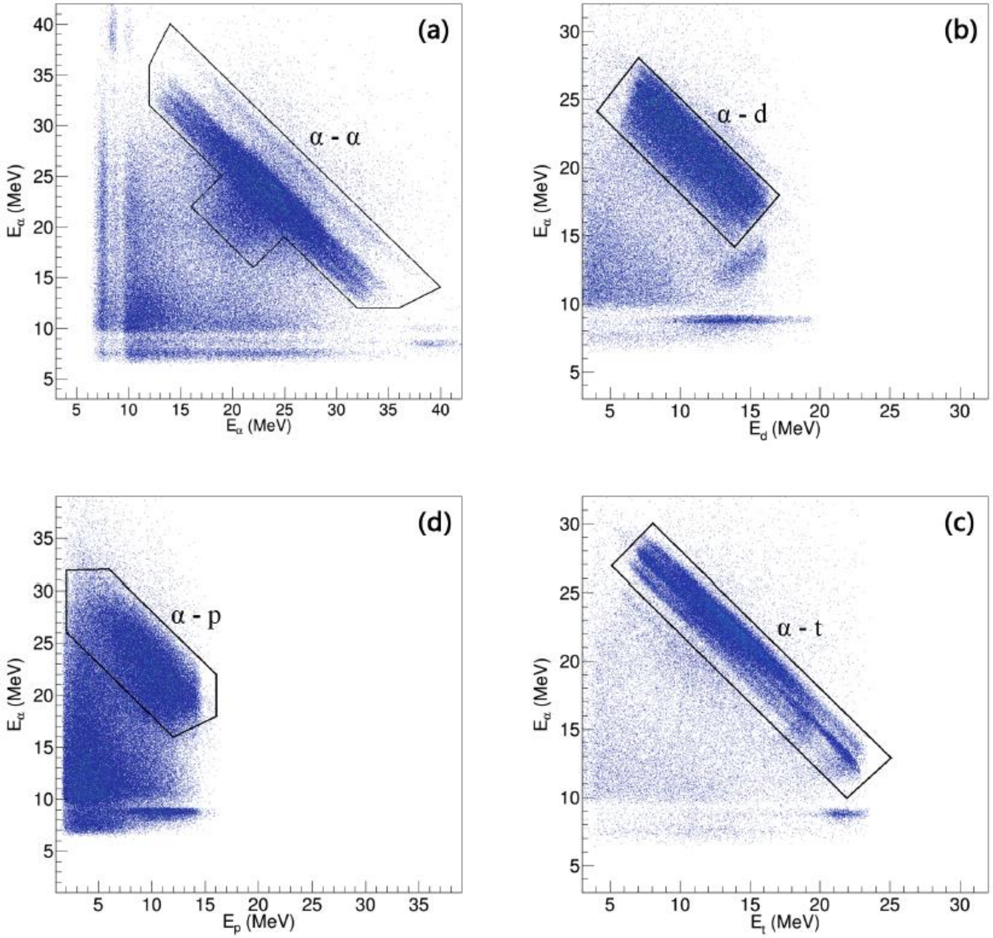




^{6,7}Li+^{209}Bi: Spectra

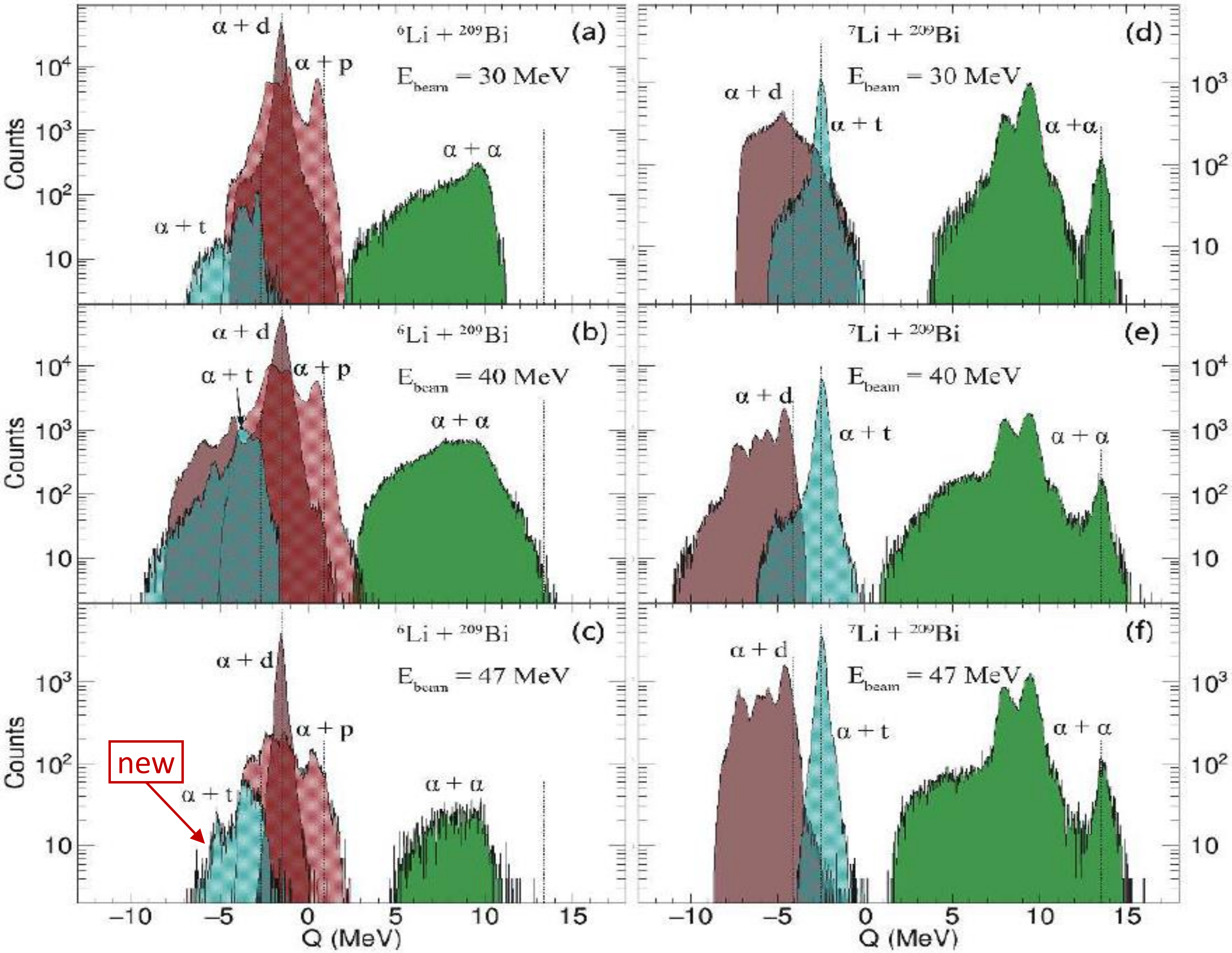


ΔE-E Spectra of ^{6,7}Li+^{209}Bi @ 40 MeV



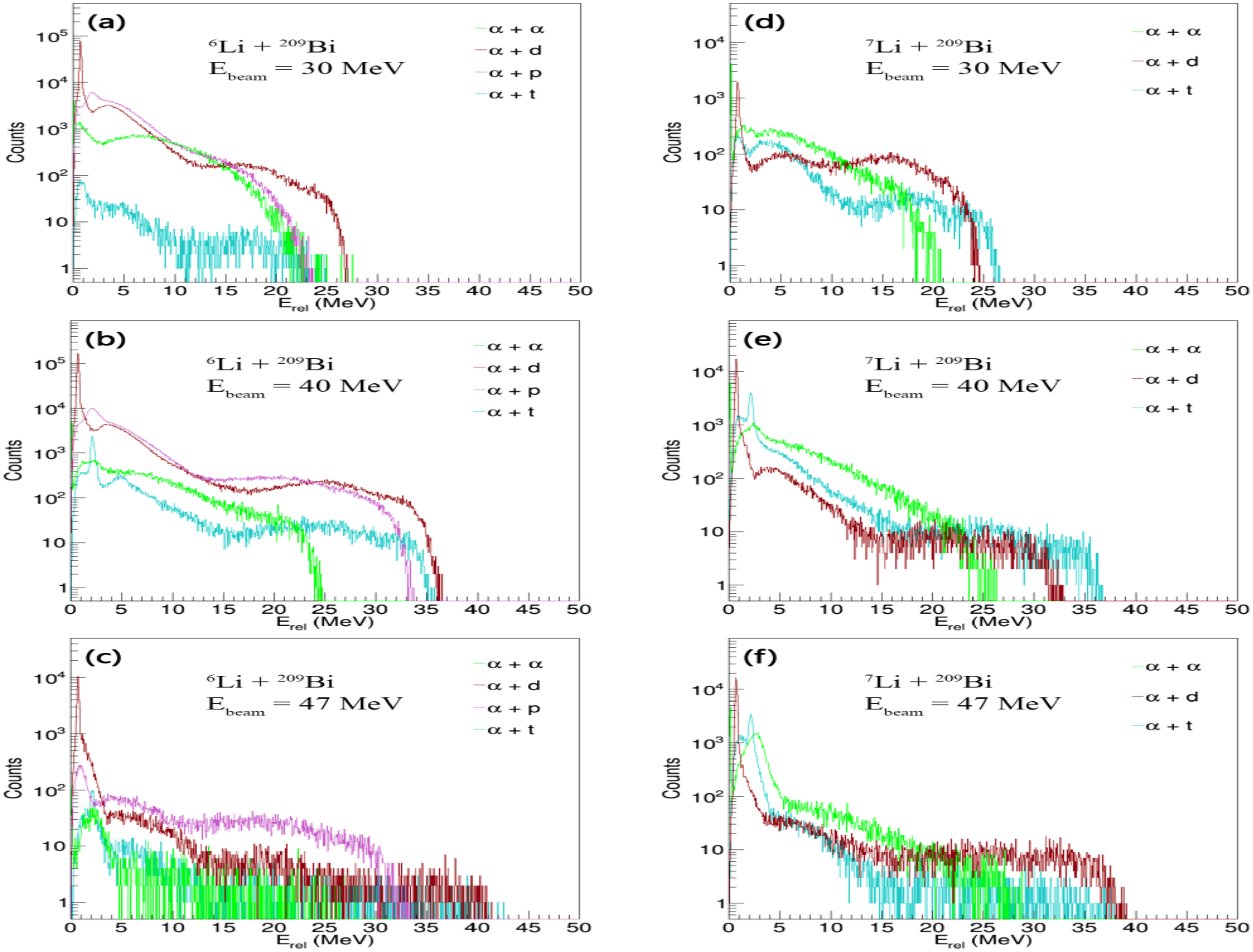
Energy correlations of breakup fragments

^{6,7}Li+^{209}Bi: *Q*-value Spectra



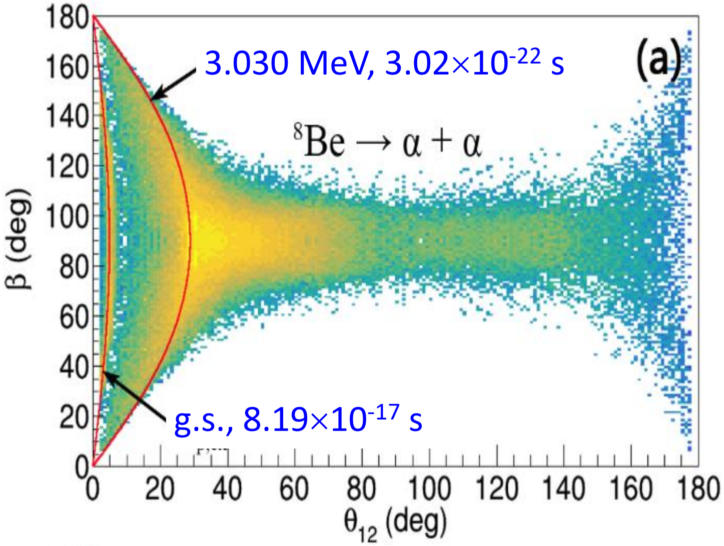
Y.J. Yao *et al*., Nucl. Sci. Tech. **32**, 14 (2021); Chin. Phys. C **45**, 054104 (2021).

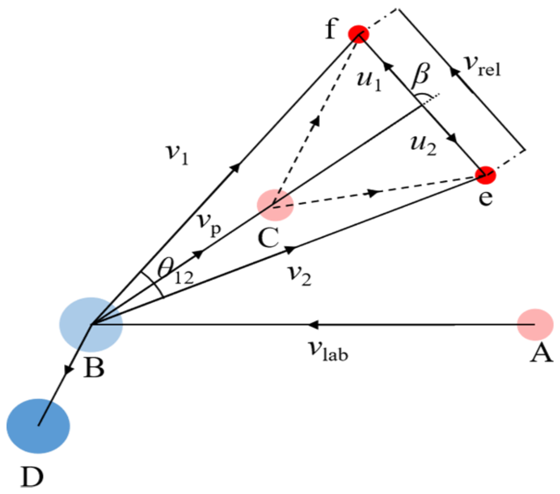
^{6,7}Li+^{209}Bi: Relative Energies

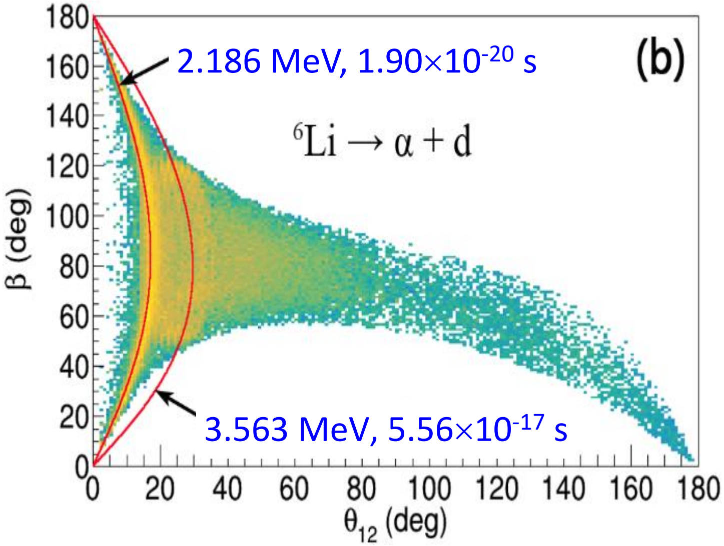


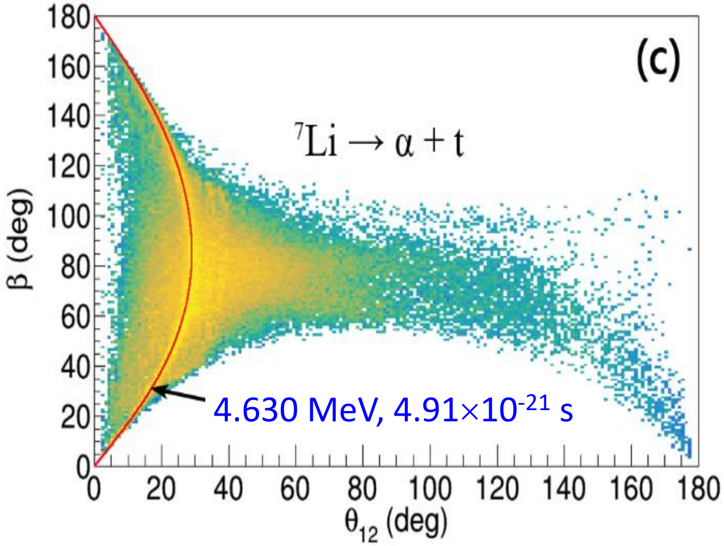
^{6,7}Li+^{209}Bi: Angular Correlations

^{7}Li+^{209}Bi @ 40 MeV

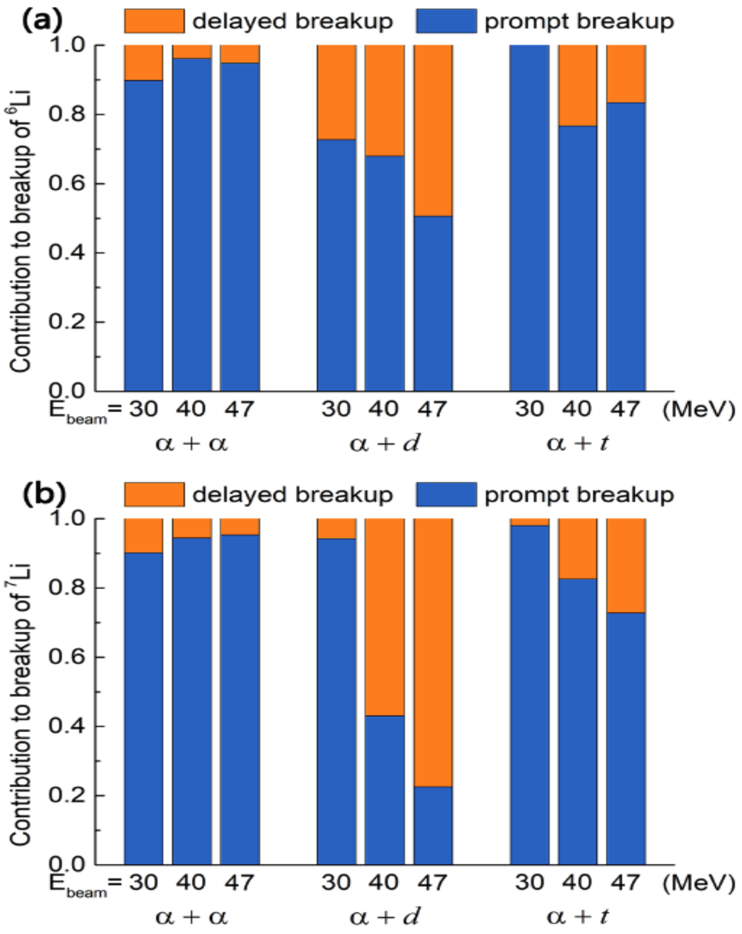


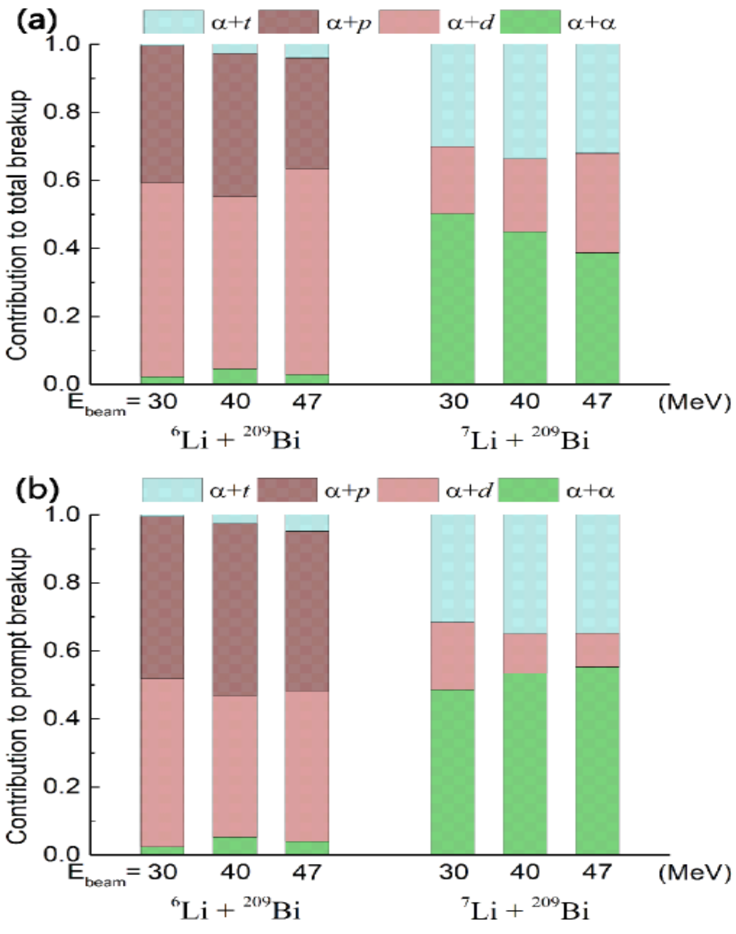






^{6,7}Li+^{209}Bi: Branch Ratios of Breakups

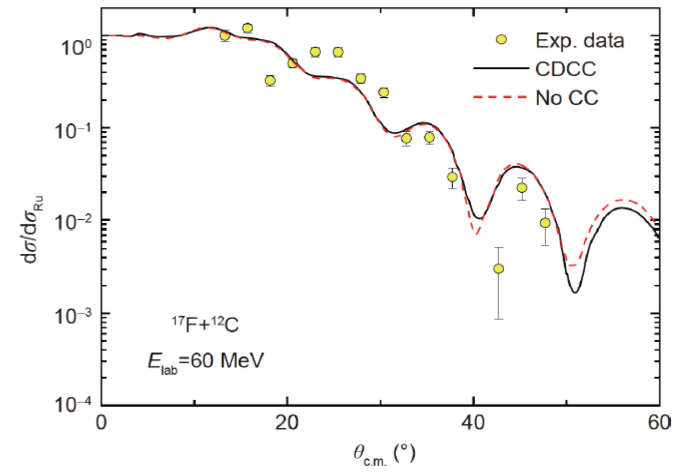


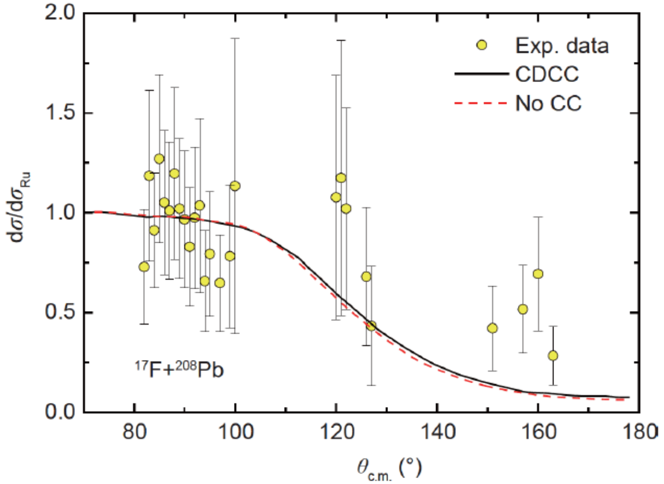


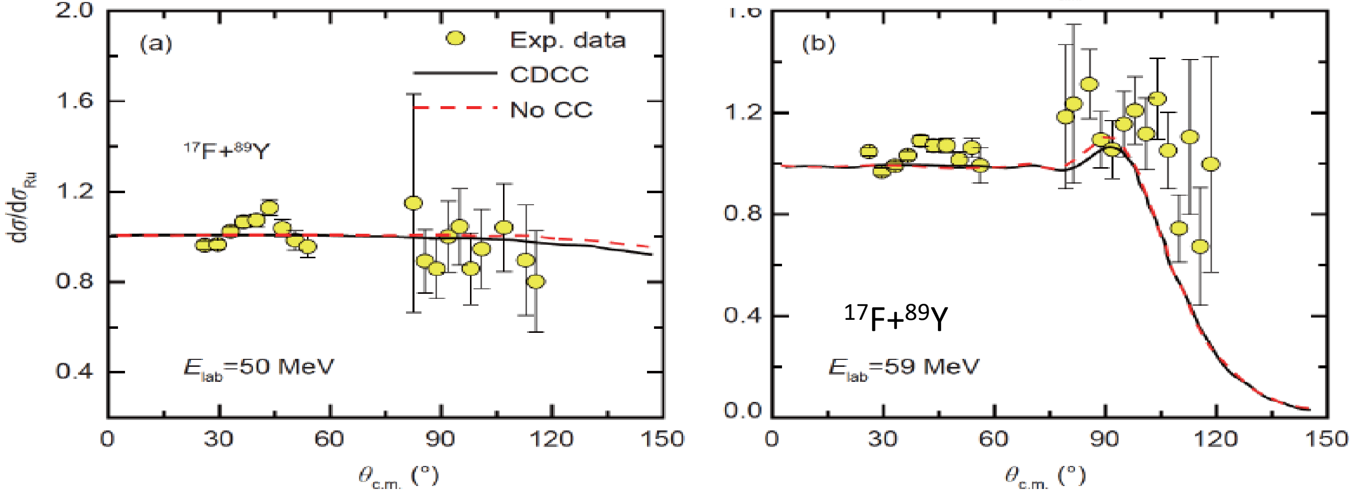
L. Yang *et al*., Fundamental Research, in press.

★ **Rich information on breakups of ^{6,7}Li+^{209}Bi was obtained experimentally, which requires a unified theory to comprehensively understand the dynamics and its influences.**

^{17}F+^{12}C, ^{89}Y, ^{208}Pb: Elastic Scattering





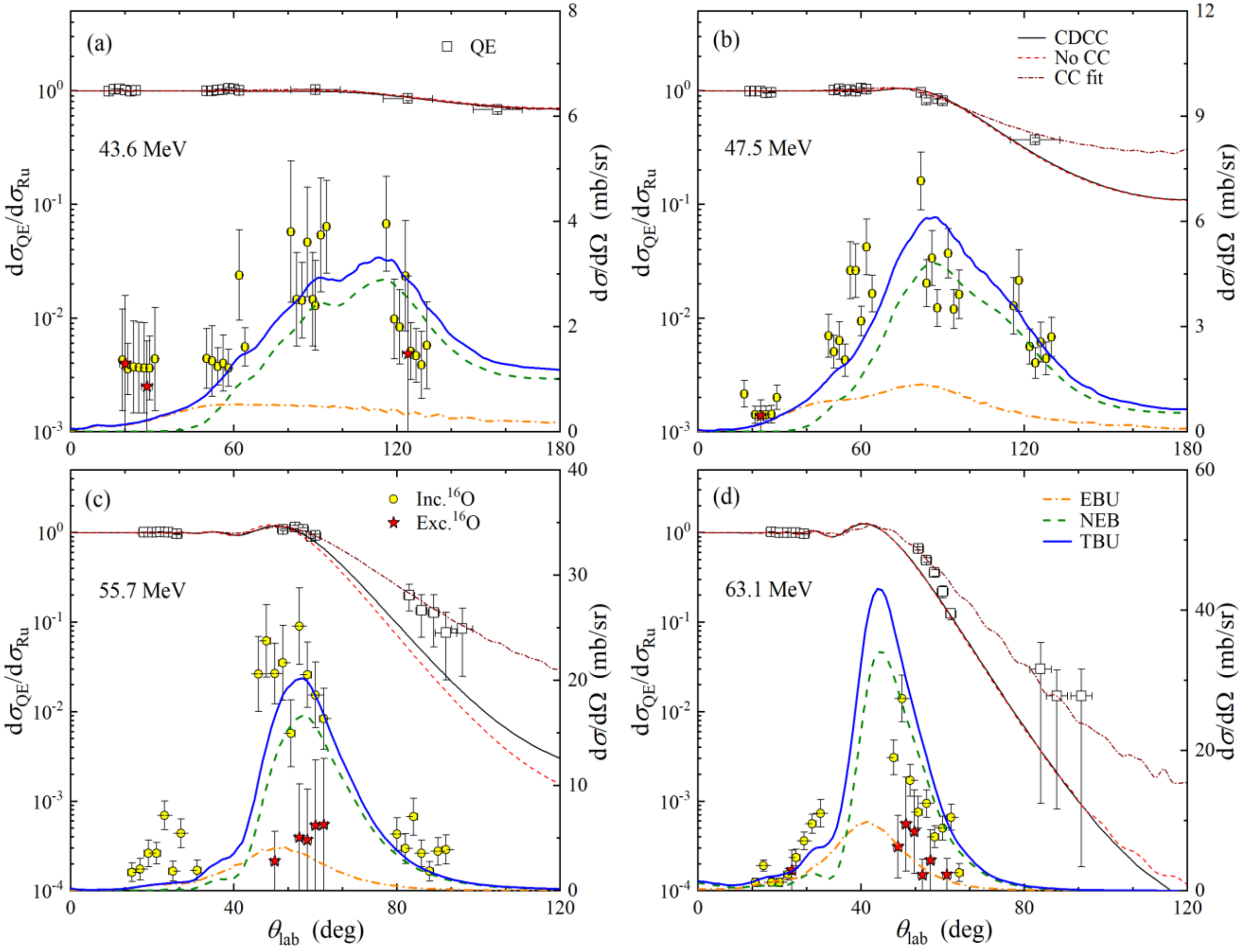


No obvious breakup effects were observed.

Eur. Phys. J. A **48**, 65 (2012); Phys. Rev. C **97**, 044618 (2018); Eur. Phys. J. A **57**, 143 (2021).

$^{17}F+^{58}Ni$: Nonelastic Breakup

Quasielastic, inclusive & exclusive breakup, total fusion have been obtained by the complete-kinematics measurement for the first time.



Quasi-elastic:

☐CDCC effects are not significant

Breakup:

☐EBU — CDCC

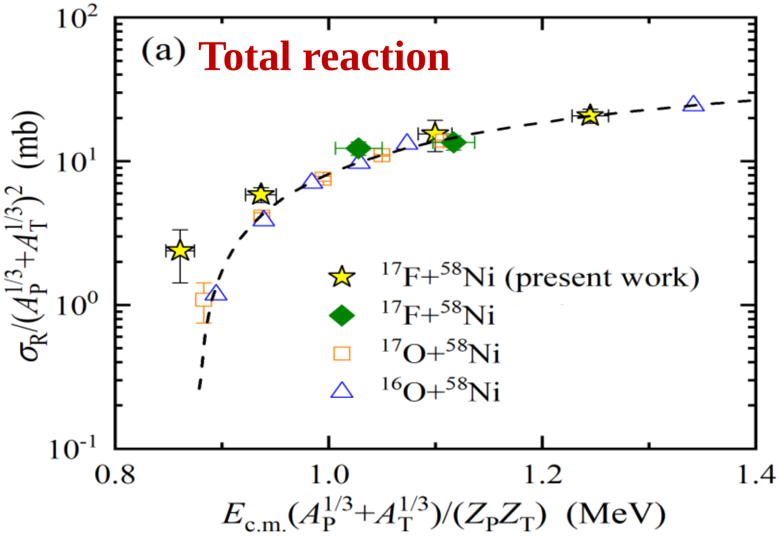
☐NEB — IAV

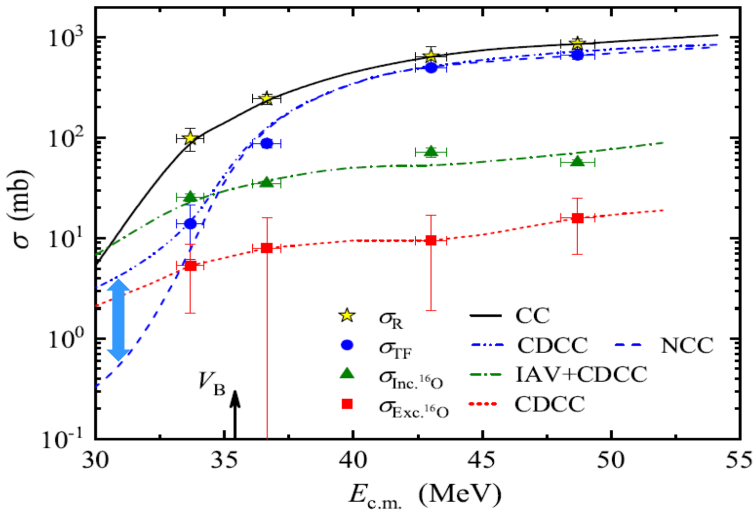
☐TBU — EBU+NEB

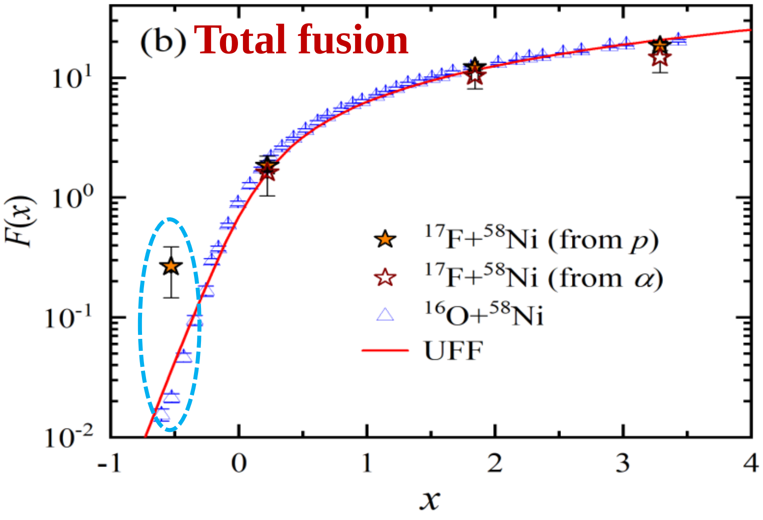
NEB is dominant

L. Yang, C. J. Lin, H. Yamaguchi *et al.*, Phys. Lett. B **813**, 136045 (2021).

^{17}F+^{58}Ni: Cross Sections



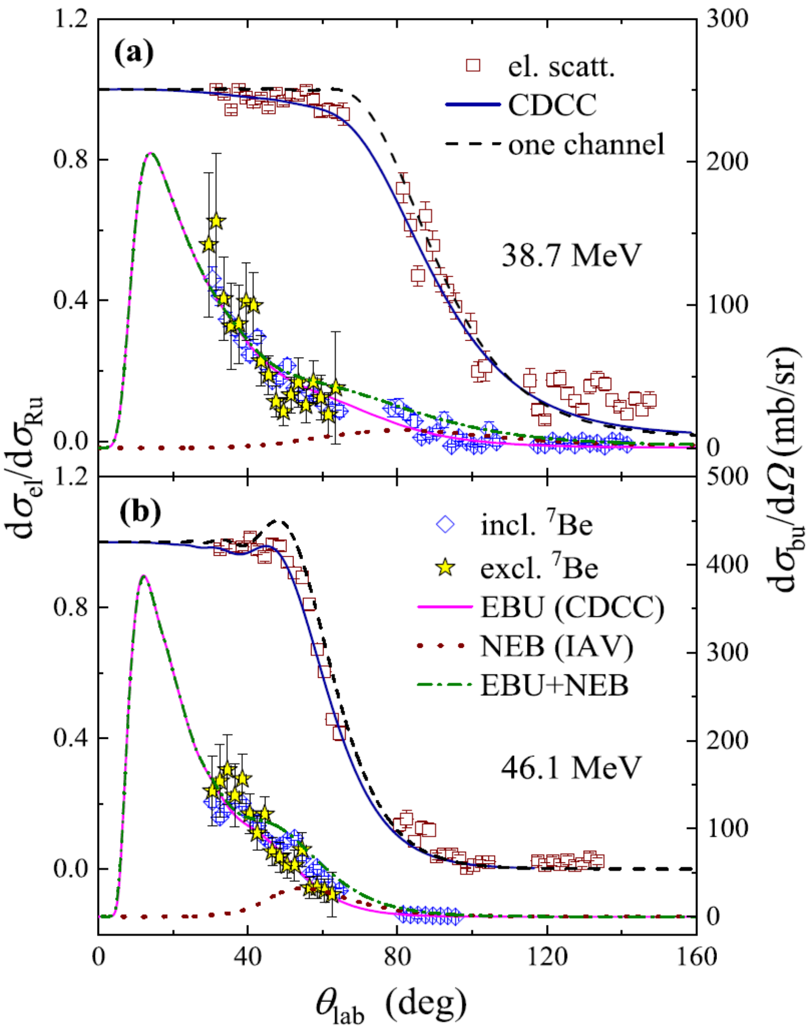


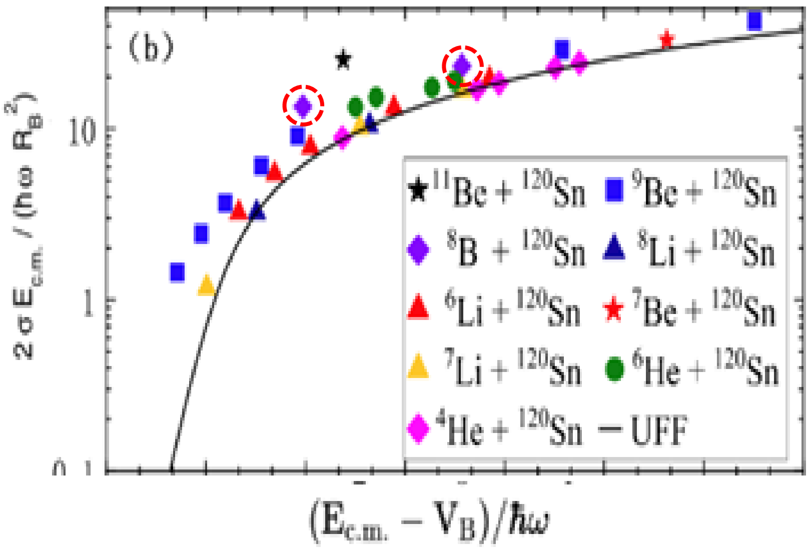


★ **Cross section of total fusion is enhanced below the barrier, mainly due to the couplings to the continuum states.**

L. Yang, C. J. Lin, H. Yamaguchi *et al.*, Phys. Lett. B **813**, 136045 (2021).

$^{8}B+^{120}Sn$: Elastic Breakup

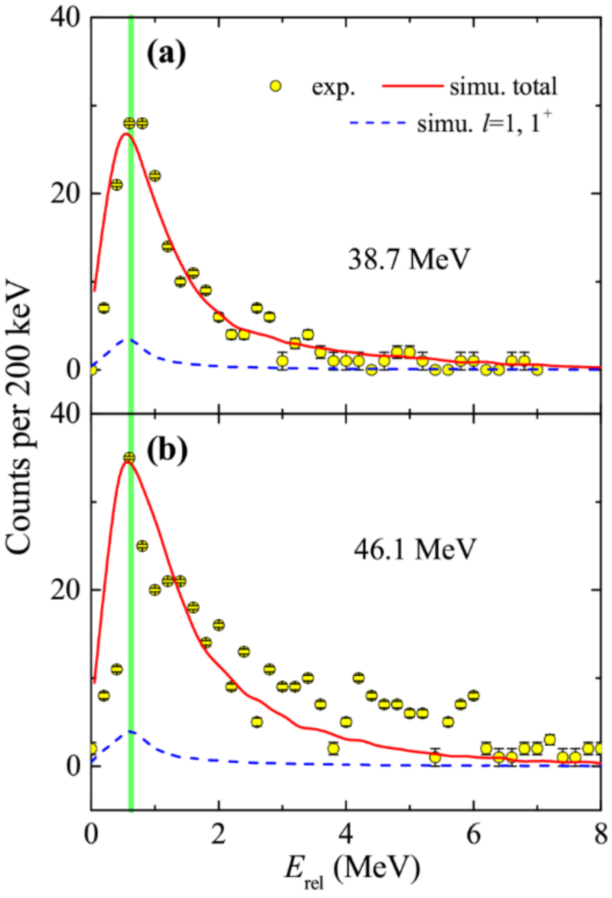


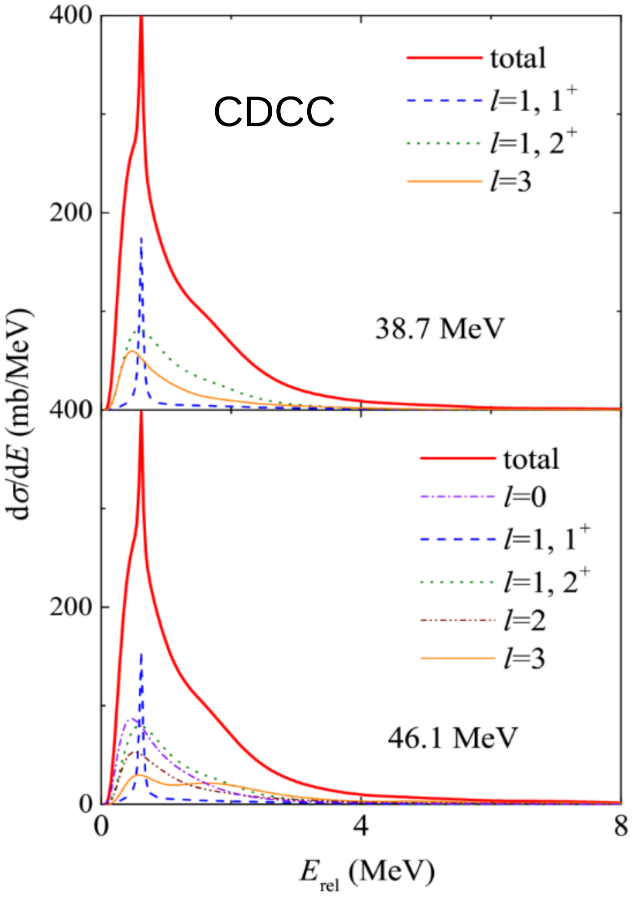


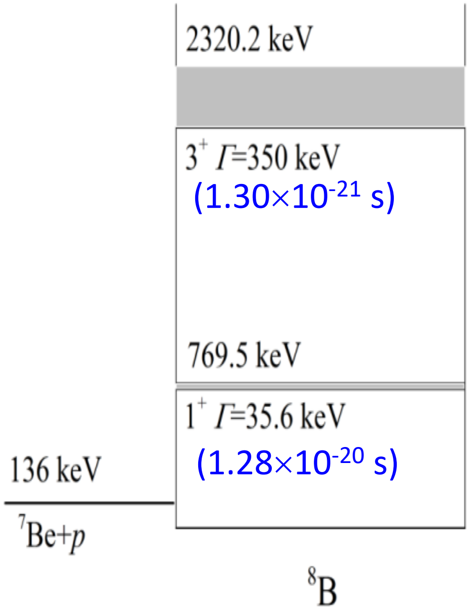
- ☐ **Couplings to the continuum cannot be neglected;**
- ☐ **The yield of ^{7}Be is almost exhausted by breakup reaction;**
- ☐ **EBU is dominant, the contribution of NEB is ~18%.**

L. Yang, C.J. Lin, H. Yamaguchi *et al.*, Nat. Commun.**13**, 7193 (2022).

$^{8}B+^{120}Sn$: Energy Correlations



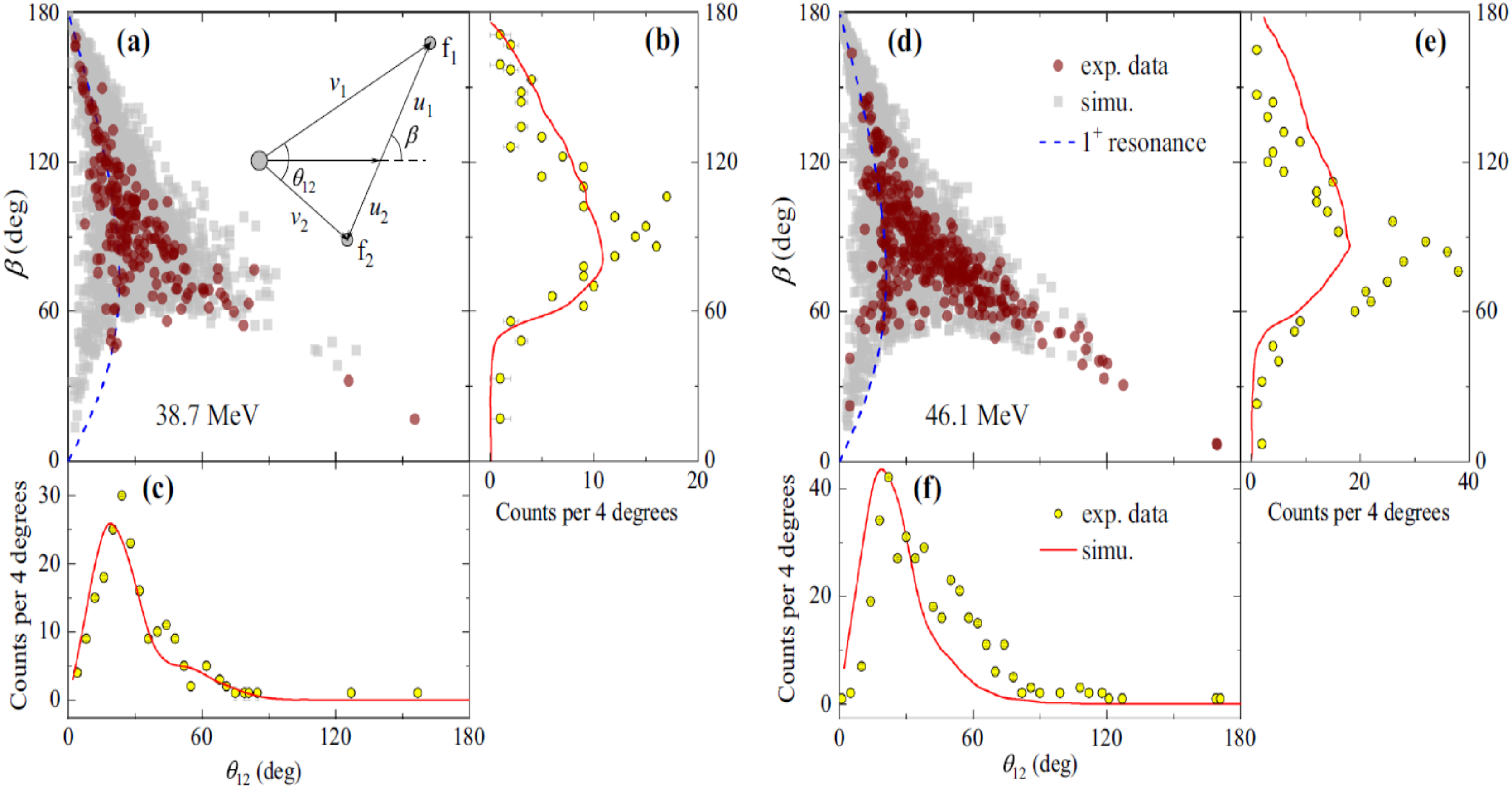




★ **Contributions of the 1st ex. state is ~ 4%, indicating prompt breakups are dominant.**

L. Yang, C.J. Lin, H. Yamaguchi *et al.*, Nat. Commun.**13**, 7193 (2022).

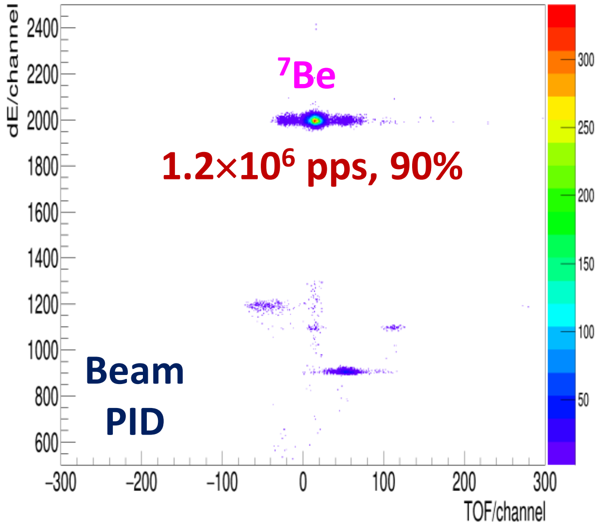
^{8}B+^{120}Sn: Angular Correlations



- **Breakup of ^{8}B occurs predominantly on the outgoing trajectory, close to the target.**
- **The continuum of ^{8}B breakup may not significantly influence the complete fusion.**

L. Yang, C.J. Lin, H. Yamaguchi *et al.*, Nat. Commun.**13**, 7193 (2022).

In Progress: ^{7}Be+^{209}Bi,^{120}Sn



^{7}Be

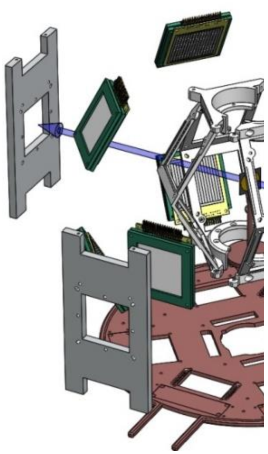
1.2×10^{6} pps, 90%

Beam PID

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

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

H_2 gas: 1000 mbar, 8 cm, 90 K

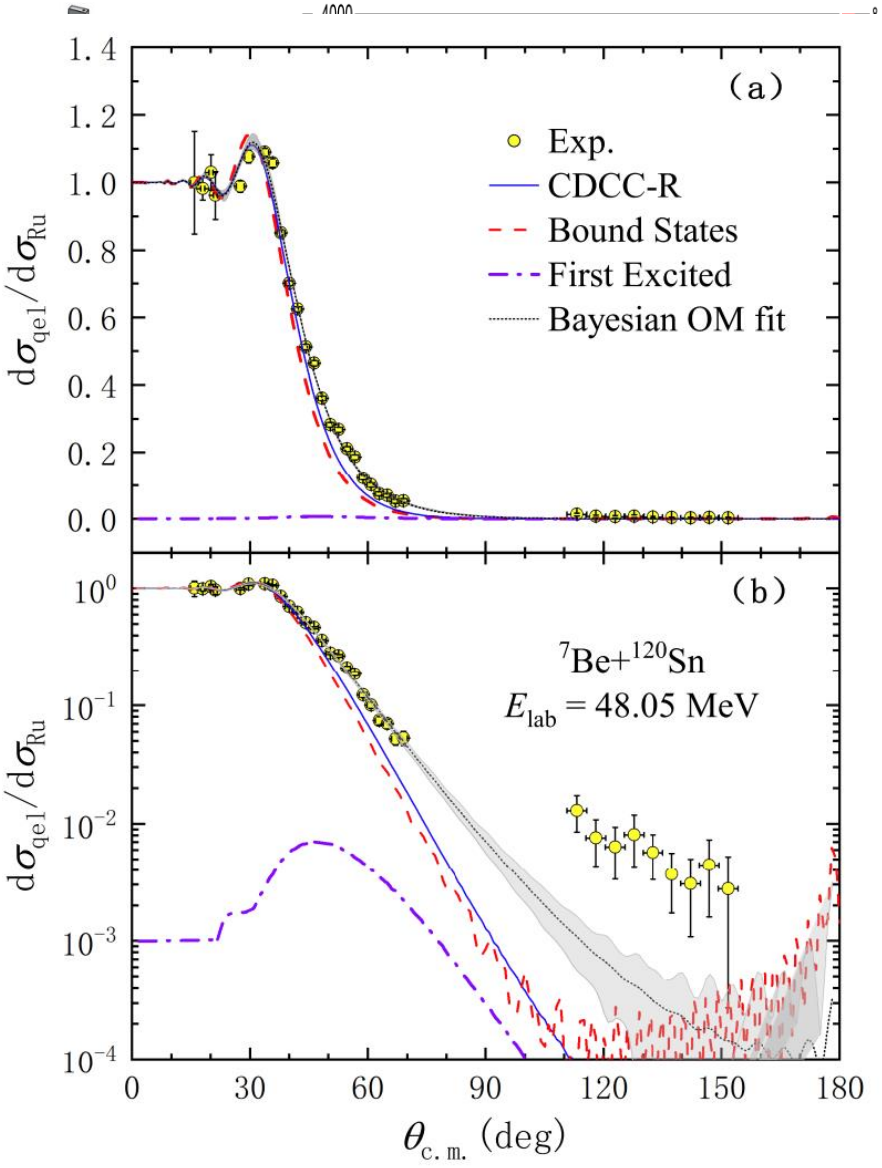


20/40μm SSD + 300μ

10 group of ΔE_1-

40%

1. Exclusive breakup: ^{7}Be → ^{3}He+^{4}He (coi
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*+
5. 1*n* pickup: ^{7}Be+^{209}Bi → ^{8}Be(→^{4}He+^{4}He)
6. 1*p* striping: ^{7}Be+^{209}Bi → ^{6}Li(→^{4}He+*d*)+
8. 1*p* pickup: ^{7}Be+^{209}Bi → ^{8}B(→???)+^{208}P
9. Fusion: ^{7}Be+^{209}Bi → ^{216}Fr → *α*, *p*, *n* eva



Summary and Outlook

★ **Optical potentials** of both ^{6}He+^{209}He and ^{6}Li+^{208}Pb show a phenomenon of **abnormal "threshold anomaly"**, where the **dispersion relation** is NOT applicable. Further investigations are strongly desired to explore the underlying physics.

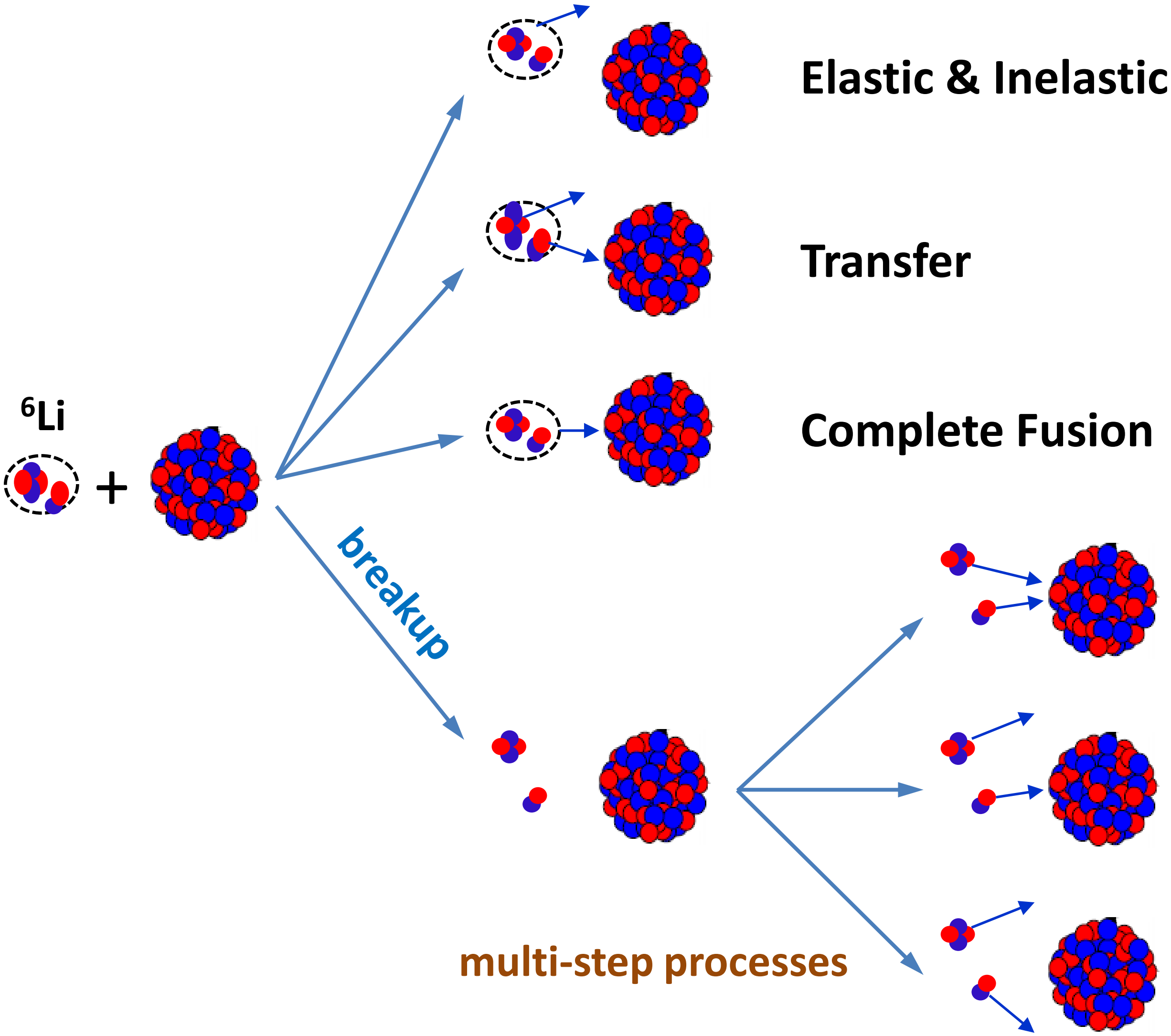
★ Rich information on **breakups of ^{6,7}Li+^{209}Bi** has been obtained experimentally (e.g. energy & angular correlations), waiting for a fully understanding.

★ For **^{17}F, NEB** is dominant, and total fusion is enhanced below the barrier; for **^{8}B, EBU** is dominant, occurring promptly on the outgoing trajectory.

★ More system with exotic nuclei are required to understand the **dynamics of open quantum systems**.

Thank you for your attention!

Reactions with Weakly-bound Nuclei



Elastic & Inelastic

Transfer

Complete Fusion

Sequential
Complete Fusion

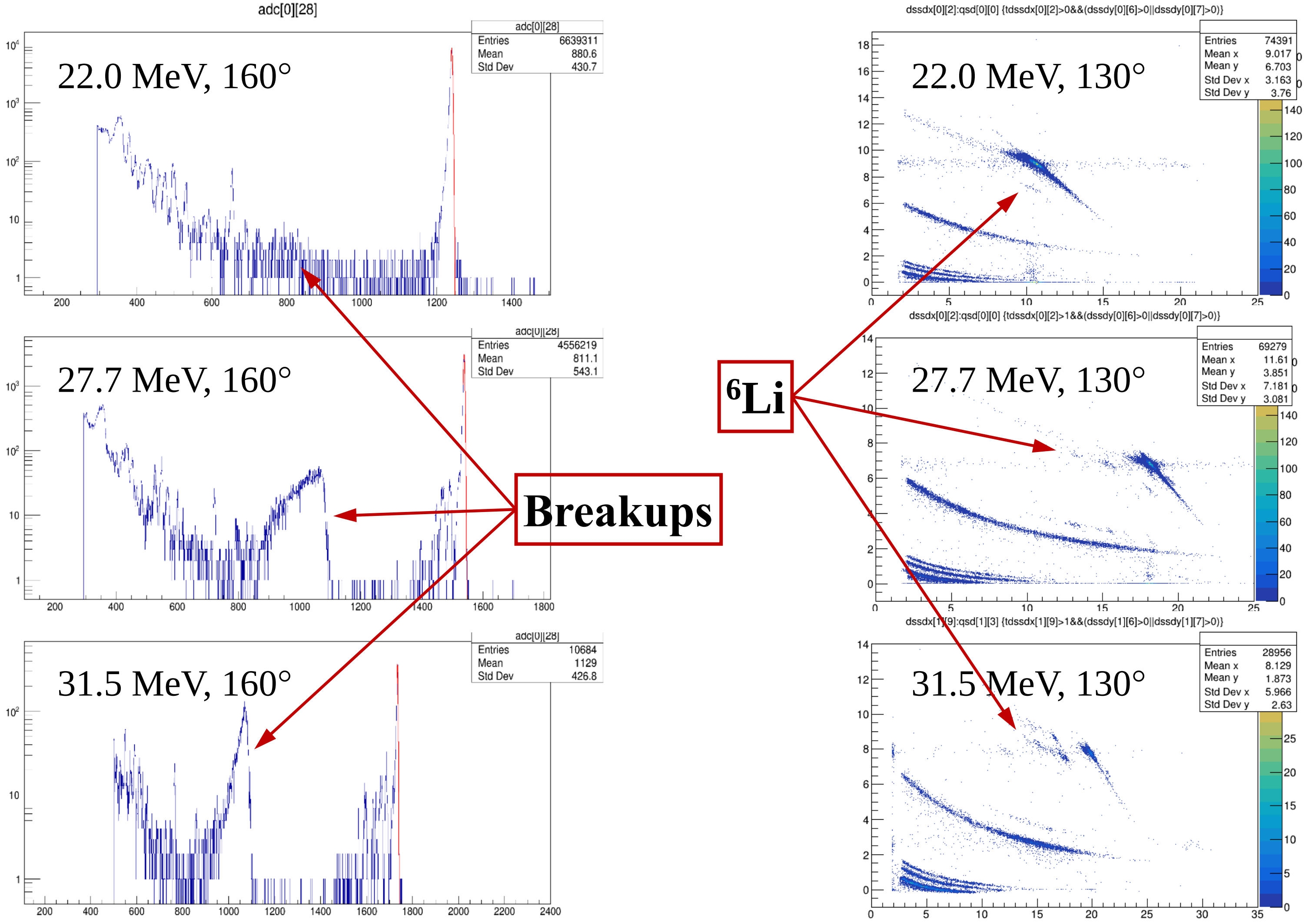
Incomplete Fusion

Breakup

Experimental Spectra

^{6}Li+^{208}Pb elastic scattering

^{207}Pb(^{7}Li,^{6}Li)^{208}Pb transfers



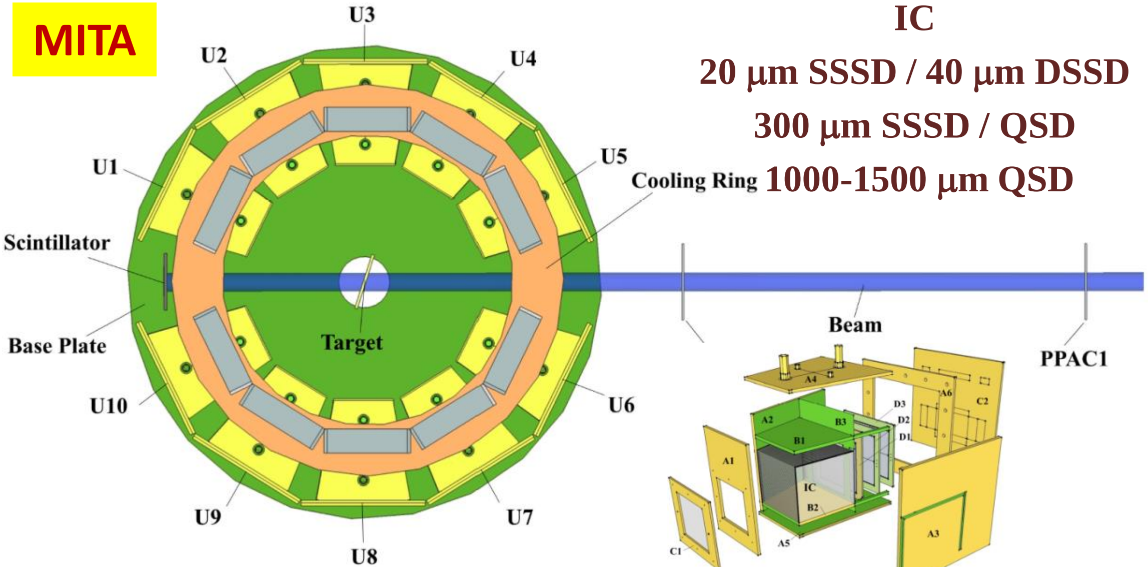
Breakups

^{6}Li

Detector Arrays

MITA

IC
20 μm SSSD / 40 μm DSSD
300 μm SSSD / QSD
1000-1500 μm QSD



10 sets of IC-based telescope, 4 layers, soli

MITA2