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# The Threshold Anomaly of Optical Potentials and the Dispersion Relation for Weakly-bound Nuclear Systems

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# Outline

I. Introduction

II. Experimental Procedure

III. Results and Discussions

IV. Summary

# Introduction: OMP

## 1. Optical Model Potential (OMP/OP)

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

♠ A successful model is the optical model, which resembles the case of light scattered by an opaque glass sphere.

**Optical Model Potential:**

$$U = V(r) + iW(r)$$

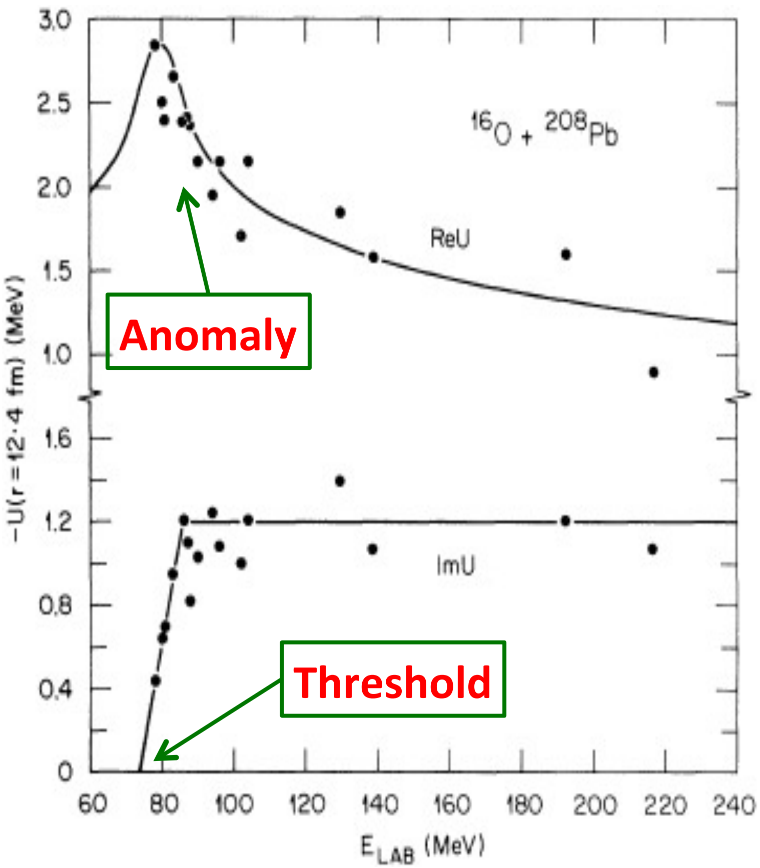
**attractive** **absorptive**

♠ The potential is independent on the energy, at beginning.

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).

## 2. Threshold Anomaly (TA)

**tightly-bound nuclear systems**




$$U(r;E) = V(r;E) + iW(r;E)$$

$$V(r;E) = \underline{V_0(r;E)} + \underline{\Delta V(r;E)}$$

Space Time

Nonlocality

**Dynamic polarization potential:**

$$\Delta V(r;E) = \frac{\mathrm{P}}{\pi}\int_0^\infty \frac{W(r;E')}{E'-E}\,dE'$$

**Dispersion relation**

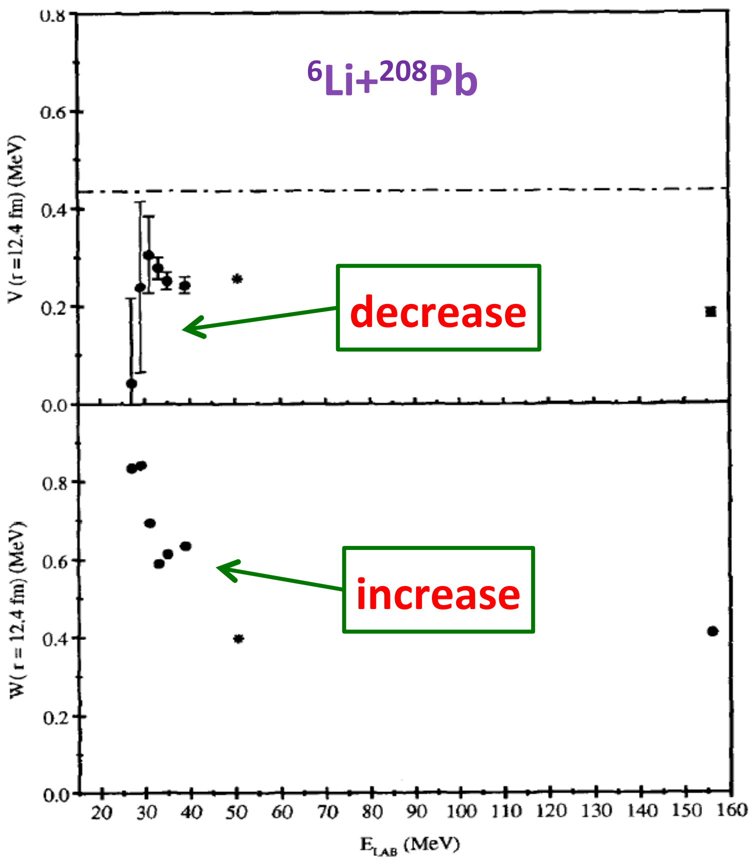
**(results from the causality)**

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. Breakup Threshold Anomaly (BTA)

**For weakly-bound nuclear systems -- $^{6,7}$Li, $^{9}$Be and RNB induced reactions**




**Questions:**

1) W increases with energy decreasing.
   - What is the reason?
     Due to the breakup? [Hussein's opinion]
   - Continue increasing?
     Where is the threshold?

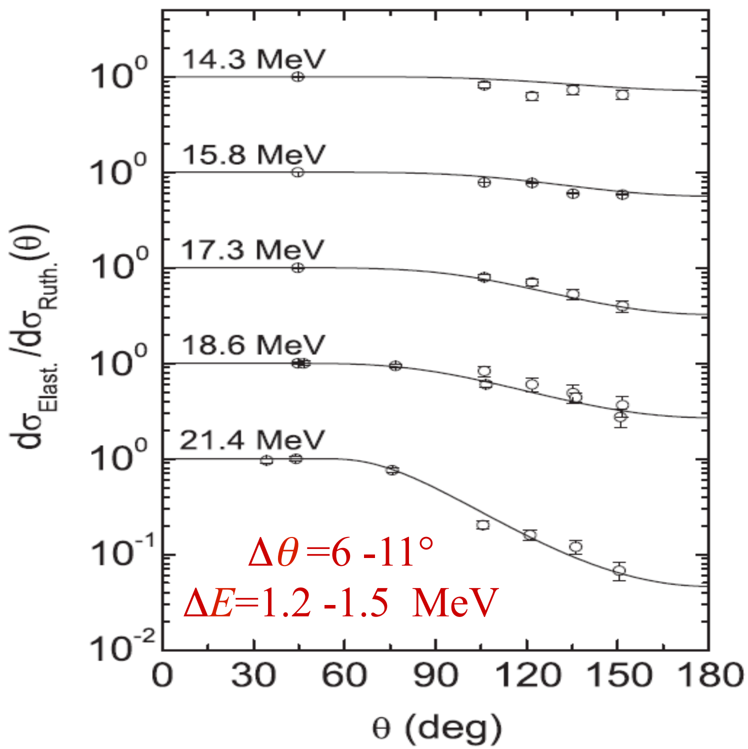
2) V behavior?

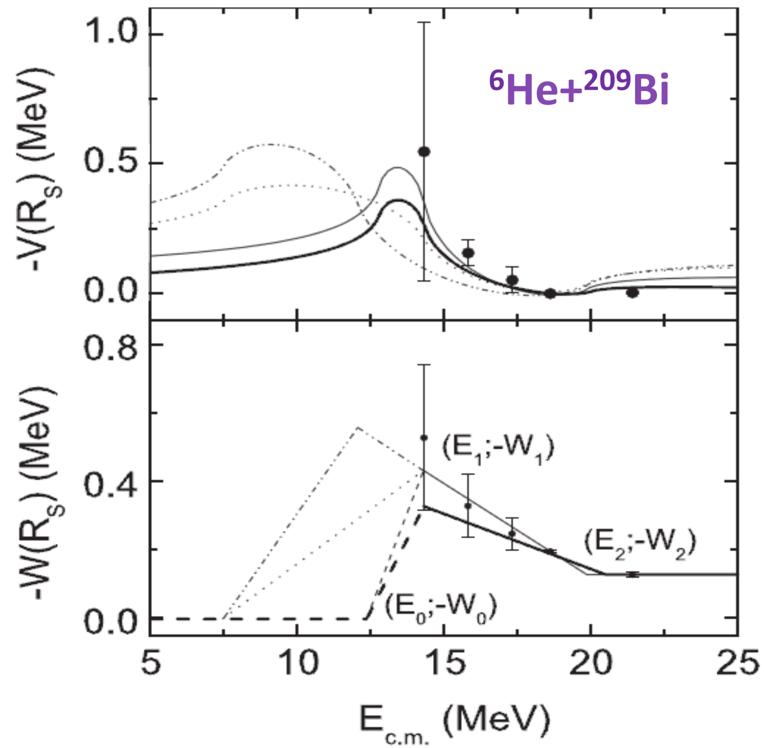
3) Dose the dispersion relation still hold for those systems?

Cf: 1) N. Keeley *et al.*, Nucl. Phys. **A571**, 326 (1994).
2) M. S. Hussein *et al.*, Phys. Rev. C **73**, 044610 (2006).

## 4. Methods to probe OMPs

In general, OMPs are extracted by fitting angular distributions of elastic scattering.



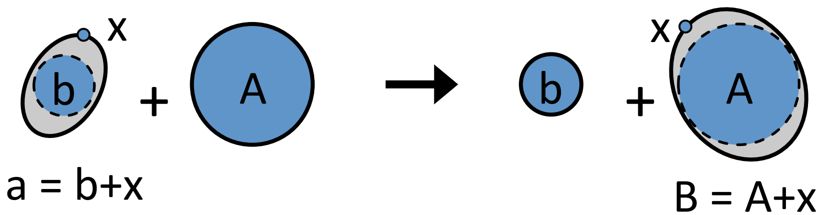




★ Almost impossible to extract an effective OMP at energy below the barrier.

Cf: 1) E.F. Aguilera *et al.*, PRL **84**, 5058 (2000); PRC **63**, 061603R (2001).

# Introduction: methods

We proposed to extract the OMPs through **transfer reactions**.




Transfer reaction A(a,b)B

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

elastic scatting cross sections

In the **DWBA** calculation,

Transition amplitude: $T = J \int d^3 r_b \int d^3 r_a \chi^{(-)}(\vec{\mathbf{k}}_\mathbf{f}, \vec{\mathbf{r}}_\mathbf{b})^* \langle bB|V|aA\rangle \chi^{(+)}(\vec{\mathbf{k}}_\mathbf{i}, \vec{\mathbf{r}}_\mathbf{a}),$

4 wave functions are needed,

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

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

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

Cf: C. J. Lin *et al*., AIP Conf. Proc. **853**, 81 (2006).

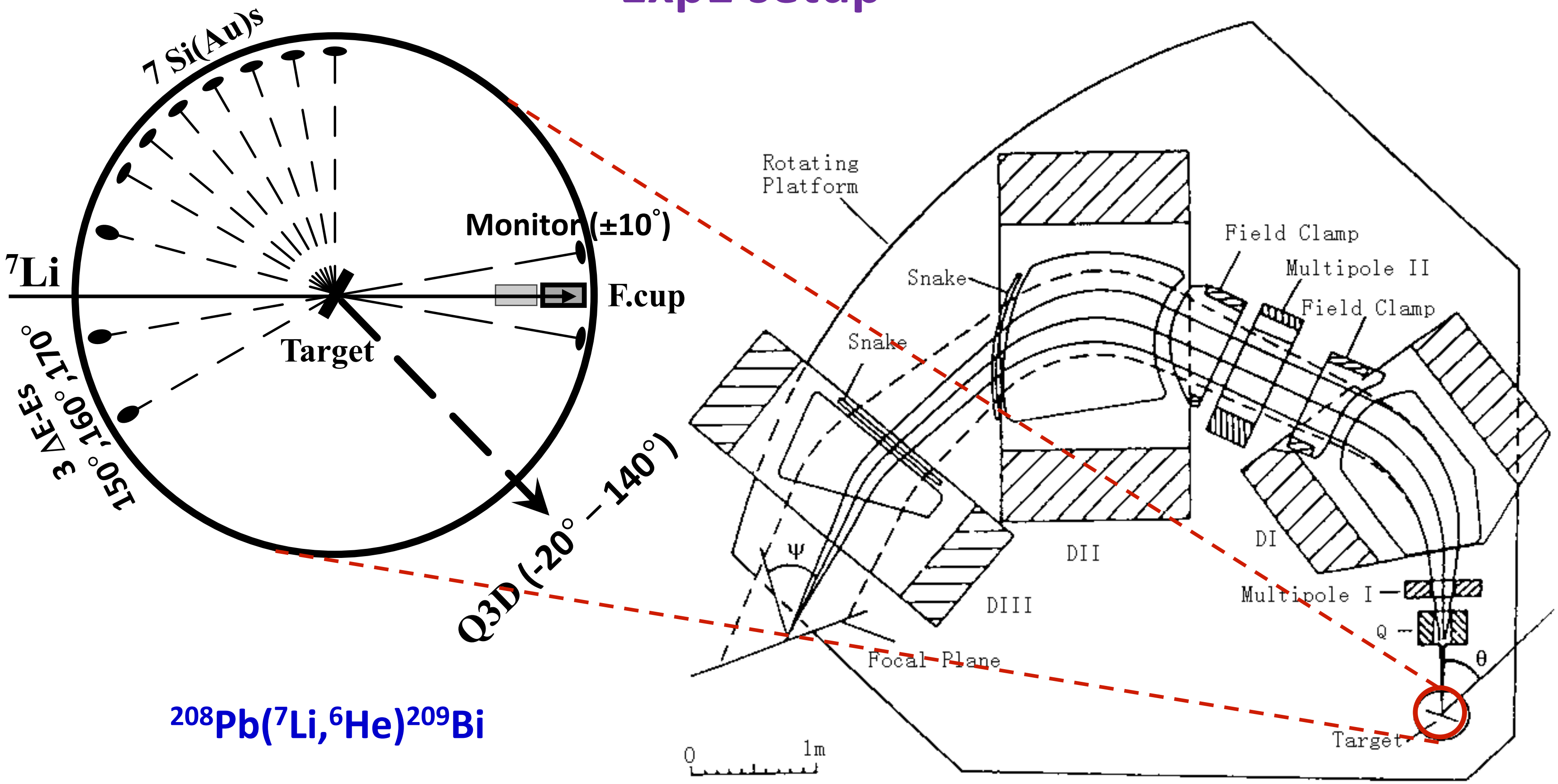
# Experiment: exp1 setup

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

Exp1: $E_{beam}$ = 42.55, 37.55, 32.55, 28.55, 25.67 MeV

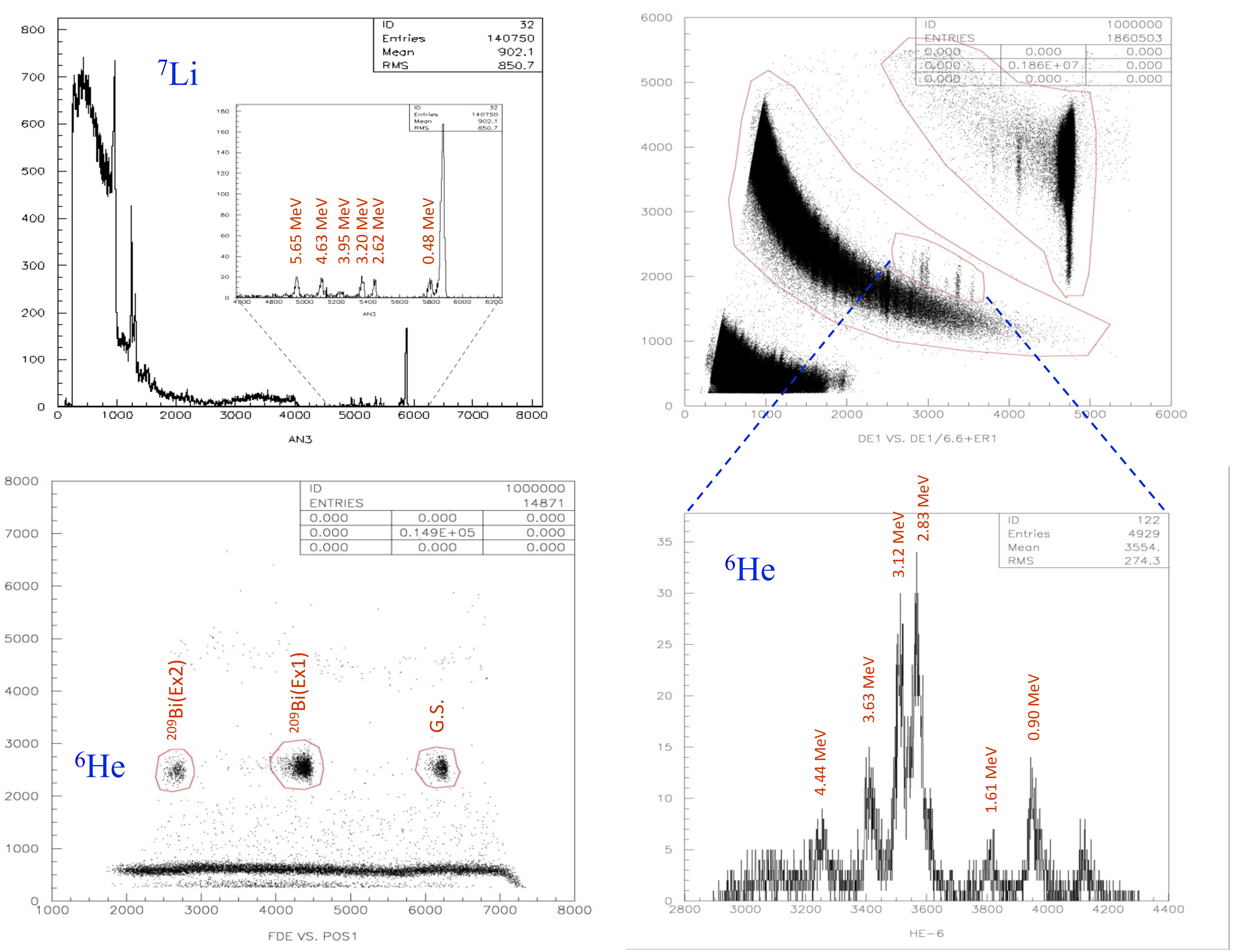
Exp2: $E_{beam}$ = 28.55, 25.67, 24.3, 21.2 MeV

## Exp1 setup



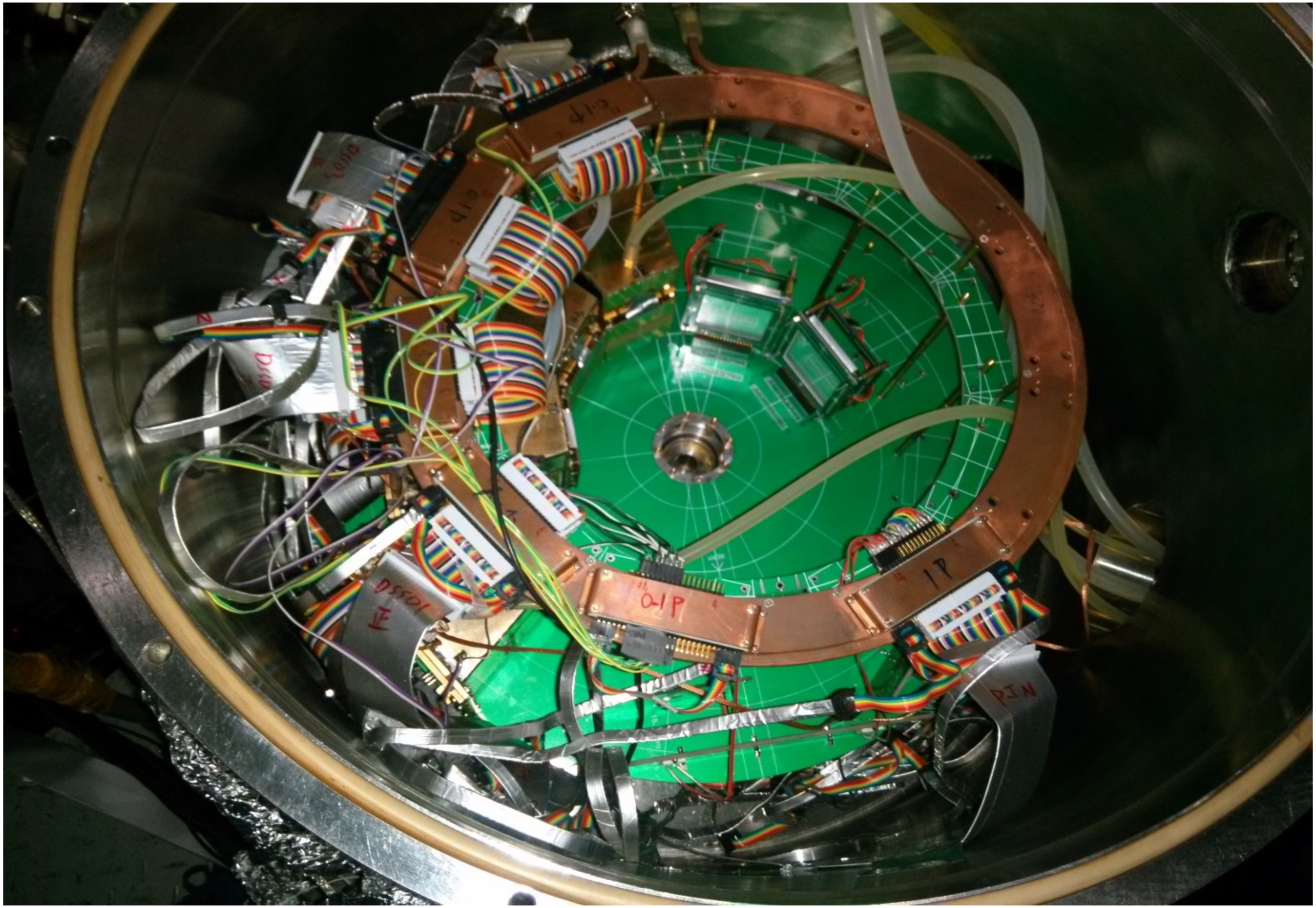

$^{208}Pb(^{7}Li,^{6}He)^{209}Bi$

# Experiment: exp1 spectrum

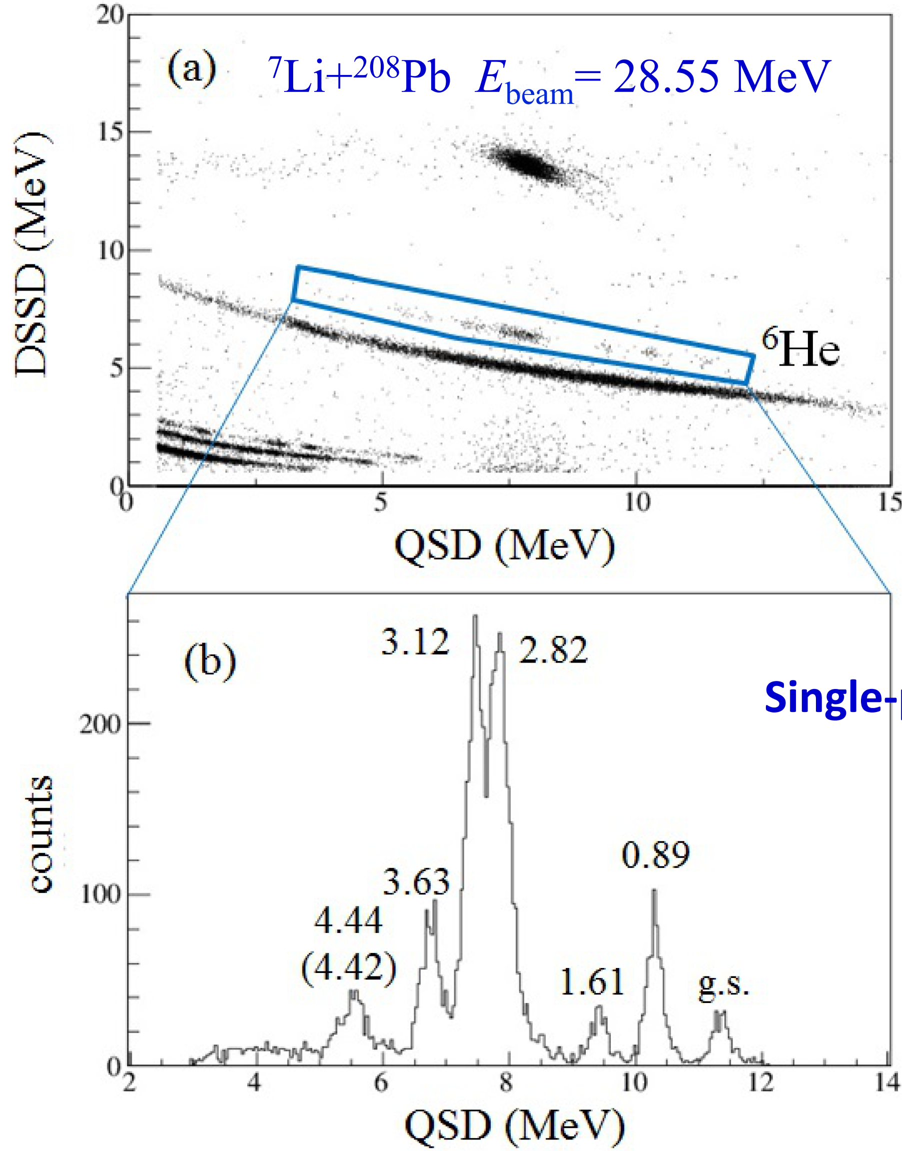


# Experiment: exp2 setup

## Exp2 setup

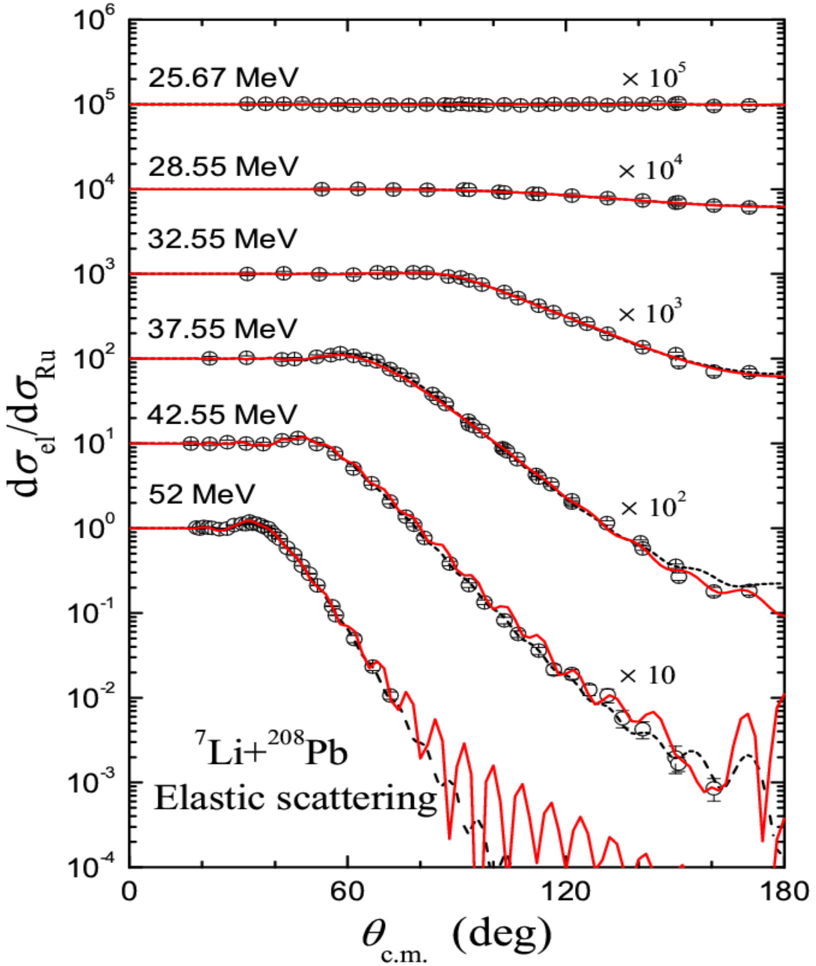


# Experiment: exp2 spectrum

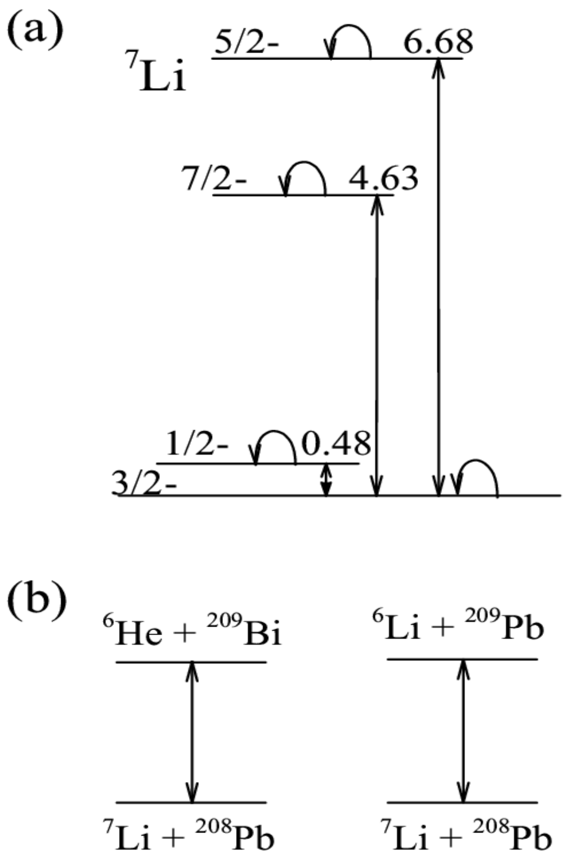



**Single-particle states**

## 1. Elastic scattering

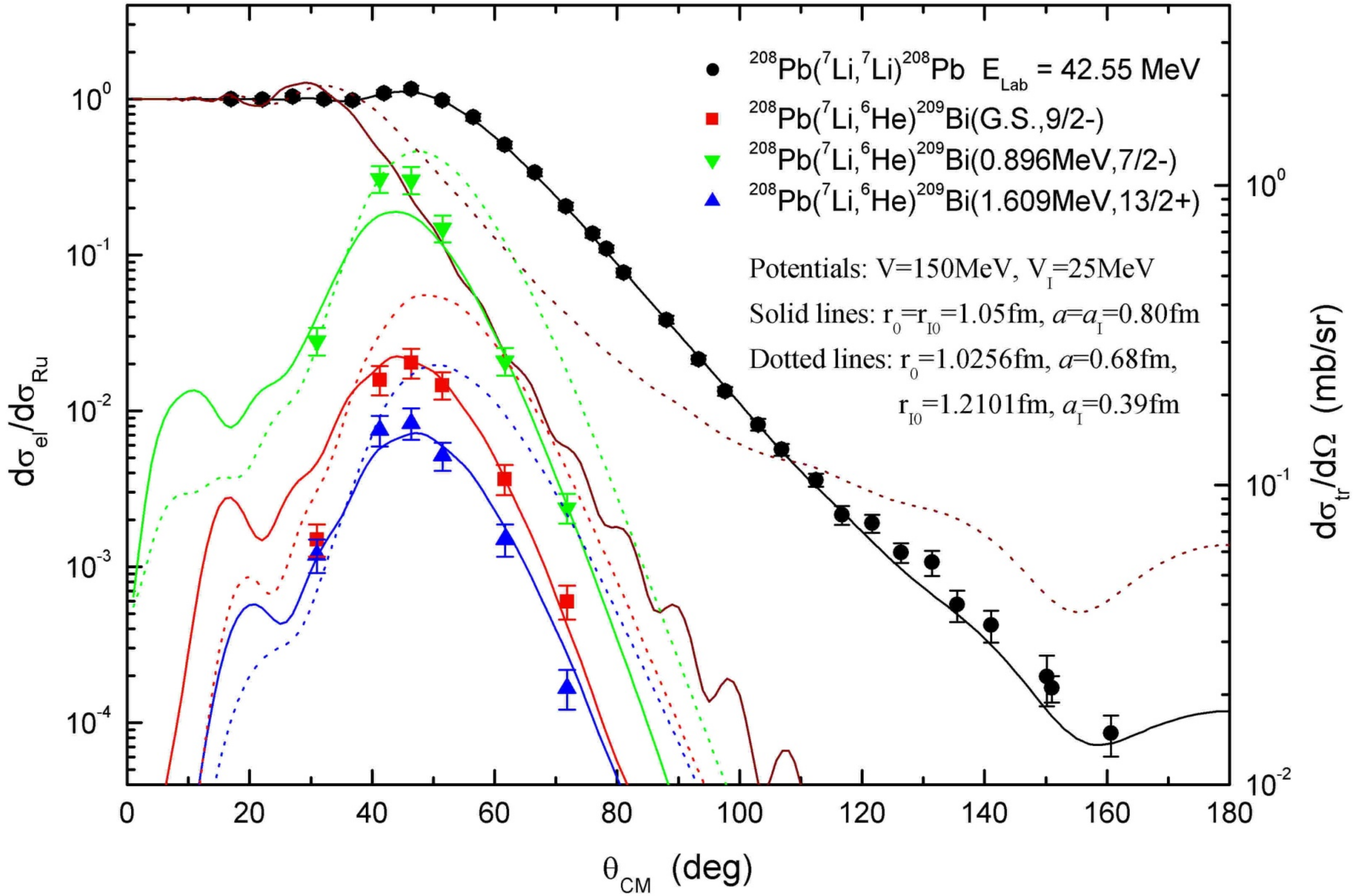



**CRC scheme**




Cf: L. Yang, C. J. Lin* *et al*. Phys. Rev. C **89**, 044615 (2014).

## 2. Transfer reactions



# Results: transfer

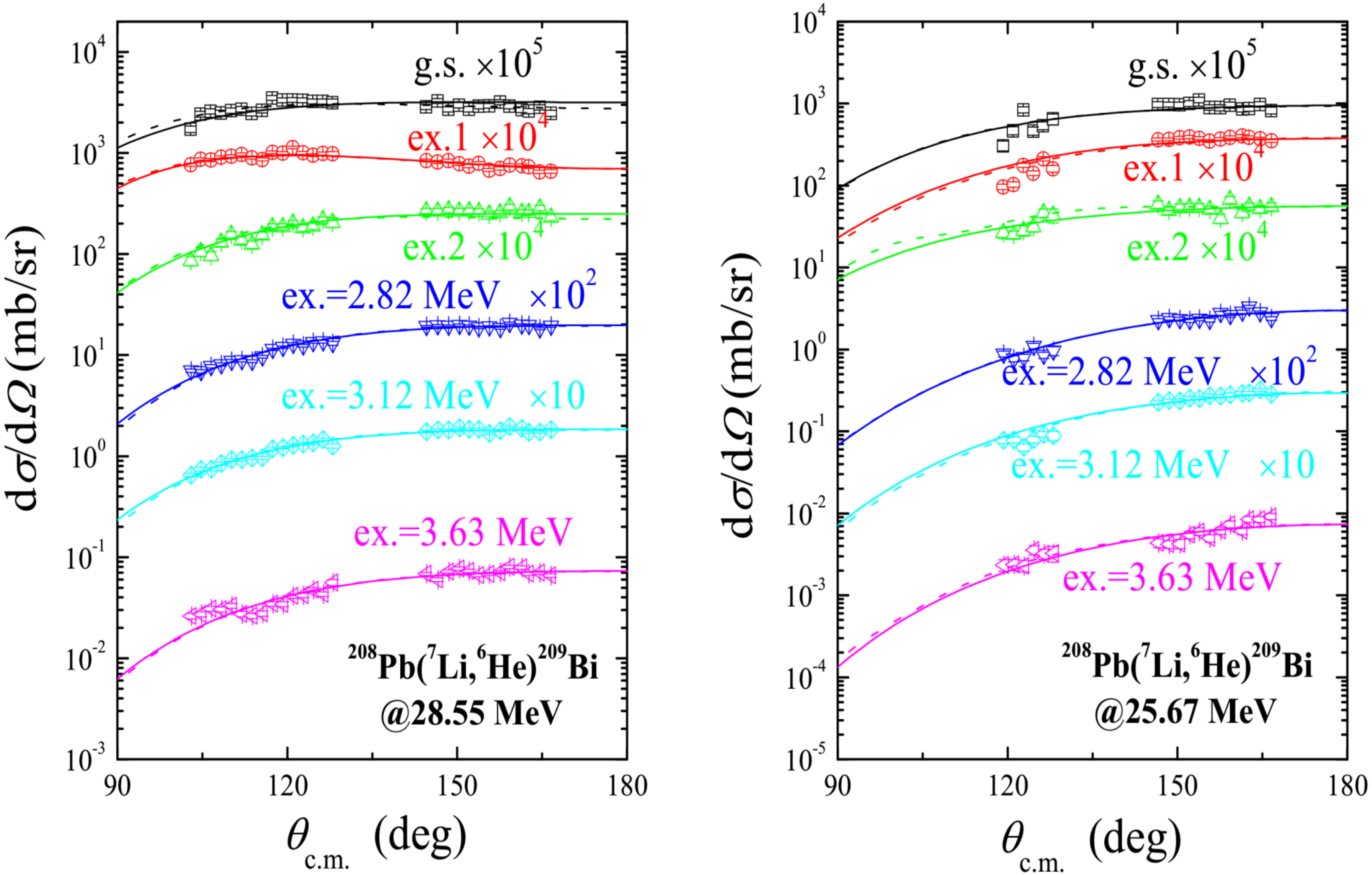
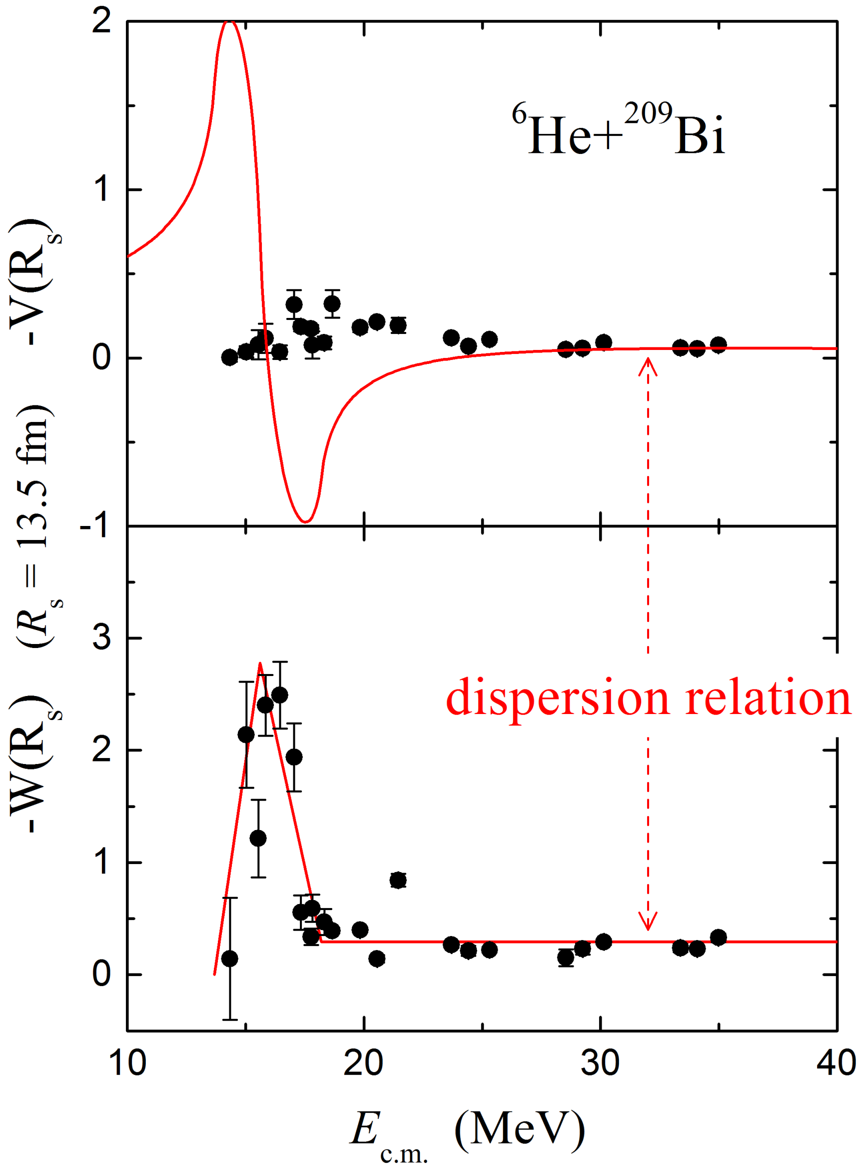



**Fig.** Angular distributions of $^{208}$Pb($^{7}$Li,$^{6}$He)$^{209}$Bi* at $E_{lab}$($^{7}$Li)=28.55 and 25.67 MeV.

# Results: $^{6}$He+$^{209}$Bi OMPs




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

★ The **decreasing trend** in the imaginary part is observed, and the **threshold energy** is about 13.69 MeV (~0.73 $V_B$);

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

★ The traditional dispersion relation **does NOT hold** in this system.

# Summary

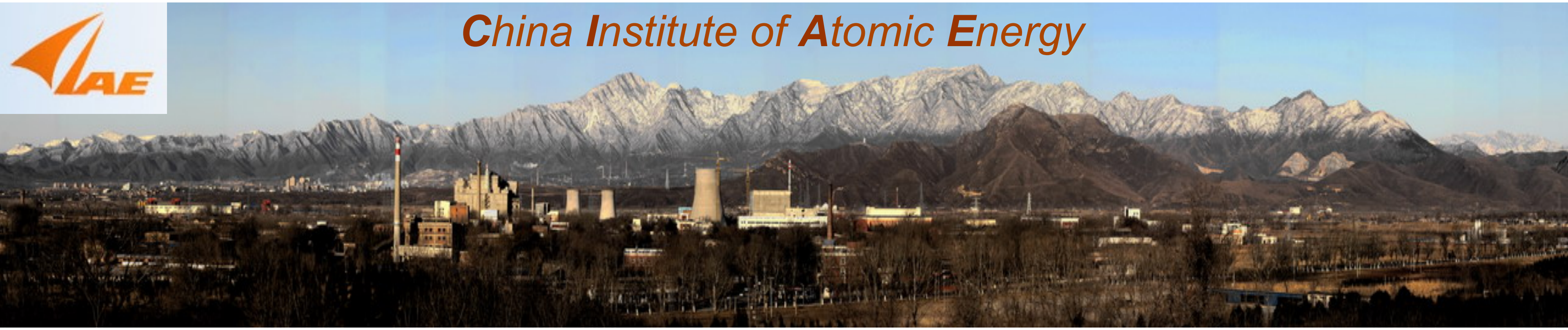
♠ Transfer reactions are employed to extract the OMPs of exotic nuclear systems in the exiting channels.

Advantage: 1) stable beam; 2) high-quality data; 3) precise OPs.
4) good for sub-barrier energy, where the absolute C.S. sections provide extra constraints on OMP.

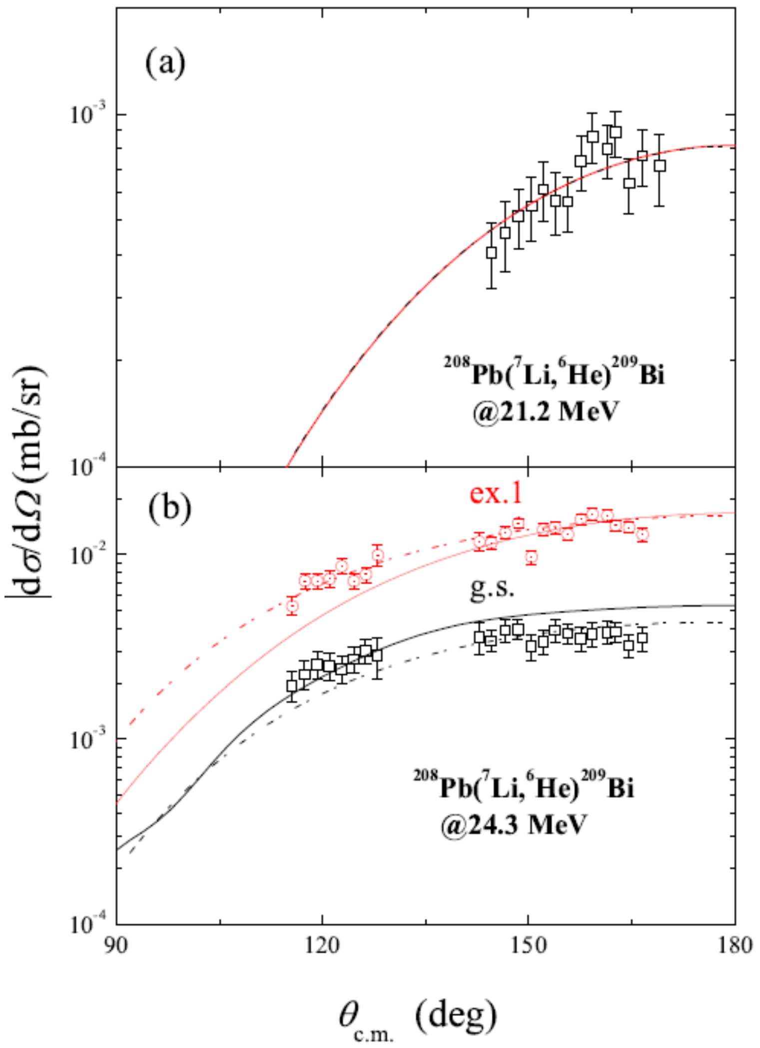
♠ OMPs of the $^{6}He+^{209}Bi$ system have been determined precisely, showing: 1) an abnormal TA behavior;
2) the threshold energy. (~0.73 $V_B$)

♠ The traditional dispersion relation does not hold for the exotic systems. A new dispersion relation are strongly called for.

# THANKS !

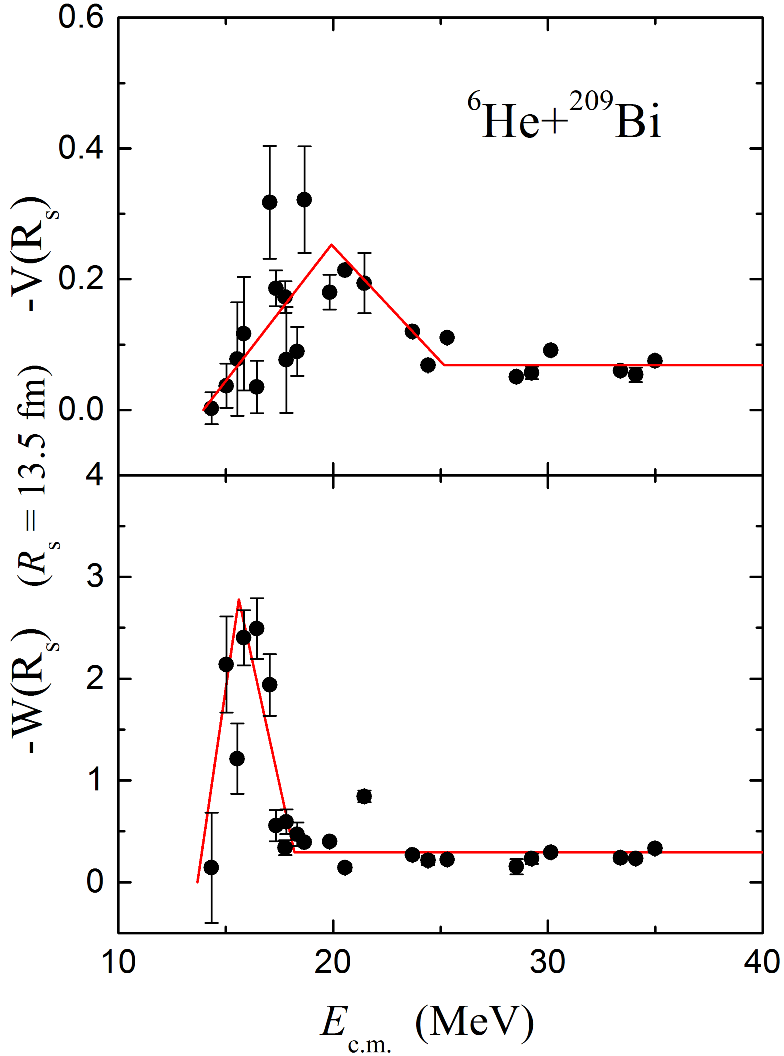


# Supplement

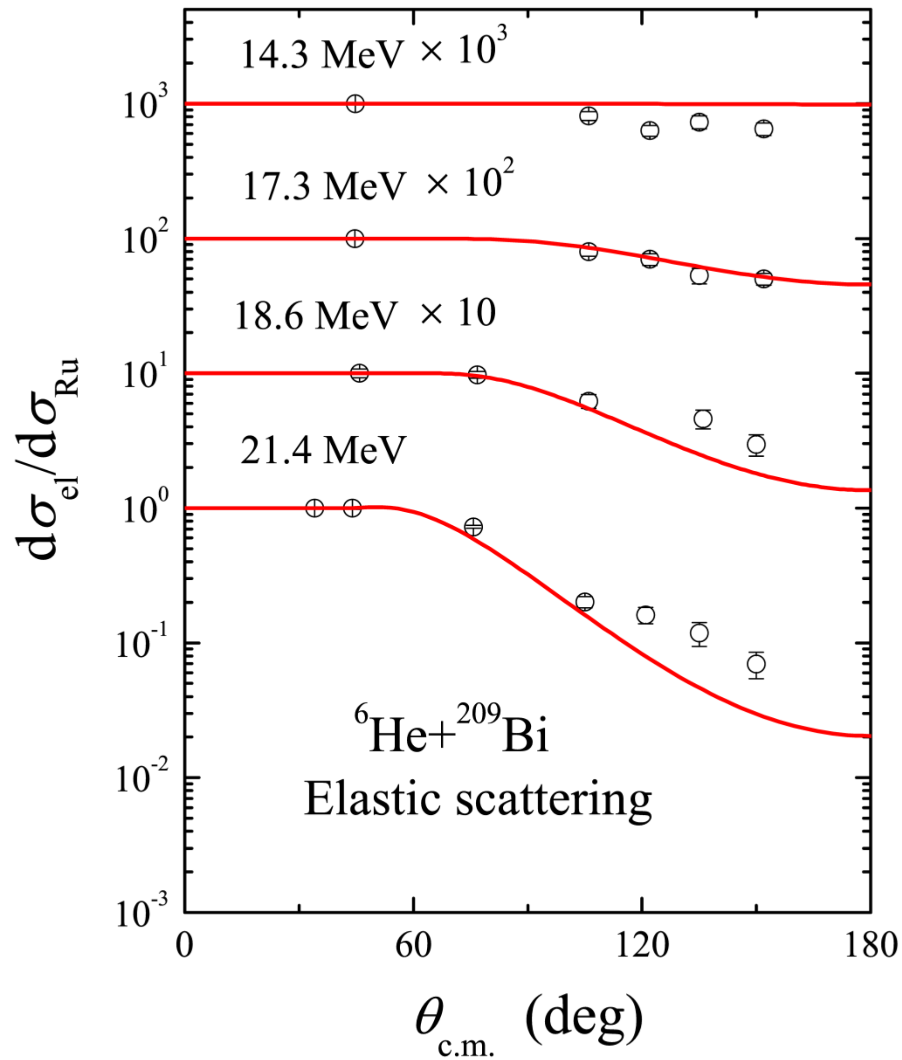


(a)
10^-3
10^-4
208Pb(7Li,6He)209Bi
@21.2 MeV
(b)
ex.1
10^-2
g.s.
10^-3
10^-4
208Pb(7Li,6He)209Bi
@24.3 MeV
dσ/dΩ (mb/sr)
90
120
150
180
θc.m. (deg)

# Supplement



$^6$He+$^{209}$Bi
-V(R$_s$)
-W(R$_s$)
($R_s$ = 13.5 fm)
$E_{c.m.}$ (MeV)
0.6
0.4
0.2
0.0
4
3
2
1
0
10
20
30
40

14.3 MeV × 10$^3$
17.3 MeV × 10$^2$
18.6 MeV × 10
21.4 MeV
$^6$He+$^{209}$Bi
Elastic scattering
$d\sigma_{el}/d\sigma_{Ru}$
$\theta_{c.m.}$ (deg)
10$^3$
10$^2$
10$^1$
10$^0$
10$^{-1}$
10$^{-2}$
10$^{-3}$
0
60
120
180