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 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):

\[ U = V(r) + iW(r) \]

- **attractive**
- **absorptive**

★ phenomenological potential, independent on energy.

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

Tightly-bound Nuclei

A universal phenomenon at energies around the Coulomb barrier


Weakly-bound Stable Nuclei

Threshold Anomaly

\[ ^7\text{Li} (\alpha + t) \]
\[ S_\alpha = 2.47 \text{ MeV} \]

\[ ^6\text{Li} (\alpha + d) \]
\[ S_\alpha = 1.47 \text{ MeV} \]

Abnormal Threshold Anomaly

\[ ^9\text{Be} (\alpha + n + \alpha) \]
\[ S_n = 1.66 \text{ MeV} \]


N. Yu et al., JPG 371, 075108 (2010).
Impossible to extract effective OMPs at energy far below the barrier.

OMPs are usually extracted from elastic scattering.

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

Transfer Method

Transfer reaction $A(a,b)B$

Transition amplitude:

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

4 wave functions are needed,

- two bound states: $b+x$ & $A+x$ (single-particle potential model)
- two scattering states: incoming & outgoing (optical potentials)


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


$^{63}$Cu($^{7}$Li,$^{6}$He)$^{64}$Zn: Phys. Rev. C 95, 034616 (2017).
Two experiments have been done at HI-13 tandem accelerator @ CIAE

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


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

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

Single-particle states S-factors are well known
**Analyses: $^{208}\text{Pb}({}^7\text{Li}, {}^6\text{He})^{209}\text{Bi}$**

**DWBA & CRC analyses**

**Elas.**

$^{\text{7Li}}+^{208}\text{Pb}$

Elastic scattering

$E_{\text{cm}} = 42.55 \text{ MeV}$

$\theta_{\text{cm}}$ (deg)

$\frac{d\sigma}{d\Omega}$ (mb/sr)

$\frac{d\sigma}{d\Omega}$ (mb/sr)

**Tran.**

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

@ $25.67 \text{ MeV}$

**24.30 MeV**

$^{7}\text{Li}+^{208}\text{Pb}$ elas.

$^{6}\text{He}+^{209}\text{Bi}$ elas.

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

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

$0.90 \text{ MeV}$

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

- OMPs of the \(^{6}\text{He}+^{209}\text{Bi}\) system are determined precisely;
- The decreasing trend in the imaginary part is observed, and the threshold energy is about 13.73 MeV (~0.68\(V_{B}\));
- 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.

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 $\rightarrow$ dispersion relation
  stable systems: causality $\leftrightarrow$ analyticity

• Cauchy integration
  infinity poles (breakup) & off-axis (multi-process)

• Negative Index of Refraction
  causality based criteria must be used with care

• Locality vs. non-locality
  equivalent local potential in
  Schrödinger equation

Metamaterials?

four-body
Outline

1. Potentials of Exotic Nuclear Systems

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Reactions with RIBs

♠ Elastic scattering
   3-body, 4-body
   CDCC ...

♠ Fusion
   TF, ICF, CF ...

♠ Breakup/transfer
   Effects & mechanisms

**BK/TR Processes**

★ How to identify the different reaction process?

**complete-kinematics measurement**

2-body kinematics

3-body kinematics

Same products

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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 $4\pi$  8% of $4\pi$

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

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]

**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 \(^{17}\text{F} \rightarrow ^{16}\text{O} + \text{p}, S_p = 0.6 \text{ MeV}\)

Our result: \(\sigma \sim 1.2 \text{ mb} @ 63 \text{ MeV};\) Liang’s result: \(\sigma \sim 15.6 \text{ mb} @ 170 \text{ MeV}.\)

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

Others \(^{7}\text{Be}, ^{8}\text{B} \ldots\) 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)

Summary

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

★ Reactions of \(^{17}\text{F}+^{12}\text{C}, \ ^{58}\text{Ni}, \ ^{89}\text{Y}, \ ^{208}\text{Pb}, \ ^{7}\text{Be}+^{209}\text{Bi}, \text{and} \ ^{8}\text{B}+^{120}\text{Sn}\) 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

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... ...
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

6Li (α+d)
\[ S_\alpha = 1.47 \text{ MeV} \]

7Li (α+t)
\[ S_\alpha = 2.47 \text{ MeV} \]

9Be (α+n+α)
\[ S_n = 1.66 \text{ MeV} \]

halo

11Be (10Be+n)
\[ S_n = 0.50 \text{ MeV} \]

6He (α+2n)
\[ S_{2n} = 0.98 \text{ MeV} \]

Borromean
Reactions with Exotic Nuclei
Reactions with light exotic nuclei (A<20)

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

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

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. $1n$ stripping: $^7$Be+$^{209}$Bi → $^6$Be($\rightarrow$$^4$He+$p$+$p$)+$^{210}$Bi;
5. $1n$ pickup: $^7$Be+$^{209}$Bi → $^8$Be($\rightarrow$$^4$He+$^4$He)+$^{208}$Bi;
6. $1p$ striping: $^7$Be+$^{209}$Bi → $^6$Li($\rightarrow$$^4$He+$d$)+$^{210}$Po;
7. $1p$ pickup: $^7$Be+$^{209}$Bi → $^8$B($\rightarrow$??)+$^{208}$Pb;
8. Fusion: $^7$Be+$^{209}$Bi → $^{216}$Fr → $\alpha$, $p$, $n$ eva. & decay (energy & angular distri.)
9. ICF (Ene-Ang corr.)