Reaction dynamics of heavy ions and exotic nuclei

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Outline

- Motivation & some important concepts
- Effects of diabaticity on fusion of heavy ions
- Elastic scattering of halo nuclei & the dynamics of open quantum systems
The interplay between **nuclear structure** & **reaction dynamics** determines the reaction observables (**cross sections**).
Effects of diabaticity on low-energy fusion of heavy ions

- To hinder both the motion to small relative distances and the growth of the neck in the dinuclear system.
- The diabatic effects support the dinuclear system model of fusion in low-energy heavy-ion collisions.

The Two-Centre Shell Model is a basic microscopic approach to the single-particle motion in low-energy heavy-ion collisions

A legacy of the Frankfurt school of theoretical nuclear physics

Walter Greiner  Joachim Maruhn
The Two-Centre Shell Model (TCSM)
Maruhn & Greiner, Z. Phys. 251 (1972) 431

\[ \lambda = \frac{l}{2R_0} \]

\[ \varepsilon = \frac{E_0}{E'} \]

\( ^{110}\text{Pd} + ^{110}\text{Pd} \)
The Adiabatic Picture of Fusion

The Adiabatic Picture of Fusion

\[ ^{110}\text{Pd} + ^{110}\text{Pd} \]

Some Problems with the Adiabatic Picture of Fusion

Adiabatic and Diabatic Single-Particle Motion
\[ \Delta V_{\text{diab}}(q) \approx \sum_{\alpha} E_{\alpha}^{\text{diab}}(q) \left( n_{\alpha}^{\text{diab}} - n_{\alpha}^{\text{adiab}} \right) \]
Diabatic Collective PES


100Mo + 100Mo

110Pd + 110Pd

V_{\text{diab}} (MeV)

\lambda

(elongation)
Dynamical Collective PES
Dynamical Collective PES

\[
\eta = \frac{(A_1 - A_2)}{(A_1 + A_2)}
\]
Charge & Mass Distributions of Quasi-Fission Products

\[ {^{48}\text{Ca}} + {^{244}\text{Pu}} \rightarrow {^{292}114} \]

\[ Y_{Z} \]

\[ Y_{A} \]

AD-T, Adamian, Antonenko & Scheid, PRC 64 (2001) 024604
Summary 1

- The **diabatic picture** supports the dinuclear system model for complete fusion of heavy nuclei at low energies.

Could the initial **fission** path of a heavy compound nucleus be the inverse path used by the dinuclear model of fusion?
Elastic Scattering of Halo Nuclei and the Dynamics of Open Quantum Systems

- The **Coulomb-nuclear interference** is crucial for the elastic-scattering angular distribution.

- The Coulomb-nuclear interference **declines** and becomes destructive due to **continuum couplings**.

Open Quantum Systems: Halo Nuclei

\[ S_n = 0.32 \text{ MeV} \]

\[ S_n = 4.06 \text{ MeV} \]

Elastic scattering of Beryllium isotopes by the $^{64}$Zn target


- Suppression of the Coulomb-nuclear interference peak for $^{11}\text{Be}$
Elastic scattering of $^{11}\text{Be} + ^{64}\text{Zn}$ at $E_{\text{cm}} = 24.5$ MeV

Elastic scattering differential cross section


\[
\frac{d\sigma(\theta)}{d\Omega} = |f_C(\theta) + f_N(\theta)|^2
\]

- Point-Coulomb (Rutherford) amplitude
- Coulomb-modified Nuclear amplitude

- The Coulomb-nuclear interference term is crucial
Some Formulae


\[
\frac{\sigma}{\sigma_R} = 1 + \frac{|f_N(\theta)|^2}{|f_C(\theta)|^2} + \frac{2 \text{ Re} [f_C^*(\theta)f_N(\theta)]}{|f_C(\theta)|^2}
\]

Nuclear Coulomb-nuclear interference

\( \frac{R}{R_0} \quad \text{V} \) Coulomb

Nuclear
Decomposition of the elastic-scattering angular distribution

$^{11}\text{Be} + ^{64}\text{Zn} \text{ @ } E_{\text{cm}} = 24.5 \text{ MeV}$

AD-T & Moro,
PLB 733 (2014) 89

one-channel

CDCC
Amplitude & Phase of the Coulomb-nuclear interference

$^{11}\text{Be} + ^{64}\text{Zn} @ E_{cm} = 24.5 \text{ MeV}$

AD-T & Moro, PLB 733 (2014) 89
Summary 2

- The **Coulomb-nuclear interference** is crucial for the elastic-scattering angular distribution.

- The Coulomb-nuclear interference **declines** due to continuum couplings.

Could the elastic scattering of halo nuclei be a tool for investigating **the dynamics of open quantum systems** in nuclear physics?

<table>
<thead>
<tr>
<th>Halo Projectile</th>
<th>→</th>
<th>Breakup Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Nucleus</td>
<td>→</td>
<td>Breakup Couplings</td>
</tr>
<tr>
<td>Incident Energy</td>
<td>→</td>
<td>Control Variable</td>
</tr>
</tbody>
</table>
EXTRA SLIDES
Some Formulae


\[ \frac{\sigma}{\sigma_R} = 1 + \frac{|f_N(\theta)|^2}{|f_C(\theta)|^2} + \frac{2 \text{Re}[f_C^*(\theta)f_N(\theta)]}{|f_C(\theta)|^2} \]

Nuclear Coulomb-nuclear interference

\[ f_C(\theta) = -\frac{\eta}{2k\sin^2(\theta/2)} e^{-i\eta\ln \sin^2(\theta/2) + 2i\sigma_0} \]

\[ g(\theta) = f_C(\theta) + \frac{i}{2k} \sum_L \left[(2L + 1) - (L + 1)S_L^+ - LS_L^-\right] e^{2i\sigma_L} P_L(\cos \theta) \]

\[ h(\theta) = \frac{i}{2k} \sum_L (S_L^- - S_L^+) e^{2i\sigma_L} P_L^1(\cos \theta) \]

\[ \frac{d\sigma(\theta)}{d\Omega} = |g(\theta)|^2 + |h(\theta)|^2 \]

Particles with spin 1/2
The cranking mass parameter of the neck coordinate is much larger than the corresponding mass in the hydrodynamical (Werner-Wheeler) model.

The neck of the dinuclear system does not grow much


(neck coordinate)
TCSM with Woods-Saxon Potentials
Elastic scattering of $^6\text{He} + ^{208}\text{Pb}$ at $E_{\text{cm}} = 26.2$ MeV

Decomposition of the elastic-scattering angular distribution

$^6\text{He} + ^{208}\text{Pb} @ E_{cm} = 26.2 \text{ MeV}$

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