Reactions with heavy nuclei

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H.I. Reactions at $E > V_b$

CDCC (break-up)

“Theory of Nuclear Reactions” Frobrich and Lipperheide
**H.I. Sub-barrier fusion reactions \((Z_p \ast Z_T < 1600)\)**

- \(^{16}\text{O} + ^{154}\text{Sm}\)
- \(^{154}\text{Sm} \rightarrow ^{16}\text{O} + ^{154}\text{Sm}\)

**deformation of \(^{154}\text{Sm}\)**

**collective excitations during fusion**

- excitation energies
- transition strengths
- multi-phonon excitations or g.s. rotational band

\[
\sigma_{\text{fus}}(E) = \int_0^1 d(\cos \theta) \sigma_{\text{fus}}(E; \theta)
\]
C.C. with a state-of-the-art nuclear structure calculation (beyond-MF)

$$\sigma_{\text{fus}} \quad (\text{mb})$$

![Graph](a)

$$\frac{d^2(E\sigma_{\text{fus}})}{dE^2} \quad (\text{mb/MeV})$$

![Graph](b)

$^{16}\text{O} + ^{208}\text{Pb}$

- No Coupling
- 2 phonon (HO)
- "2 phonon" (GCM)


C.C. with RPA

$^{40}\text{Ca} + ^{40}\text{Ca}$

$B(E3)$

Damping Factor

T. Ichikawa and K. Matsuyanagi

$^{64}\text{Ni} + ^{64}\text{Ni}$

- Expt.
- No Coupling
- Standard C.C.
- + hindrance

T. Ichikawa and K. Matsuyanagi

PRC88(‘13) 011602(R)
Fusion of halo nuclei

1. Lowering of potential barrier due to a halo structure → enhancement
2. effect of breakup
3. effect of transfer

$^{12,13,14,15}\text{C} + ^{232}\text{Th}$

M. Alcorta et al., PRL106(‘11)172701
Two-neutron transfer reactions: pairing correlations

$^6\text{He} + ^{238}\text{U}$

$^1\text{H} (^{11}\text{Li}, ^9\text{Li}) ^3\text{H}$

I. Tanihata et al., PRL100(‘08)192502

✓ reaction mechanics?
✓ role of unbound intermediate states?
H.I. Sub-barrier fusion reactions ($Z_p * Z_T > 1600 \sim 1800$)

\[ Z_1*Z_2 = 2000 \]
\[ Z_1*Z_2 = 1296 \]

C.-C. Sahm et al., Z. Phys. A319('84)113

- Fusion hindrance
- Modern understanding
- Quasi-Fission
- Compound Nucleus
- Re-separation before CN = Quasi-Fission
closely related phenomenon: deep inelastic collision (~ 70-80’s)

\[^{40}\text{Ca} + ^{238}\text{U} (E = 5.9 \text{ MeV/A})\] highly damped reaction

W.Q. Shen et al., PRC36(’87)115

\(\checkmark\) many phenomenological models

\(\checkmark\) TDHF

a big success of TDHF:

a big success of TDHF for DIC

TDHF seems to work for QF as well

mass-angle distribution


nuclear friction from TDHF

K. Washiyama, D. Lacroix, and S. Ayik, PRC79(‘09)024609

A.S. Umar and V.E. Oberacker, NPA944(‘15)238
c.f. expt.: ANU group (D.J. Hinde et al.)
Super-heavy nuclei

coupled-channels method

Langevin approach

V.I. Zagrebaev and W. Greiner, NPA944(‘15)257

\[ m \frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma \frac{dq}{dt} + R(t) \]

statistical model

Evap. resid. cross section (pb)
still a very challenging problem for nuclear theory

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<tr>
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<th>Time-indep. approach</th>
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<td>Induced fission</td>
<td>✓ Bohr-Wheeler</td>
<td>✓ Langevin-type</td>
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<td>Wheeler (Goutte et al.)</td>
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<td>(after the barrier)</td>
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J. Sadhukhan, W. Nazarewicz, N. Schunck, PRC93(‘16)011304(R)
Fission

still a very challenging problem for nuclear theory

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**issues:**
- which degrees of freedom? (time-indep. approaches)
- how to deal with many-body tunneling? (time-dep. approaches)
Summary and discussions

- Heavy-ion reactions around the Coulomb barrier: strong interplay between structure and reaction
  - sub-barrier fusion reactions (coupled-channels effects)
  - fusion of massive nuclei (nuclear friction)
  - spontaneous and induced fissions
  - two-neutron transfer (pairing correlations)

- From phenomenological models to more microscopic models
  - C.C. with microscopic inputs
  - DFT for spontaneous fission
  - TDHF approach

- "Beyond mean-field" approximations
  - Full time-dependent GCM?
    \[ |\Psi(t)\rangle = \int dq \ f(q, t) |\Phi_q(t)\rangle \]
  - many-body tunneling
    cf. “Quantum tunneling using entangled classical trajectories”
    A. Donoso and C.C. Martens, PRL87 (‘01) 223202
closely related phenomenon: deep inelastic collision (~ 70-80’s)

\[ ^{40}\text{Ca} + ^{238}\text{U} \quad (E = 5.9 \text{ MeV/A}) \]

highly damped reaction

J. Toke et al., NPA440('85)327

W.Q. Shen et al., PRC36('87)115

\[ E_K \quad \begin{array}{c} 0.0025 \quad 0.01 \quad 0.04 \\ 5.9 \end{array} \]

FRAGMENT MASS (u)

W. Q. Shen et al., PRC36('87)115

J. Toke et al., NPA440('85)327

COMPOUND NUCL. FISSION
QUASI-FISSION
DEEP INELASTIC SCATTERING
nuclear friction

- damping of giant resonances
- neutron induced fission (Kramers factor)
- deep-inelastic collisions and quasi-fission
  - wall-and-window formula
  - linear response theory
  - attempts with TDHF and QMD

\[
M \ddot{q} = -V'(q) - \gamma \dot{q}
\]

K. Washiyama, D. Lacroix, and S. Ayik, PRC79(‘09)024609

K. Wen et al., PRL111(‘13)012501

\(\gamma\) (in units of 0.0001c/fm)