Heavy-ion fusion reactions for superheavy elements

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1. H.I. sub-barrier fusion reactions
2. Coupled-channels approach and barrier distributions
3. Application to superheavy elements
4. Hot fusion reactions of a deformed target
5. Summary and discussions

Recent review article:
Fusion reactions: compound nucleus formation

energy production in stars

nucleosynthesis

superheavy elements

Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

microscopic understanding: an ultimate goal of nuclear physics

cf. Bohr ‘36
Fusion reactions: compound nucleus formation

1. Coulomb force: long range, repulsive
2. Nuclear force: short range, attractive

Coulomb barrier

Fusion reactions in the sub-barrier energy region

\(|E - V_b| \lesssim 10\text{MeV}\)
Why sub-barrier fusion?

two obvious reasons:

superheavy elements

cf. $^{209}\text{Bi} (^{70}\text{Zn},n) ^{278}\text{Nh}$

$V_B \sim 260 \text{ MeV}$

$E_{cm}^{(exp)} \sim 262 \text{ MeV}$

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Why sub-barrier fusion?

two obvious reasons:

- nuclear astrophysics (nuclear fusion in stars)
  - cf. extrapolation of data

figure: M. Aliotta
Why sub-barrier fusion?

Two obvious reasons:

- discovering new elements (SHE)
- nuclear astrophysics (fusion in stars)

Other reasons:

- reaction mechanism
  strong interplay between reaction and nuclear structure
  cf. high $E$ reactions: much simpler reaction mechanism

- many-particle tunneling
  - many types of intrinsic degrees of freedom
  - energy dependence of tunneling probability
  cf. alpha decay: fixed energy

H.I. fusion reaction = an ideal playground to study quantum tunneling with many degrees of freedom
Discovery of large sub-barrier enhancement of $\sigma_{\text{fus}}$

potential model: $V(r) + \text{absorption}$

cf. seminal work:
R.G. Stokstad et al., PRL41(‘78) 465
Effects of nuclear deformation

$^{154}\text{Sm}$ : a typical deformed nucleus

$^{16}\text{O} + ^{154}\text{Sm}$

$V(r)$ (MeV)

$E_{\text{c.m.}}$ (MeV)

$r$ (fm)

$P(l=0)$

$\theta = 0$ deg.

$\theta = 90$ deg.

Spherical
Effects of nuclear deformation

$^{154}\text{Sm}$: a typical deformed nucleus

Fusion: strong interplay between nuclear structure and reaction

$P(l=0)$ vs $E_{\text{c.m.}}$ (MeV)

$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos \theta) \sigma_{\text{fus}}(E; \theta)$
Enhancement of fusion cross sections: a general phenomenon

Strong correlation with nuclear spectrum → coupling assisted tunneling

Potential model

\[ \sigma_{\text{fus}} / \pi R_b^2 \]

\[ E_{\text{c.m.}} - V \]

\[ (\text{MeV}) \]

\[ 1.81 \quad 1.66 \quad 1.18 \quad 1.16 \quad 0.55 \quad 0.90 \]

\[ 0^+ \quad 0^+ \quad 0^+ \quad 0^+ \quad 0^+ \quad 0^+ \]

\[ {_{144}}\text{Sm} \quad {_{148}}\text{Sm} \quad {_{154}}\text{Sm} \]
Coupled-channels method: a quantal scattering theory with excitations

many-body problem

still very challenging
TDHF simulation

TDHF = Time Dependent Hartree-Fock

S. Ebata, T. Nakatsukasa, JPC Conf. Proc. 6 (‘15) 020056

“ab-initio”, but no tunneling

C. Simenel,
EPJA48 (’12) 152
Coupled-channels method: a quantal scattering theory with excitations

many-body problem

two-body problem, but with excitations (coupled-channels approach)

coupling

scattering theory with excitations

still very challenging
C.C. approach: a standard tool for sub-barrier fusion reactions
cf. CCFULL (K.H., N. Rowley, A.T. Kruppa, CPC123 (‘99) 143)

✓ Fusion barrier distribution [Rowley, Satchler, Stelson, PLB254(‘91)]

\[
D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}
\]

K.H., N. Takigawa, PTP128 (‘12) 1061
Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254 ('91))

\[
D_{\text{fus}}(E) = \frac{d^2(E \sigma_{\text{fus}})}{dE^2}
\]

a nice tool to understand the reaction dynamics

Data: J.R. Leigh et al., PRC52 ('95) 3151

K.H., N. Takigawa, PTP128 ('12) 1061
Recent application to SHE: Quasi-elastic B.D.

hot fusion reactions

\[ ^{48}\text{Ca} + \text{actinide target} \to \text{SHE} \]

= deformation reaction dynamics with barrier distributions?

Quasi-elastic scattering: reflected flux at the barrier

- a sum of elastic, inelastic, and transfer
- easier to measure than capture

Quasi-elastic barrier distribution

\[
D_{\text{qel}}(E) = -\frac{d}{dE} \left( \frac{\sigma_{\text{qel}}(E, \pi)}{\sigma_R(E, \pi)} \right)
\]

H. Timmers et al., NPA584(’95)190
K.H. and N. Rowley, PRC69(’04)054610
previous attempts

S. Mitsuoka et al.,
PRL99 (‘07) 182701

S. S. Ntshangase et al.,
PLB651 (‘07) 27

GARIS

T. Tanaka et al.,
JPSJ 87 (‘18) 014201
Analysis for a hot fusion reaction $^{48}\text{Ca} + ^{248}\text{Cm}$

K.H. and T. Tanaka (2017)
(T. Tanaka et al., JPSJ 87 (‘18) 014201)

$^{48}\text{Ca} + ^{248}\text{Cm} \rightarrow ^{296}_{116}\text{Lv}^*$

single-channel calculation
(spherical $^{248}\text{Cm}$)

$$D_{qel}(E) = -\frac{d}{dE} \left( \frac{\sigma_{qel}(E, \pi)}{\sigma_R(E, \pi)} \right)$$
Analysis for a hot fusion reaction $^{48}\text{Ca} + ^{248}\text{Cm}$

$^{48}\text{Ca} + ^{248}\text{Cm} (\beta_2 = 0.297, \beta_4 = 0.04) \rightarrow ^{296}_{116}\text{Lv}^*$

[\beta_2 and \beta_4 from P. Moller]

$$\frac{d\sigma_{qel}}{d\Omega} = \int_0^1 d(\cos \theta) \left( \frac{d\sigma_{el}}{d\Omega} \right)_\theta$$
Analysis for a hot fusion reaction $^{48}\text{Ca} + ^{248}\text{Cm}$

K.H. and T. Tanaka (2017)

$^{48}\text{Ca} + ^{248}\text{Cm} (\beta_2 = 0.297, \beta_4 = 0.04) \rightarrow ^{296}_{116}\text{Lv}^*$

In transfer

$^{48}\text{Ca} + ^{248}\text{Cm}$

$\rightarrow ^{49}\text{Ca} + ^{247}\text{Cm}$

($Q_{gg} = -1.06\text{ MeV}$)
Connection to the ER cross sections

barrier distribution

compound nucleus

re-separation (quasi-fission)
Connection to the ER cross sections

\[ {}^{48}\text{Ca} + {}^{248}\text{Cm} \rightarrow {}^{296}_{116}\text{Lv}^* \]

notion of compactness:

D.J. Hinde et al., PRL74 (‘95) 1295

= more compact at the touching

→ favorable for CN
Extension of the fusion-by-diffusion model

K.H., arXiv: 1803.02036

Fusion-by-diffusion model
W.J. Swiatecki et al., Acta Phys. Pol. B34 (‘03) 2049
PRC71 (‘05) 014602

simplified C.C.
diffusion of a 1D parabolic barrier (inner barrier)
statistical model
2-body potential

1-body potential

compound nucleus

thermal fluctuation

heat up

re-separation

\((b)^{86}\text{Kr} + ^{208}\text{Pb}\)

\(V(r) \text{ (MeV)}\)

\(r \text{ (fm)}\)
Langevin in the overdamped limit:

\[
P_{CN}(E) = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{\Delta V}{T} \right) \right]
\]
$s_{\text{inj}}(\theta) = s_{\text{inj}}^{(0)} + R_T \sum_{\lambda} \beta_{\lambda T} Y_{\lambda 0}(\theta)$

$P_{\text{CN}}(E, \theta) = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{\Delta V(\theta)}{T(\theta)} \right) \right]$
Extension of the fusion-by-diffusion model

K.H., arXiv: 1803.02036
\[ \sigma_{\text{ER}}(E) = \frac{\pi}{k^2} \sum_{l} (2l + 1) \int_{0}^{1} d\cos \theta T_l(E, \theta) P_{\text{fus}}(E, l, \theta) W_{\text{sur}}(E^*, l) \]
\[ \sigma_{ER}(E) = \frac{\pi}{k'^2} \sum_{l} (2l + 1) \int_{0}^{1} d \cos \theta \, T_l(E, \theta) P_{\text{fus}}(E, l, \theta) W_{\text{sur}}(E', l) \]
Summary and discussions

Reaction dynamics for SHE formation reactions

- Recent measurement of barrier distributions with GARIS
  - $^{48}\text{Ca} + ^{248}\text{Cm}$
  - coupled-channels analysis
  - notion of compactness: ER formation with side collisions
    - more data coming soon

Open problems

- reaction dynamics?
  - quantum theory for friction

cf. M. Tokieda and K.H., PRC95 (‘17) 054604
Quantum friction  

Classical eq. of motion: \[ \dot{p} = -V'(x) - \gamma p \]

A quantization: Kanai model  

E. Kanai, PTP 3 (1948) 440

\[
H = \frac{p^2}{2m} + V(x) \rightarrow \frac{\pi^2}{2m} e^{-\gamma t} + e^{\gamma t} V(x) \quad (\pi = e^{\gamma t} p)
\]

\[ \frac{d}{dt} \langle p \rangle = -\langle V'(x) \rangle - \gamma \langle p \rangle \]

time-dep. wave packet approach

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M. Tokieda and K.H., PRC95 (‘17) 054604
Summary and discussions

Reaction dynamics for SHE formation reactions

➢ Recent measurement of barrier distributions with GARIS
  ✓ $^{48}$Ca + $^{248}$Cm
  ✓ coupled-channels analysis
  ✓ notion of compactness: ER formation with side collisions
    more data coming soon

➢ Open problems
  ✓ reaction dynamics?
    quantum theory for friction
  ✓ shape evolution with a deformed target?
    how does the deformation disappear during heat-up?
  ✓ towards island of stability
    reaction dynamics with neutron-rich beams?

cf. M. Tokieda and K.H., PRC95 (‘17) 054604
Towards the island of stability

neutron-rich beams: indispensable

➢ how to deal with low beam intensity?

➢ reaction dynamics of neutron-rich beams?
  ✓ capture: role of breakup and (multi-neutron) transfer?
  ✓ diffusion: neutron emission during a shape evolution?
  ✓ survival: validity of the statistical model?

structure of exotic nuclei

more studies are required
formation of SHE

chemistry of SHE

the origin of (S)HE

reaction dynamics

Nuclear Physics (RIBF/FRIB)
Astrophysics

structure of SHE

interdisciplinary SHE science
with physics, chemistry, and astronomy