Dynamical approach to synthesis of superheavy elements

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Voyage to SUPERHEAVY Island

the RIBF Nuclear Physics Seminars 169th
29th October, 2013
Contains

1. Introduction
   Superheavy Elements and Theoretical approaches

2. Model
   Dynamical model with Langevin equation
   Two center shell model

3. Results
   Evaporation residue cross section
   Mass distribution of Fission fragments

4. The way to synthesize new Superheavy elements by secondary beam

5. Summary
Periodic Table

Super Heavy Elements → less stable
1. Introduction  
Nuclear Chart and Stability of Nuclei
Our Interests

- **Next magic number** $\longleftrightarrow Z=82, \ N=126$
- Verification of ‘*Island of Stability*’
  (predicted by macroscopic-microscopic model in 1960’s)
- **Synthesis of new elements**
Potential energy (in MeV)

Deformation

Liquid Drop Model

G. Flerov and K. Petrjzak
Leningrad 1940

22 years later.

Microscopic Theory

Models:

Macro-microscopic
Hartry-Fock-Bogolubov
Relativistic-mean-field

N. Bohr and J.A. Wheeler (1939)

Mayer and Jensen (1949)

Magic numbers

Microscopic Theory

Hartry-Fock-Bogolubov
Relativistic-mean-field

More

FERMI ENERGY

Less

BOUND NUCLEUS
Fission barrier of Superheavy Elements

Shell correction energies in the macroscopic-microscopic model
Stability of Superheavy nuclei

fissility parameter

\[ x = \frac{E_c}{2E_s} = \frac{Z^2/A}{50.883\left[1-1.7826\left(\frac{N-Z}{A}\right)^2\right]} \]

Spherical nucleus

Surface energy

\[ E_s = 4\pi r^2 A^{2/3} \gamma \]

Coulomb energy

\[ E_c = \frac{3e^2 Z^2}{5r_0 A^{1/3}} \]

Experimental setup for synthesis of SHE

<table>
<thead>
<tr>
<th>Lab</th>
<th>Country</th>
<th>City</th>
<th>Accelerator</th>
<th>Separator</th>
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<tbody>
<tr>
<td>FLNR</td>
<td>Russia</td>
<td>Dubna</td>
<td>U400</td>
<td>DGFRS</td>
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<td>Japan</td>
<td>Wako</td>
<td>RILAC</td>
<td>GALIS</td>
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<td>LBNL</td>
<td>USA</td>
<td>Berkeley</td>
<td>88-inch Cyclotron</td>
<td>BGS</td>
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<tr>
<td>GANIL</td>
<td>France</td>
<td>Caen</td>
<td>SPIRAL2's LINAC accelerating</td>
<td>S3 (Super Separator Spectrometer)</td>
</tr>
</tbody>
</table>
Fusion process in Superheavy mass region

FUSION

TRANSFER, QUASI-FISSION

Nuclear Molecule

Compound Nucleus (CN)

FUSION-FISSION

Evaporation Residue (ER)

Fission Fragments

90~99%
Cold Fusion → doubly magic target nuclei: Pb, Bi;
E*(CN) = 10 – 20 MeV; evaporation of 1 – 2 neutrons;
up to now successful for Z ≤ 113

Hot Fusion → actinide targets (U, Cm, …) and \(^{48}\text{Ca}\) projectiles;
E*(CN) = 30 – 40 MeV; evaporation of 3 – 4 neutrons;
up to now successful for Z ≤ 118
# Synthesis of New Elements

## Reports of new elements

<table>
<thead>
<tr>
<th>Year</th>
<th>Atomic Number</th>
<th>Element</th>
<th>Reaction</th>
<th>Target</th>
<th>Nuclei</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>110</td>
<td>Ds</td>
<td>$^{62}\text{Ni} + ^{208}\text{Pb} \rightarrow ^{269}110 + n$</td>
<td>(GSI)</td>
<td></td>
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<tr>
<td>2012</td>
<td>119</td>
<td></td>
<td>$^{50}\text{Ti} + ^{249}\text{Bk} \rightarrow ^{296,295}119 + 3-4n$</td>
<td>(GSI-TASCA)</td>
<td></td>
<td></td>
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<td>1999</td>
<td>114</td>
<td>Fl</td>
<td>$^{48}\text{Ca} + ^{244}\text{Pu} \rightarrow ^{292}114 + 3n$</td>
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Evaporation residue cross sections

Experimental data

Pb target
Actinide target

Cross section $\sigma_{ER}$ (pb)

Element number

cold fusion reaction 1n
hot fusion reaction 3n–5n
2. Model

2-1. Estimation of cross sections
2-2. Dynamical Equation
\[ \sigma_{ER} = \frac{\pi \hbar^2}{2\mu_0 E_{cm}} \sum_{\ell=0}^{\infty} (2\ell + 1) T_\ell(E_{cm}, \ell) P_{CN}(E^*, \ell) W(E^*, \ell) \]
\[ \sigma_{ER} = \frac{\pi \hbar^2}{2\mu_0 E_{cm}} \sum_{\ell=0}^{\infty} (2\ell + 1) T_{\ell} (E_{cm}, \ell) P_{CN} (E^*, \ell) W (E^*, \ell) \]

1st stage
- Reaction time \( t < 10^{-22} \text{ s} \)
- Touching probability

2nd stage
- Formation probability
- \( 10^{-22} < t < 10^{-18} \text{ s} \)
- Quasi-fission 90~99% (QF)

3rd stage
- \( \sim 10^{-18} < t \text{ s} \)
- Fusion-fission (FF)
- Survival probability

1st stage
- Survival probability

2nd stage
- Touching probability

3rd stage
- Reaction time

Formation probability
- Survival probability

Touching probability
- Quasi-fission 90~99%
# Recent Development of Theoretical Models

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\[ I(E, l) = \int f(B) \frac{1}{1 + \exp \left( \frac{2\pi}{\hbar \omega_B(l)} \left[ B + \frac{\hbar^2}{2\mu R_B^2(l)} (l(l+1) - E) \right] \right)} dB. \]

\[
f(B) = N \times \begin{cases} \exp \left[ -\frac{(B - B_m)^2}{\Delta_1} \right], & B < B_m \\ \exp \left[ -\frac{(B - B_m)^2}{\Delta_2} \right], & B > B_m \end{cases}
\]

FIG. 1. Capture cross sections in the $^{16}$O+$^{208}$Pb [11], $^{48}$Ca + $^{208}$Pb [12], and $^{48}$Ca+$^{244}$Pu [13] fusion reactions. Dashed lines represent one-dimensional barrier penetration calculations. Solid lines show the effect of dynamic deformation of nuclear surfaces (see the text). The arrows marked by $B_0$ and $B_S$ show the positions of the corresponding Coulomb barrier at zero deformation and at the saddle point.
Fission width

Bohr and Wheeler (1939)
Statistical model (transition state method)
initial state and final state

\[ \Gamma_f^{BW} = \frac{1}{2\pi\rho(E^*)} \int_0^{E^*-U_B} dK \rho(E^*-U_B-K) \]

\[ \sim \frac{T}{2\pi} \exp\left\{ -\frac{U_B}{T} \right\} \]

Figure 10.5  Schematic illustration of the fission mode of compound-nucleus decay. See text for a description.
## Recent Development of Theoretical Models

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The macroscopic dynamical model.
Fusion of two nuclear liquid drops.

Nuclear shape is described by
Two center parametrization

The *dinuclear system concept*.
Conservation of nuclear individualities.
\[ \sigma_{ER} = \frac{\pi \hbar^2}{2 \mu_0 E_{cm}} \sum_{\ell=0}^{\infty} (2\ell + 1) T_{\ell}(E_{cm}, \ell) P_{CN}(E^*, \ell) W(E^*, \ell) \]
2. Model

2-1. Potential
   Two-center shell model \((z, \delta, \alpha)\)

2-2. Equation
   trajectory calculation
Overview of Dynamical Process in reaction $^{36}\text{S} + ^{238}\text{U}$

- Potential energy surface
- Trajectory described by equations

Time-evolution of nuclear shape in fusion-fission process

1. Potential energy surface
2. Trajectory $\rightarrow$ described by equations
Nuclear shape

two-center parametrization \((z, \delta, \alpha)\)

(Maruhn and Greiner, Z. Phys. 251(1972) 431)

\[
q(z, \delta, \alpha)
\]

\[
z = \frac{z_0}{BR}
\]

\[
B = \frac{3 + \delta}{3 - 2\delta}
\]

\(R\) : Radius of the spherical compound nucleus

\[
\delta = \frac{3(a - b)}{2a + b}
\]

\((\delta_1 = \delta_2)\)

\[
\alpha = \frac{A_1 - A_2}{A_{CN}}
\]
Potential Energy

\[ V(q, \ell, T) = V_{DM}(q) + \frac{\hbar^2 \ell(\ell + 1)}{2I(q)} + V_{SH}(q, T) \]

\[ V_{DM}(q) = E_S(q) + E_C(q) \]

\[ V_{SH}(q, T) = E_{shell}^0(q) \Phi(T) \]

\( T \): nuclear temperature  
\( E^* = aT^2 \)  
\( a \): level density parameter  
Toke and Swiatecki

\( E_S \): Generalized surface energy (finite range effect)  
\( E_C \): Coulomb repulsion for diffused surface  
\( E_{shell}^0 \): Shell correction energy at \( T=0 \)

\( I \): Moment of inertia for rigid body

\( \Phi(T) \): Temperature dependent factor

\[ \Phi(T) = \exp \left\{ -\frac{aT^2}{E_d} \right\} \]

\( E_d = 20 \text{ MeV} \)
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\( E_d = 20 \text{ MeV} \)

Fission barrier recovers at low excitation energy
2. Model

2-1. Potential

Two-center shell model \((z, \delta, \alpha)\)

2-2. Equation

Taking into account the fluctuation around the mean trajectory

Thermal fluctuation of nuclear shape

\(\rightarrow\) thermal fluctuation of collective motion
Multi-dimensional Langevin Equation

\[ \frac{dq_i}{dt} = (m^{-1})_{ij} p_j \]

\[ \frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2} \frac{\partial}{\partial q_i} (m^{-1})_{jk} p_j p_k - \gamma_{ij} (m^{-1})_{jk} p_k + g_{ij} R_j(t) \]

\[ \langle R_i(t) \rangle = 0, \langle R_i(t_1) R_j(t_2) \rangle = 2\delta_{ij}\delta(t_1-t_2) : \text{white noise (Markovian process)} \]

\[ \sum_k g_{ik} g_{jk} = T\gamma_{ij} \]

**Newton equation**

ordinary differential equation

**Einstein relation**

\[ (\text{nuclear shape}) \]

\( q_i : \) deformation coordinate

\( p_i : \) momentum

\( m_{ij} : \) Hydrodynamical mass

\( \gamma_{ij} : \) Wall and Window (one-body) dissipation

\( E_{\text{int}} = E^* - \frac{1}{2} (m^{-1})_{ij} p_i p_j - V(q) \)

\( E_{\text{int}} : \) intrinsic energy, \( E^* : \) excitation energy
Fission process \( ^{240}\text{U} \) \( E^* < 20 \text{ MeV} \)

Trajectory on potential energy surface

C.M. distance vs. Mass asymmetry

\[ \alpha \]
$t = 6.582 \times 10^{-23}$ sec.
Overview of Dynamical Process in reaction $^{36}\text{S}+^{238}\text{U}$
3. Results

Evaporation residue cross section
Mass distribution of fission fragments
Calculation results \( ^{48}\text{Ca} + ^{244}\text{Pu} \)

Itkis et al.
4. Way to synthesize new SHE

Ti, Cr, Fe etc. beams

Transfer reaction U+Th, U+Cm

Secondary beams
Synthesis of New Elements

Reports of new elements

Cold fusion reaction  Hot fusion reaction

1994

110 Ds  $^{62}\text{Ni} + ^{208}\text{Pb} \rightarrow ^{269}110 + n$  (GSI)

111 Rg  $^{64}\text{Ni} + ^{209}\text{Bi} \rightarrow ^{272}111 + n$  (GSI)

1996

112 Cn  $^{70}\text{Zn} + ^{208}\text{Pb} \rightarrow ^{277}112 + n$  (GSI) ← named in Feb. 2010

1999

114 Fl  $^{48}\text{Ca} + ^{244}\text{Pu} \rightarrow ^{292}114 + 3n$  (FLNR) ← named in May. 2012

2000

116 Lv  $^{48}\text{Ca} + ^{249}\text{Cm} \rightarrow ^{292}116 + 4n$  (FLNR) ← named in May. 2012

2002

118 $^{48}\text{Ca} + ^{249}\text{Cf} \rightarrow ^{294}118 + 3n$  (FLNR)

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2010

117 $^{48}\text{Ca} + ^{249}\text{Bk} \rightarrow ^{294,293}117 + 3-4n$  (FLNR)
3. Survival Process

Possibility of synthesizing $^{298}_{114}$

Model Calculation

$A=304$

Yu. Ts. Oganessian and K. Morita
\[ \sigma_{ER} = \frac{\pi \hbar^2}{2 \mu_0 E_{cm}} \sum_{\ell=0}^{\infty} (2\ell + 1) T_\ell (E_{cm}, \ell) P_{CN} (E^*, \ell) W (E^*, \ell) \]
One-dimensional Smoluchowski equation

$$\frac{\partial}{\partial t} P(q, \ell; t) = \frac{1}{\mu \beta} \frac{\partial}{\partial q} \left\{ \frac{\partial V(q, \ell; t)}{\partial q} P(q, \ell; t) \right\} + \frac{T}{\mu \beta} \frac{\partial^2}{\partial q^2} P(q, \ell; t)$$

- $P(q, \ell; t)$: probability distribution
- $\mu$: inertia mass
- $\beta$: reduced friction
- $q$: separation distance

$T(t)$: temperature ↔ statistical code SIMDEC

Cooling curve

$W(E_0^*, \ell; t) = \int_{\text{insidesaddle}} P(q, \ell; t) \, dq$

$W$: survival probability

We assume the particle emissions are limited to neutron emission in the neutron-rich heavy nuclei.
\[ V(q, \ell, T) = V_{LD}(q) + \frac{\hbar^2 \ell (\ell + 1)}{2I(q)} + V_{SH}(q, T) \]

\[ V_{LD}(q) = E_S(q) + E_C(q) \]

\[ V_{SH}(q, T) = E_{shell}^0(q) \Phi(T) \]

\( T \): nuclear temperature

\( E^* = aT^2 \) \( a \): level density parameter

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\( \Phi(T) \): Temperature dependent factor

\[ \Phi(T) = \exp\left\{ -\frac{aT^2}{E_d} \right\} \]

\( E_d = 20 \text{ MeV} \)
Fission barrier recovers at low excitation energy

\[ \Phi(T) = \exp \left( -\frac{E^*}{E_d} \right) \]

\[ E_d = 20 \text{ MeV} \]
3. Survival process

- Rapid cooling

- Approaching to the closed shell
\[ A = 298 \]

\[ A = 304 \]

Smoluchowski equation

survival

\[ W_{\text{sur}} \]

\[ E^* \] (MeV)

\[ t \] (\(10^{-21}\) sec)

\[ B_f \] (MeV)

\[ A_{CN} = 298 \]

\[ A_{CN} = 304 \]
4. Summary

1. The possibility of synthesizing a doubly magic superheavy nucleus, $^{298}{\text{114}}_{184}$, was investigated on the basis of fluctuation dissipation dynamics.

2. Owing to the neutron emissions, we must generate more neutron-rich compound nuclei.

3. To calculate the survival probability, we employ the dynamical model.

4. $^{304}{\text{114}}$ has two advantages to achieving a high survival probability.

   1) small neutron separation energy and rapid cooling
   2) the neutron number of the nucleus approaches that of the double closed shell

   $\rightarrow$ obtain a large fission barrier

5. The systematical investigation compared with the statistical model and dynamical one is necessary. We must apply the dynamical model for known systems.
What we can obtain under the conditions

Phenomenalism
Dynamical Model based on Fluctuation-dissipation theory
(Langevin eq, Fokker-Plank eq, etc) ← Classical trajectory analysis

We can obtain....
- Mass and TKE distribution of fission fragments
- Neutron multiplicity
- Charge distribution
- Cross section (capture, mass symmetric fission, fusion)
- Angle of ejected particle, Kinetic energy loss (← two body)

Fission, Synthesis of SHE
A<sub>CN</sub> : 200~300

Conditions
- Nuclear shape parameter
- Potential energy surface (LDM, shell correction energy, LS force)
- Transport coefficients (friction, inertia mass) ← Linear Response Theory
- Dynamical equation (memory effect, Einstein relation)
Collaborators

S. Chiba
Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology

K. Hagino
Department of Physics, Tohoku University

K. Nishio
Advanced Science Research Center, Japan Atomic Energy Agency

V.I. Zagrebaev, A.V. Karpov
Flerov Laboratory of Nuclear Reactions

W. Greiner
Frankfurt Institute for Advanced Studies, J.W. Goethe University