Time-dependent density functional calculations applied to the synthesis of superheavy elements

Yoritaka Iwata @EMMI, GSI, Darmstadt
Contents

• Intro. to TDHF
  several advantages, but some problems
• Intro. to Reaction dynamics of low-energy HIC
  as a dominant one, charge equilibration

• Present status of TDHF calculations for SHE
• New direction of TDHF-based theoretical researches; nuclear pasta

This presentation consists mostly of movies (calculation dynamics) for your entertainment and a concrete sight for the collision dynamics.
Motivation: Science of producing elements in the peninsula & the island towards the limit of chemical elements

\[ ^{248}\text{Cm} + ^{24}\text{Ne} \rightarrow (^{272}106) \]
\[ ^{248}\text{Cm} + ^{48}\text{Ca} \rightarrow (^{296}116) \] are calculated;

Understanding the reaction dynamics of producing neutron-rich and heavy elements in a microscopic manner.

Picture from Sophie's presentation
Introduction to TDHF

Skyrme Energy Density Functional (Skryme EDF)

(i) particle density,
\[ \rho(r) = \rho(r, r), \]
(ii) kinetic energy density,
\[ \tau(r) = [\nabla \cdot \nabla' \rho(r, r')]_{r=r'}, \]
(iii) spin density,
\[ s(r) = s(r, r), \]
(iv) momentum density,
\[ j(r) = \frac{1}{2i} [(\nabla - \nabla')\rho(r, r')]_{r=r'}, \]
(v) spin current tensor,
\[ J_{\mu\nu}(r) = \frac{1}{2i} [(\nabla_{\mu} - \nabla'_{\mu})s(r, r')]_{r=r'}, \]
(vi) kinetic energy density (vector part)
\[ T(r) = [\nabla \cdot \nabla' s(r, r')]_{r=r'}. \]

Basic quantities

(As far as I know) in the context of tensor force, we should consider ...

Note: more terms in modern EDF

\[ \delta E = \sum_q \int d^3r \left( \frac{\hbar^2}{2m_q^*(r)} \delta \tau_q(r) + U_q(r) \delta \rho_q(r) + \vec{B}_q(r) \cdot \vec{J}_q(r) + I_q(r) \cdot \delta j_q(r) \right. \]
\[ + C_q(r) \cdot \delta T_q(r) + \left. \Sigma_q(r) \delta s_q(r), \right) \]

where
\[ \frac{\hbar^2}{2m_q^*(r)} = \frac{\hbar^2}{2m} + \frac{3}{8}(t_1 + t_2)\rho + \frac{3}{8}(t_2 - t_1)\rho_q, \]
\[ U_q(r) = \frac{1}{2}(1 + \frac{3}{2}x_0)\rho - \frac{1}{2}(t_2 - t_1)\nabla^2 \rho + \frac{1}{3}x_0(3t_1 + t_2)\nabla^2 \rho_q + \frac{3}{8}(t_1 + t_2)\tau + \frac{3}{8}(t_2 - t_1)\tau_q + \frac{3}{8}(\rho^2 - \rho_q^2 - (s - s_q)^2) - \frac{1}{2}V_{s.o.} \nabla \cdot (J + J_q), \]
\[ \vec{B}_q = -\frac{1}{2}(t_2 - t_1)\vec{J}_q + \frac{1}{2}V_{s.o.} \nabla (\rho + \rho_q), \]
\[ I_q(r) = -\frac{1}{2}(t_1 + t_2)j - \frac{1}{2}(t_2 - t_1)j_q - \frac{1}{2}V_{s.o.} \nabla \times (s + s_q), \]
\[ C_q(r) = \frac{1}{8}(t_2 - t_1)s_q, \]
\[ \Sigma_q(r) = \frac{1}{2}t_0(x_0 s - s_q) + \frac{1}{8}(t_2 - t_1)T_q + \frac{1}{8}t_0(t_2 + 3t_1)\nabla^2 s_q - \frac{1}{8}t_3(\rho - \rho_q)s_q - \frac{1}{8}V_{s.o.} \nabla \times (j + j_q). \]

Engel et. al, NPA (1975)
Skyrme Energy Density Functional (Skryme EDF)

Basic quantities

\[
\begin{align*}
\rho_q(r) &= \rho_q(r, r')|_{r=r'}, \\
\mathbf{s}_q(r) &= \mathbf{s}_q(r, r')|_{r=r'}, \\
\tau_q(r) &= \nabla \cdot \nabla' \rho_q(r, r')|_{r=r'}, \\
T_{q,\mu}(r) &= \nabla \cdot \nabla' s_{q,\mu}(r, r')|_{r=r'}, \\
\mathbf{j}_q(r) &= -\frac{i}{2} (\nabla - \nabla') \rho_q(r, r')|_{r=r'}, \\
J_{q,\mu\nu}(r) &= -\frac{i}{2} (\nabla_{\mu} - \nabla'_{\mu}) s_{q,\nu}(r, r')|_{r=r'}, \\
F_{q,\mu}(r) &= \frac{1}{2} \sum_{\nu=x}^{z} (\nabla_{\mu} \nabla'_{\nu} + \nabla'_{\mu} \nabla_{\nu}) s_{q,\nu}(r, r')|_{r=r'}
\end{align*}
\]

Tensor-kinetic pseudo-vector density

\[
\mathcal{E}_{\text{Skyrme}} = \mathcal{E}_c + \mathcal{E}_{LS} + \mathcal{E}_t
\]

\[
= \int d^3r \sum_{i=0,1} \left\{ C_i^f [\rho_0] \rho_i^2 + C_i^s [\rho_0] s_i^2 + C_i^{\Delta \rho} \rho_i \Delta \rho_i + C_i^{\nabla s} (\nabla \cdot s_i)^2 + C_i^{\Delta s} s_i \cdot \Delta s_i + C_i^T (\rho_i \tau_i - j_i^2) + C_i^T \left( s_i \cdot T_i - \sum_{\mu,\nu=x}^{z} J_{t,\mu\nu} J_{t,\mu\nu} \right) + C_i^F \left[ s_i \cdot F_i - \frac{1}{2} \left( \sum_{\mu=x}^{z} J_{t,\mu\mu} \right)^2 \right] - \frac{1}{2} \sum_{\mu,\nu=x}^{z} J_{t,\mu\nu} J_{t,\nu\mu} \right\} + \mathcal{C}_t^{\nabla \cdot J}
\times (\rho_t \nabla \cdot \mathbf{J}_t + s_t \cdot \nabla \times \mathbf{j}_t)
\}
\]

Lesinski et al, PRC (2007)
Advantage

- It is possible to have a self-consistent treatment, as well as microscopic treatment.
  → There is no discrepancy between the density distribution and the interaction

- A kind of “ab-initio” calculation is possible w.r.t. reaction dynamics
  → All the heavy-ion reactions can be studied equivalently without changing any parameters (no free-parameter for fitting)

Disadvantage (focusing on the incident energy)

- It is impossible to treat high-energies (collisionless framework)
- It is impossible to treat extremely low-energies (difficulty in tunneling)
  → Possibly, it is valid for moderate low-energies (a few MeV per nucleon)

(Note) particle motion contained in one mean-field potential.
Clue/evidence to believe TDHF in low-energies

“(roughly) the radius of a nucleus < 10 fm (R = 1.2 * A^(1/3))”

Collision times for a nucleon passing through 20fm-length nuclear matter is the problem:

Let us assume the situation with colliding ground state nuclei with boost:

If the energy is set to the Fermi energy (25 ~ 30% of the speed of light) +10MeV/A, the mean-free path is less than 20fm. If the incident energy is less than that, the expected collision time becomes less than 1.

→ Collisionless framework such as TDDFT/TDHF is sufficient to study low-energy heavy-ion collisions

Mean free path of nucleon

Fig. 2. The calculated nucleon mean free path, λ, in a nuclear Fermi gas of temperature T and Fermi energy, $E_F = 38$ MeV. The nucleon mean free path is given as a function of its energy above the Fermi energy, $(E_i - E_F)$, for various values of T. The curves are obtained by calculating the expression (9), which assumes isotropic differential cross sections. The four circled points are computed from (8) using more realistic anisotropic cross sections and a temperature of $T = 1$. They show that the error involved in the isotropic assumption is not important in the present discussion.
• Movie of TDHF

$^{52}\text{Ca} + ^{36}\text{Ca}$ several impact parameters

Four cases are shown:

$b = 0.0 \text{ fm} \quad \ldots \quad \text{Fusion}$

$b = 4.0 \text{ fm} \quad \ldots \quad \text{Fusion}$

$b = 8.0 \text{ fm} \quad \ldots \quad \text{Fusion}$

$b = 12.0 \text{ fm} \quad \ldots \quad \text{Untouchable}$

to show what is TDHF ...
\[ ^{52}\text{Ca} + ^{36}\text{Ca} \rightarrow (^{88}\text{Zr}) \]

with a fixed incident energy 100 MeV (c.m.)
\[ \sim 1 \text{ MeV/A (c.m.)} \]

**Intro. Reaction dynamics**

- Movie of TDHF

\[ ^{52}\text{Ca} + ^{36}\text{Ca} \] several impact parameters

Four cases are shown:

- \( b = 0.0 \text{ fm} \) ... Fusion (central collision; quite rare case !)
- \( b = 4.0 \text{ fm} \) ... Fusion (peripheral collision)
- \( b = 8.0 \text{ fm} \) ... Fusion (peripheral collision; probable)
- \( b = 12.0 \text{ fm} \) ... Untouchable (elastic scattering; disregard)

- Larger angular momentum of the merged system is realized by larger impact-parameter.

- For such a low-energy case with light-mass nuclei, reaction generally consists of
  - fusion (charge is fully equilibrated)
  - (relatively small possibility of) DIC (= a few nucleon transfer)
  - elastic collision

and another type of reaction can appear in higher energy cases with heavy-mass nuclei.
Introduction to Reaction dynamics

- **Charge equilibration** is a dominant and rapid process in low-energy heavy-ion reactions;
  among reaction dynamics, charge equilibration (CE, for short) is mainly discussed in this talk.

- Charge equilibration consists of
  - fusion
  - “fission arising from collisions”; fusion-fission/quasi-fission

Theoretical model: **TDHF3d with evaporation prescription**

as is seen later, standard TDHF holds some problems to study the synthesis of heavy and n-rich elements
Intro. Reaction dynamics

Charge equilibration dynamics

<table>
<thead>
<tr>
<th>E/A = 1.0 MeV</th>
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<th>E/A = 2.0 MeV</th>
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</tr>
</thead>
<tbody>
<tr>
<td>b = 5.6 fm</td>
<td>b = 6.1 fm</td>
<td>b = 5.6 fm</td>
<td>b = 6.1 fm</td>
</tr>
<tr>
<td>6.00 (10^{-22}) s</td>
<td>6.00 (10^{-22}) s</td>
<td>3.00 (10^{-22}) s</td>
<td>3.00 (10^{-22}) s</td>
</tr>
<tr>
<td>6.75 (10^{-22}) s</td>
<td>6.75 (10^{-22}) s</td>
<td>3.75 (10^{-22}) s</td>
<td>3.75 (10^{-22}) s</td>
</tr>
<tr>
<td>7.50 (10^{-22}) s</td>
<td>7.50 (10^{-22}) s</td>
<td>4.50 (10^{-22}) s</td>
<td>4.50 (10^{-22}) s</td>
</tr>
</tbody>
</table>

FIG. 1: (Color online) Propagation of neutron-rich flow is depicted for the collision between \(^{52}\)Ca and \(^{36}\)Ca, where \(^{52}\)Ca and \(^{36}\)Ca correspond to the ions coming from the left and right hand sides, respectively. The colored parts correspond to the parts with \(N/Z > 1\) (each frame is \(40 \times 30\) fm\(^2\)), and the density contour equal to 0.02 fm\(^{-3}\) is shown by a thick black curve. Three-dimensional time-dependent Hartree-Fock calculations with a Skyrme interaction (SLy4d) is carried out; the single-particle wave functions are represented on a Cartesian grid with the spacing of 0.8 fm, and the time unit of calculation is set to \(1.5 \times 10^{-24}\) s. The initial distance between the two colliding ions are set to 20 fm, then the relative velocity of collision is given.
TABLE I: Comparison of speeds, where $|v_F|$ is fixed to 1/3 of the speed of light (corresponding to the nuclear standard value). The propagation speed of charge-equilibrating flow is calculated by the propagation speed of the wave front of $N/Z = 1.10$. The relative velocity of collision at the contact is slower than that at the initial time, because of the deceleration due to the Coulomb repulsion.

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<td>v_F</td>
</tr>
<tr>
<td>Relative velocity for $E/A=2.0$ MeV</td>
<td>0.36 $</td>
<td>v_F</td>
</tr>
<tr>
<td>Relative velocity for $E/A=1.0$ MeV</td>
<td>0.23 $</td>
<td>v_F</td>
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Almost at the speed of $|v_F|$  
Independent of relative velocity and impact parameter

FIG. 1: (Color online) Propagation of neutrons is depicted for the collision between $^{52}$Ca and $^{36}$Ca, where $^{52}$Ca and $^{36}$Ca correspond to the ions coming from the left and right hand sides, respectively. The colored parts correspond to the parts with $N/Z > 1$ (each frame is $40\times30$ fm$^2$), and the density contour equal to 0.02 fm$^{-3}$ is shown by a thick black curve. Three-dimensional time-dependent Hartree-Fock calculations with a Skyrme interaction (SLy4d) is carried out; the single-particle wave functions are represented on a Cartesian grid with the spacing of 0.8 fm, and the time unit of calculation is set to $1.5 \times 10^{-24}$ s. The initial distance between the two colliding ions are set to 20 fm, then the relative velocity of collision is given.
Fast charge equilibration
- a dominant mechanism in low-energy heavy-ion collisions -

  dynamical mixture between neutrons and protons
  averaging (local) N/Z ratio
  very fast mechanism taking only \( \sim 10^{-22} \) s
governing the early stage of heavy-ion collision
  prevents to produce exotic nuclei
decisive to exotic nuclear synthesis

- There exists an upper-limit energy for fast charge equilibration.

- The mechanism of fast charge equilibration is ultimately reduced to the propagation of nucleon wave propagation at the speed almost equal to the (amplitude of) Fermi velocity.
  = zero sound propagation (collective dynamics \sim mean-field effect)

*Y.I., JMP (2012); ArXiv:1204.3723*  
*Y.I. et al., PRL (2010)*
Upper energy limit formula (Iwata-Otsuka-Maruhn-Itagaki; PRL2010)

Nucleons with the fermi velocity are decisive to the (all the) equilibration:

→ rapid process (0.3c)
→ independent of relative velocity of collision
→ dependence of the sort of colliding nuclei

\[
\frac{E_{CE,lab}^2}{A} = \frac{\hbar^2(3\pi^2 \rho_{\text{min}})^{2/3}}{2m} + e^2Z_1Z_2 \frac{A_1 + A_2}{4\pi\epsilon_0 r_0 A_1A_2(A_1^{1/3} + A_2^{1/3})},
\]

(1)

\[
\rho_{\text{min}} = \min_i \left( \frac{N_i(\frac{4\pi\rho_0}{3}A_i^{1/3})^{-1}}{(1 - 3\bar{\varepsilon})(1 + \delta)} \right).
\]

(2)

where \( m, e, \epsilon_0, \) and \( r_0 \) are the nucleon mass, the charge unit, the vacuum permittivity, and the usual nuclear radius parameter (1.2 fm), respectively.

Numerical calculations and experiments are well explained by this formula.

<table>
<thead>
<tr>
<th>Collision</th>
<th>TDHF (SLy4d)</th>
<th>TDHF (SkM*)</th>
<th>Equation (1)</th>
<th>Fermi gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) ( ^{208}\text{Pb} + ^{238}\text{U} )</td>
<td>6.5 ± 0.5</td>
<td>6.5 ± 0.5</td>
<td>6.91</td>
<td>9.46</td>
</tr>
<tr>
<td>(ii) ( ^{208}\text{Pb} + ^{132}\text{Xe} )</td>
<td>6.5 ± 0.5</td>
<td>6.5 ± 0.5</td>
<td>6.50</td>
<td>9.03</td>
</tr>
<tr>
<td>(iii) ( ^{208}\text{Pb} + ^{132}\text{Sn} )</td>
<td>6.5 ± 0.5</td>
<td>6.5 ± 0.5</td>
<td>6.36</td>
<td>9.03</td>
</tr>
<tr>
<td>(iv) ( ^{208}\text{Pb} + ^{40}\text{Ca} )</td>
<td>3.5 ± 0.5</td>
<td>3.5 ± 0.5</td>
<td>3.66</td>
<td>5.14</td>
</tr>
<tr>
<td>(v) ( ^{208}\text{Pb} + ^{24}\text{Mg} )</td>
<td>2.5 ± 0.5</td>
<td>2.5 ± 0.5</td>
<td>2.36</td>
<td>3.52</td>
</tr>
<tr>
<td>(vi) ( ^{208}\text{Pb} + ^{24}\text{O} )</td>
<td>2.5 ± 0.5</td>
<td>2.5 ± 0.5</td>
<td>2.18</td>
<td>3.52</td>
</tr>
<tr>
<td>(vii) ( ^{208}\text{Pb} + ^{16}\text{O} )</td>
<td>1.5 ± 0.5</td>
<td>1.5 ± 0.5</td>
<td>1.75</td>
<td>2.50</td>
</tr>
<tr>
<td>(viii) ( ^{208}\text{Pb} + ^{4}\text{He} )</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>0.48</td>
<td>0.70</td>
</tr>
<tr>
<td>(ix) ( ^{24}\text{Mg} + ^{24}\text{O} )</td>
<td>5.5 ± 1.0</td>
<td>5.5 ± 1.0</td>
<td>5.99</td>
<td>9.50</td>
</tr>
</tbody>
</table>
Indeed, the physics around the limit is calculated as follows:

Charge is equilibrated (rate: more than 50%)

Charge is not equilibrated (rate: less than 50%)

Energy Threshold (6.5MeV±0.5MeV)

Y.I. et. al, PRL (2010)
Charge equilibration

v.s.

dipole-oscillation

- Charge equilibration; very fast mechanism taking only one-kick (1/4 T) of dipole vibration, where the vibration is not necessary for charge equilibration to be achieved.

- Charge equilibration does not necessarily consist of iv-GDR, which can consist of any kind of collective dynamics.

Y.I. et al., EPJA (2009)

208Pb + 238U

Y.I. et al., PRL (2010)

24Mg + 24O

24Mg + 208Pb

Charge equilibration is almost finished here

Time

Dipole-mode

\( E1(\ell) [\text{fm}] \)

1/4 ~ 1/2 period

(vibration is not necessary)

Red: proton-rich part

 Intro. Reaction dynamics
Consequently, this type of fast wave propagation (reaction dynamics) is universal to any low-energy heavy-ion reactions. 

E.g. fusion is achieved by this type of wave propagation.

TABLE I: Comparison of speeds, where $|v_F|$ is fixed to 1/3 of the speed of light (corresponding to the nuclear standard value). The propagation speed of charge-equilibrating flow is calculated by the propagation speed of the wave front of $N/Z = 1.10$. The relative velocity of collision at the contact is slower than that at the initial time, because of the deceleration due to the Coulomb repulsion.

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Almost at the speed of $|v_F|$ 
Independent of relative velocity and impact parameter

Propagation of Charge equilibrating wave
Competition arises!

Controlling energies in order to produce what is wanted.

- **Neutron-rich fragments** are difficult to produce, if fast charge equilibration is present (for lower energies).

- **Heavy fragments** are difficult to produce, if fast charge equilibration is absent (for higher energies).

(Naively) there should be a strict constraint/limitation for producing neutron-rich & heavy fragment.

This is main viewpoint of our research for superheavy synthesis.
Producing elements in the peninsula

\[ ^{248}\text{Cm} + ^{24}\text{Ne} \rightarrow (^{272}106) \] is calculated;
Movie of TDHF

$^{248}\text{Cm} + ^{24}\text{Ne}$ from lower to higher energies

Six cases are shown:

- $E = 200$ MeV … Untouchable (elastic scattering)
- $E = 600$ MeV … Fusion with a few emission C. E. (Fragments with almost the same N/Z)
- $E = 1200$ MeV … Fragmentation (Fusion with severe emission) No C. E.
- $E = 1800$ MeV … Fragmentation (Fusion with severe emission) No C. E.
- $E = 2400$ MeV … Fragmentation No C. E.
- $E = 6000$ MeV … Fragmentation (Very small exchange) No C. E.

$^{248}\text{Cm} + ^{24}\text{Ne} \rightarrow \ (^{272}\text{106})$

with a fixed impact parameter (10 fm)
Calculation Result
-standard TDHF-

\[ ^{248}\text{Cm} + ^{24}\text{Ne} \rightarrow (^{272}\text{106}) \] is calculated;

Frag. without CE
Frag. with CE
Fusion
Untouchable

Larger fragment

Consists of
- quasi-fission
- neutron-drip
- multi-frag.

Consists of
- fusion-fission
- quasi-fission
(multi-N-transfer)

Overestimating Hot-Fusion Cross Section

Energy [MeV]

Impact parameter [fm]

200MeV
600MeV
2400MeV

Around 2000 MeV
Around 300 MeV

Nominal fusion barrier
No Compound nucleus

Energy

200 MeV
1000 MeV
8000 MeV

It is too happy to believe...

...if it is true, there is no problem to produce element on the peninsula & the island;

...fusion and quasi-fission arising from CE is the most effective way of producing large fragment;

however, according to experiments and so on, the nature is not so simple.
In this TDHF calculation, fragmentation does not appear no matter how long time calculation is performed.

In nature, this state is too hot to survive, and fragmentation/fission/evaporation appears depending on the excitation energy.

As far as very low energies are concerned, it does not cause any big problems.

In our formalism, instability arising from the localized high/low temperature is suppressed. Additional quantity of heat/temperature should be necessary just like Navier-Stokes eqns.

**Missing Piece:**
thermal property cannot be correctly treated, if we introduce only the (Skryme) EDF

**TDHF yield:**
hot-bound state

1200 MeV

Hotness causes instability (which is not correctly taken into account)

Breaks up

In this TDHF calculation, fragmentation does not appear no matter how long time calculation is performed.

In nature, this state is too hot to survive, and fragmentation/fission/evaporation appears depending on the excitation energy.
Outline of implementation 1

CS for evaporation residue

\[ \sigma_{ER} = \sigma_{CAP} P_{CN} P_{Surv} \]

\[ \sigma_{CAP} \]: fully-included in TDHF

\[ P_{CN} \]: whether CN is formed or not.

(sufficiently-included in TDHF)
- a kind of mass equilibration -

\[ P_{Surv} \]: effect after CN/incomplete-CN

not enough; evaporation
How correct ? ; quasi-fission
- a kind of thermal equilibration -

In this TDHF calculation, fragmentation does not appear no matter how long time calculation is performed.

In nature, this state is too hot to survive, and fragmentation/fission/evaporation appears depending on the excitation energy.
The detail of “evaporation prescription” is explained.
Let us assume ...

\[ P_{\text{Surv}} = P_{n,\text{evap}} \]

Note that several factors are included: e.g., quasi-fission, p-evap., D-evap, alpha-evap ...

0) Fragment information (A and Z) with excitation and kinetic energies are obtained by TDHF calculations.

1) Calculate 1-neutron evaporation energy

\[ E_{1n,\text{evap}} = E_{1n,\text{sep}} + E_{\text{kin},n} \]

cf) Boltzmann distribution

3) For the TDHF results, the expected number of evaporated neutrons is calculated.

2) Find maximum \( n \) (integer) satisfying

\[ E^* > n E_{1n,\text{evap}} \]
Towards high predictability

• Brand new results including the effect of neutron evaporation … will appear before long;

First results will be presented in Varrena conf. on reaction mechanism in June 2012.
Movie of TDHF

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

$^{248}\text{Cm} + ^{48}\text{Ca} \rightarrow ( ^{296}_{116} )$

with a fixed impact parameter (10 fm)
a fixed energy 1800 MeV

For comparison, $^{248}\text{Cm} + ^{24}\text{Ne}$

effectively the same energy & impact parameter
New direction

Here we focus on two directions

- develop methodology; TDHF+
- go into the nuclei/elements, which must not exist on the earth
Gross plan of developing TDHF

- TDHF with prescriptions (with S. Heinz & Y. Aritomo)
- Within TDHF (with J. A. Maruhn & P. G-. Reinhard)
  _ full-tensor interaction described by the physical quantity “F”
- Within TDHF especially for the potential landscape (with H. Feldmeier)
- Beyond TDHF (with T. Otsuka)
  _ hopefully, new code will appear in the beginning of 2013

3rd stage _ higher energy treatment (if possible)
2nd stage _ sub-barrier treatment
1st stage C _ barrier-top treatment
1st stage B _ quasi-fission
1st stage A _ evaporation
Nuclear pasta; a kind of extremal existence beyond superheavy

- Its existence; naively out of understandings
  if we believe such an existence naively, there should not be any limits for superheavies.

Motivation:

In the context of the extension of superheavy research, how can we understand it?

- Is it real entity or a kind of idealized entity

Here I would like to show how its formation is theoretically calculated within time-dependent density functional framework.
Movie of TDHF

$^{78}\text{Zn} + ^{78}\text{Zn} + ^{78}\text{Zn} \rightarrow ( ^{234}_{90} \text{Zn} )$

with a fixed reference length 32 fm

Without having very high pressure, it is calculated (quite stable).

Is it actual entity?

or

Is it an idealization/limit of certain actual entities?

or

Is this due to a theoretical trick due to the periodic B. C.?

Now we are studying these formations an extension of superheavy synthesis.
• Movie of TDHF

\(^{117}\text{Rh} + ^{117}\text{Rh}\)

Movie of pasta formation

\(^{117}\text{Rh} + ^{117}\text{Rh} \rightarrow (^{234}\text{90}^+ )\)

with a fixed impact parameter (10 fm) & a fixed incident energy (MeV)

Exactly the same merged system, while the number of colliding nuclei

Multi nucleus simultaneous collision appears rather frequently in the universe.

In the formations of long-connected pasta (an extreme matter), multi-nucleus simultaneous collisions are actually important.

Y. I.
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SLy6
Summary

- **Lower energy** is required] for heavy elements
  → **appearance** of fast charge equilibration
- **Higher energy** is required] for neutron-rich elements
  → **disappearance** of fast charge equilibration
- In addition, to avoid the instability due to the Coulomb repulsion, neutron-richness is indispensable …

Problem to be answered quantitatively:

for given mass and neutron numbers (of final products),
  _ can we clarify the optimal incident energy ?
  _ can we clarify the production limit for the mass number ?