Fission Dynamics of Superheavy Compound Nuclei

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Contents

- Introduction to TDDFT calculations

Motivation:
Study fission using the TDDFT

- Present status
- Difficulty in front of us

- TDDFT for collision dynamics

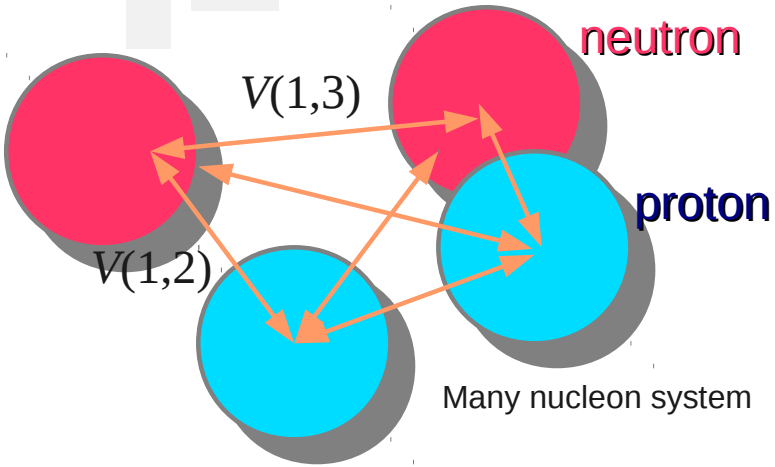
- TDDFT for superheavy synthesis & more

Iwata-Otsuka-Maruhn-Itagaki PRL (2010)
Iwata-Otsuka-Maruhn-Itagaki EPJA (2010)
Iwata-Otsuka-Maruhn-Itagaki NPA (2010)
Iwata JMP (2012); arXiv:1204.3723
Iwata-Heinz J. Phys Conf. Ser. (2012); arXiv:1208.6215
Iwata-Heinz CERN Rep. (2012); arXiv:1209.6142
Iwata-Heinz IJMPE (2012); arXiv:1212.0161
Iwata J. Phys Conf. Ser. (2013); arXiv:1303.4698

Skyrme EDF

Iwata-Maruhn
"Energy Density Functional in Nuclear Physics"
Nova publishers, New York in press; arXiv:1211.2355

EDF = energy density functional



1) Starting from 2-body interaction

$$V(i,j) = V(r_i, r_j, p_i, p_j, s_i, s_j, t_i, t_j)$$

2) Invaliance is imposed

Translation invariance
Galilean invariance
Rotational invariance
Isospin invariance
Parity Invariance
Time reversal invariance

Skyrme, 1950s

$$v_{i,j}(\boldsymbol{k},\boldsymbol{k}') = t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)) + \tfrac{t_1}{2}(1+x_1P_\sigma)\{\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}^2 + \boldsymbol{k}'^2\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\} + t_2(1+x_2P_\sigma)\boldsymbol{k}'\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}$$
$$+\tfrac{t_e}{2}[\{3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k}')(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}') - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}'^2\}\delta(\boldsymbol{r}_i-\boldsymbol{r}_j) + \delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\{3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k})(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}) - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}^2\}]$$
$$+\tfrac{t_o}{2}[3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k}')\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}) - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}'\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}],$$

- 1st order of ***k*** is absent; time reversal invariance.
- Interaction is described by the delta function; zero-range formalism

$$v_{i,j}(\boldsymbol{k},\boldsymbol{k}') = t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)) + \tfrac{t_1}{2}(1+x_1P_\sigma)\{\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}^2 + \boldsymbol{k}'^2\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\} + t_2(1+x_2P_\sigma)\boldsymbol{k}'\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}$$
$$+\tfrac{t_e}{2}[\{3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k}')(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}') - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}'^2\}\delta(\boldsymbol{r}_i-\boldsymbol{r}_j) + \delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\{3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k})(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}) - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}^2\}]$$
$$+\tfrac{t_o}{2}[3(\boldsymbol{\sigma}_i\cdot\boldsymbol{k}')\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)(\boldsymbol{\sigma}_j\cdot\boldsymbol{k}) - (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\boldsymbol{k}'\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\boldsymbol{k}],$$

After adding some terms, which cannot be derived from invariance argument
e.g., spin-orbit interaction, three-body type medium effect

$$v^{LS}_{i,j}(\boldsymbol{k},\boldsymbol{k}') = iW_0\ \boldsymbol{k}'\ \delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\ (\sigma_i+\sigma_j)\times\boldsymbol{k}$$
$$v^{DD}_{i,j}(\boldsymbol{k},\boldsymbol{k}') = \tfrac{t_3}{6}(1+x_3P_\sigma)\rho(\tfrac{\boldsymbol{r}_i+\boldsymbol{r}_j}{2})^\alpha\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)$$

$$V_{i,j}(\boldsymbol{k},\boldsymbol{k}') = v_{i,j}(\boldsymbol{k},\boldsymbol{k}') + v^{LS}_{i,j}(\boldsymbol{k},\boldsymbol{k}') + v^{DD}_{i,j}(\boldsymbol{k},\boldsymbol{k}')$$

Total Energy:

$$E_{V_K} = \int V_K\Psi\ \bar{\Psi}\ dr^3 = \int H_{V_K}(\mathbf{r})\ dr^3$$

Variational Principle
(Gateaux differential)

V_{eff}

Obtain the condition for the total energy to have the minimum with respect to the functional form

not only in Hilbert spaces but in Banach spaces as well

Nonlinear problem

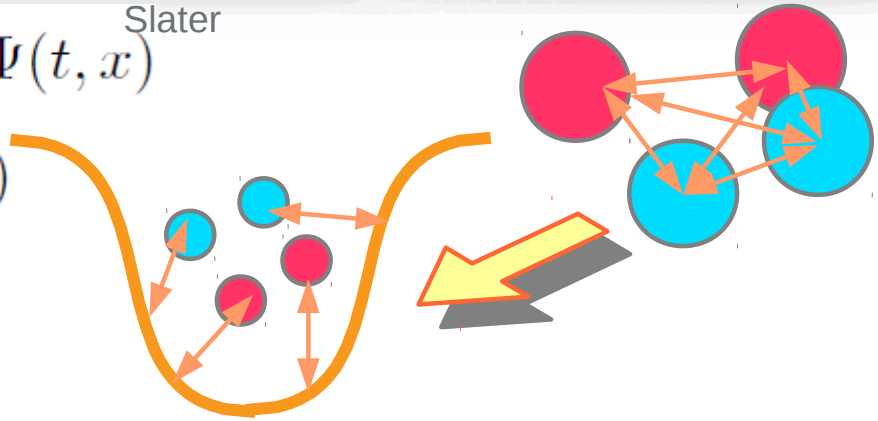
Actual calculation is in the form of

$$\tfrac{1}{2}\sum_{l,m}\int\bar{\psi}_l(\boldsymbol{r}'_i)\bar{\psi}_m(\boldsymbol{r}'_j)V_{i,j}(\boldsymbol{k},\boldsymbol{k}')(1-P_rP_\sigma P_\tau)\psi_l(\boldsymbol{r}_i)\psi_m(\boldsymbol{r}_j)d\boldsymbol{r}_i d\boldsymbol{r}_j d\boldsymbol{r}'_i d\boldsymbol{r}'_j$$

Interaction term

$$V(\rho, s, \tau, T, j, J, F) \longrightarrow \begin{cases} i\hbar\partial_t \Psi(t,x) = \mathcal{H}\Psi(t,x) \\ \mathcal{H} = -\Delta + V(\Psi) \end{cases}$$

Slater



potential

Every interaction is described by the densities

The densities forms the potential:

For a fixed coordinate ***r*** ------ Interaction ***V***

Basic quantities = densities

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

$$\begin{aligned}
E = \int d^3r \sum_{t=0,1}\Bigg\{ & C_t^\rho[\rho_0]\rho_t^2 + C_t^s[\rho_0]\mathbf{s}_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t \\
& + C_t^{\nabla s}(\nabla\cdot\mathbf{s}_t)^2 + C_t^{\Delta s}\mathbf{s}_t\cdot\Delta\mathbf{s}_t + C_t^\tau\left(\rho_t\tau_t - \mathbf{j}_t^2\right) \\
& + C_t^T\left(\mathbf{s}_t\cdot\mathbf{T}_t - \sum_{\mu,\nu=x}^{z} J_{t,\mu\nu}J_{t,\mu\nu}\right) \\
& + C_t^F\Bigg[\mathbf{s}_t\cdot\mathbf{F}_t - \frac{1}{2}\left(\sum_{\mu=x}^{z} J_{t,\mu\mu}\right)^2 \\
& - \frac{1}{2}\sum_{\mu,\nu=x}^{z} J_{t,\mu\nu}J_{t,\nu\mu}\Bigg] + C_t^{\nabla\cdot J} \\
& \times(\rho_t\nabla\cdot\mathbf{J}_t + \mathbf{s}_t\cdot\nabla\times\mathbf{j}_t)\Bigg\}.
\end{aligned}$$

Hamiltonian density

This framework is expected to reproduce collective dynamics.

Lesinski *et al.*, PRC (2007)

Nice description in low-energy HIC

"(roughly) the radius of a nucleus < 10 fm (R = 1.2 * A^(1/3))"
Collision times for a nucleon passing through 20 fm is the problem:

Mean free path of a nucleus

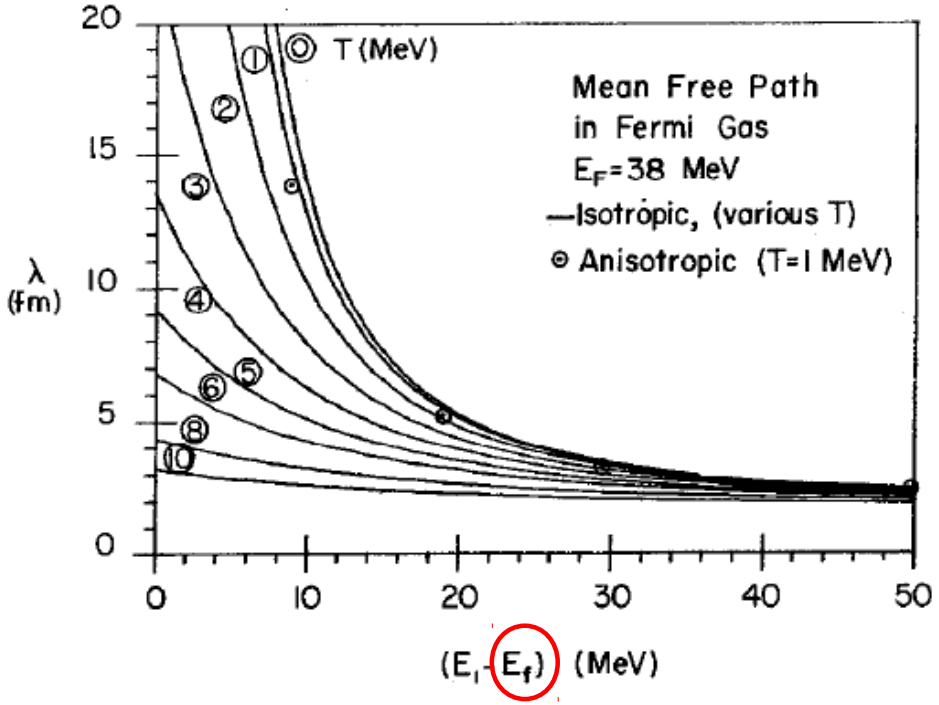


Fig. 2. The calculated nucleon mean free path, λ, in a nuclear Fermi gas of temperature T and Fermi energy, $E_F = 38$ MeV. The nucleon mean free path is given as a function of its energy above the Fermi energy, $(E_1 - E_F)$, for various values of T. The curves are obtained by calculating the expression (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.

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 gives a sufficient framework to study low-energy heavy-ion collision

Collins-Griffin, NPA (1980)

Remarks on Skyrme EDF

The Skyrme energy density functional is zero-range interaction.

The zero-range formalism in nuclear physics revives (compared to the finite-range force necessity) in the context of making the ultimate density function formalism, which is well developed in condensed matter physics.

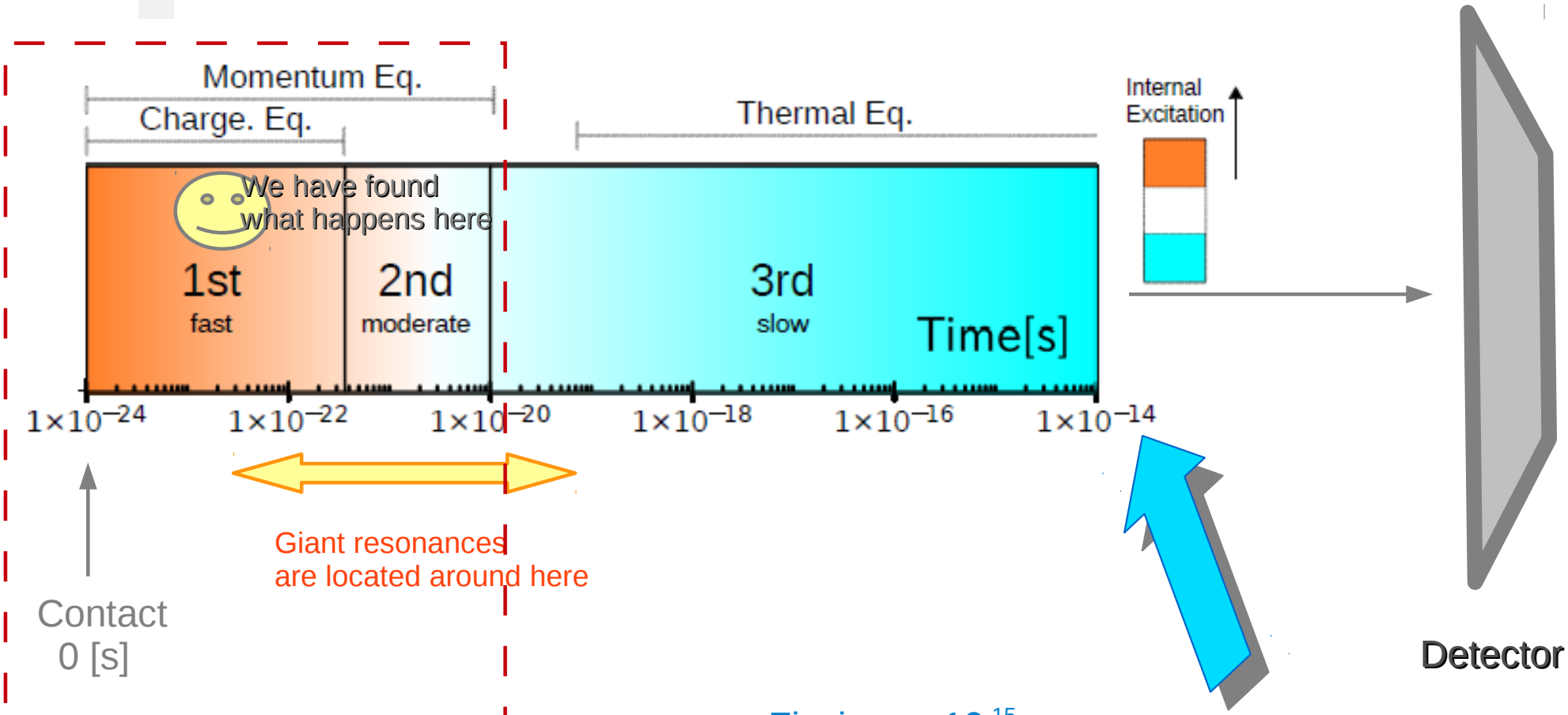
Towards finding the ultimate energy density functional

- Today there are so many Skyrme parameter sets;
  the predictability of Skyrme EDF calculations is limited.
- We do not know whether such an ultimate functional exists or not;
  nuclear force is not so simple as the Coulomb force.
- We have already stopped sticking to the interaction obtained by the mean-field approx.;
  all the possible terms described by the densities are the candidate for the interaction terms nowadays.
- Skyrme type functional form can be derived without assuming the single Slater formalism (shown by Iwata-Maruhn).

Towards including more than the time-dependent mean-field description

Time-scaled scenario of low-energy HICs

Iwata JPCS, to appear



Described by TDDFT

~ 10000 steps (a few 1000 fm/c ~ 10^{-20}s)

Fission ~ 10^{-15}s:

- Collectivity
- Localization (single particle degrees of freedom)
- Thermal effect (beyond the eq. of motion)

Universal wave propagation property

$^{52}Ca + {}^{36}Ca \rightarrow (\ ^{88}Zr\ )$

Theoretical result

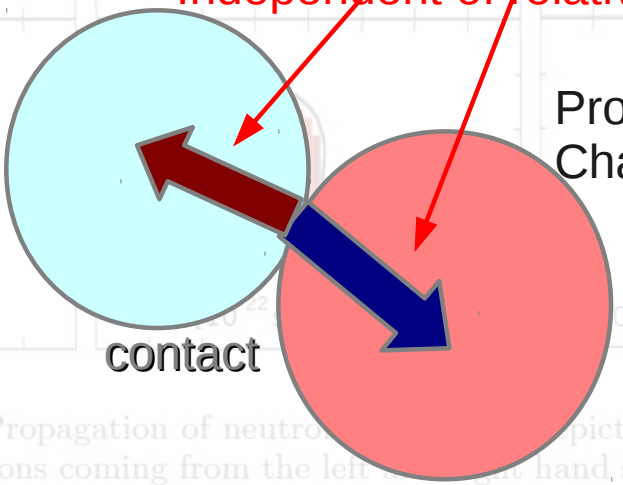
TABLE I: Comparison of speeds, where $|v_F|$ is fixed to 1/3 of the speed of light (corresponding to the nuclear standard value). The propagation speed of charge-equilibrating flow is calculated by the propagation speed of the wave front of $N/Z = 1.10$. The relative velocity of collision at the contact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

Motion	Speed	Description
Propagation of charge-equilibrating flow	0.90 $\|v_F\|$	$\sim 6.5/(0.75\times10^{-22})$ fm/s
Relative velocity for E/A=2.0 MeV	0.36 $\|v_F\|$	Speed given at the initial time
Relative velocity for E/A=1.0 MeV	0.23 $\|v_F\|$	Speed given at the initial time

Almost at the speed of $|v_F|$

Independent of relative velocity and impact parameter

Iwata JMP (2012)



This type of fast wave propagation (reaction dynamics), which contributes to achieve fusion (not necessarily successful), is universal to any low-energy heavy-ion reactions independent of "energies", impact parameters, reaction type (whether fusion or fragmentation).

Charge equilibration dynamics

Corresponding energy to Previously shown cases

$^{52}Ca + {}^{36}Ca \rightarrow (\ ^{88}Zr\ )$

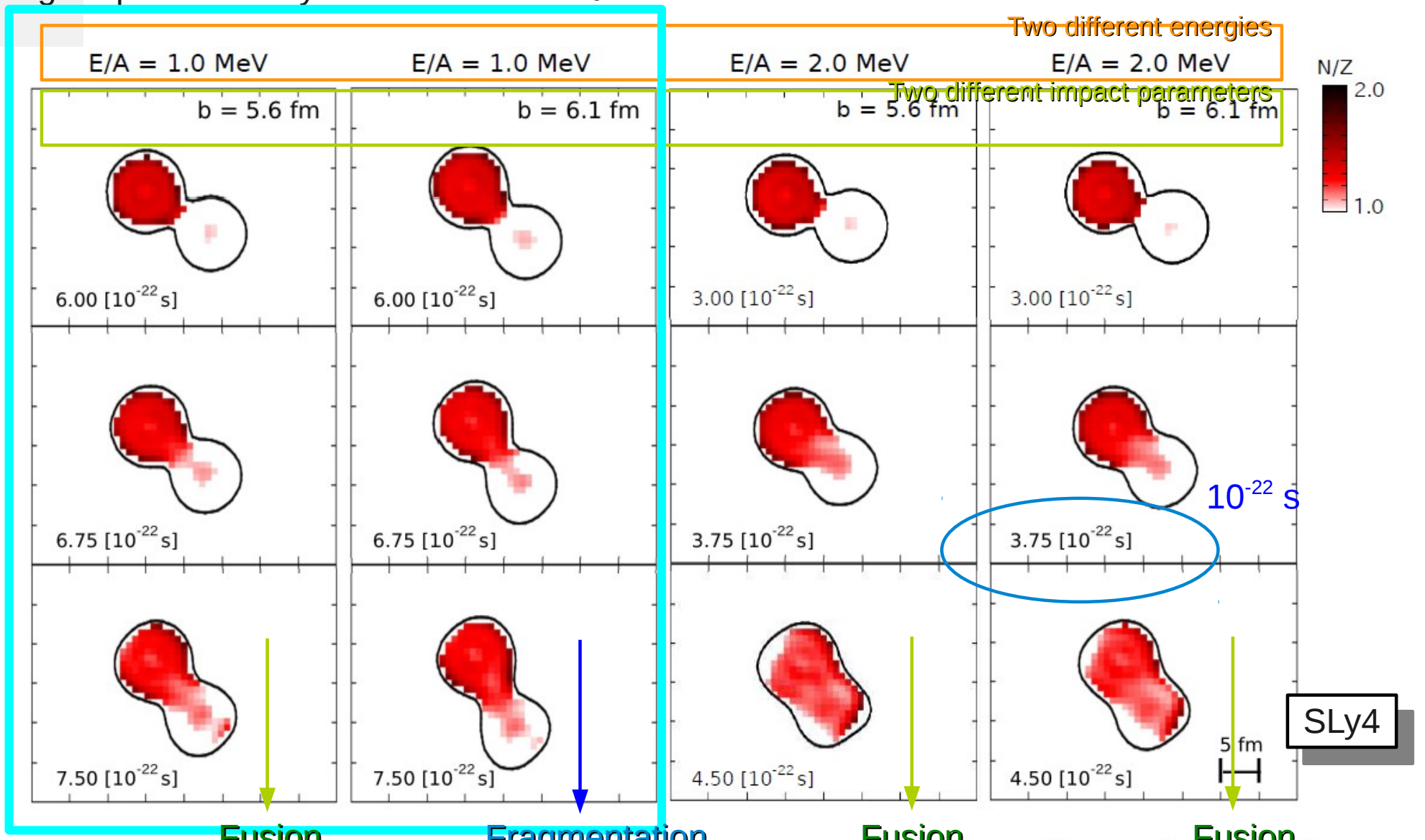


FIG. 1: (Color online) Propagation of neutron-rich flow is depicted for the collision between ^{52}Ca and ^{36}Ca, where ^{52}Ca and ^{36}Ca correspond to the ions coming from the left and right hand sides, respectively. The colored parts correspond to the parts with $N/Z > 1$ (each frame is 40×30 fm^2), 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 $\times10^{-24}$ s. The initial distance between the two colliding ions are set to 20 fm, then the relative velocity of collision is given.

- # Upper energy limit formula (Iwata-Otsuka-Maruhn-Itagaki)

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

Calculations and Experiments are well explained.

$$\frac{E_{\mathrm{CE,lab}}}{A} = \frac{\hbar^2(3\pi^2\rho_{\min})^{2/3}}{2m} + \frac{e^2 Z_1 Z_2}{4\pi\epsilon_0 r_0}\frac{A_1 + A_2}{A_1 A_2 (A_1^{1/3} + A_2^{1/3})}, \quad (1)$$

$$\rho_{\min} = \min_i\left(\frac{N_i(\frac{4\pi r_0}{3}A_i^{1/3})^{-1}}{(1-3\bar{\epsilon})(1+\bar{\delta})}, \frac{Z_i(\frac{4\pi r_0}{3}A_i^{1/3})^{-1}}{(1-3\bar{\epsilon})(1-\bar{\delta})}\right), \quad (2)$$

where m, e, ϵ_0, and r_0 are the nucleon mass, the charge unit, the vacuum permittivity, and the usual nuclear radius parameter (1.2 fm), respectively.

TABLE I. $E_{\mathrm{CE,cm}}/A$ values [MeV] obtained by TDHF calculations compared to those obtained by transforming the results of Eq. (1) into the center-of-mass frame. For reference, the values obtained by the Fermi gas model with the standard parameter are also shown.

	Collision	TDHF (SLy4d)	TDHF (SkM*)	Equation (1)	Fermi gas
(i)	^{208}Pb + ^{238}U	6.5 ± 0.5	6.5 ± 0.5	6.91	9.46
(ii)	^{208}Pb + ^{132}Xe	6.5 ± 0.5	6.5 ± 0.5	6.50	9.03
(iii)	^{208}Pb + ^{132}Sn	6.5 ± 0.5	6.5 ± 0.5	6.36	9.03
(iv)	^{208}Pb + ^{40}Ca	3.5 ± 0.5	3.5 ± 0.5	3.66	5.14
(v)	^{208}Pb + ^{24}Mg	2.5 ± 0.5	2.5 ± 0.5	2.36	3.52
(vi)	^{208}Pb + ^{24}O	2.5 ± 0.5	2.5 ± 0.5	2.18	3.52
(vii)	^{208}Pb + ^{16}O	1.5 ± 0.5	1.5 ± 0.5	1.75	2.50
(viii)	^{208}Pb + ^{4}He	<1.0	<1.0	0.48	0.70
(ix)	^{24}Mg + ^{24}O	5.5 ± 1.0	5.5 ± 1.0	5.99	9.50

Charge equilibration is dominant at the early stage of low-energy heavy-ion reactions

- dynamical mixture between neutrons and protons

  averaging local N/Z ratio (arising from "the symmetry energy")

- very fast mechanism taking only ~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, which is represented by the upper energy-limit formula (Iwata-Otsuka-Maruhn-Itagaki)

- The mechanism of fast charge equilibration is ultimately reduced to the propagation of nucleon wave at the speed almost equal to the (amplitude of) Fermi velocity.

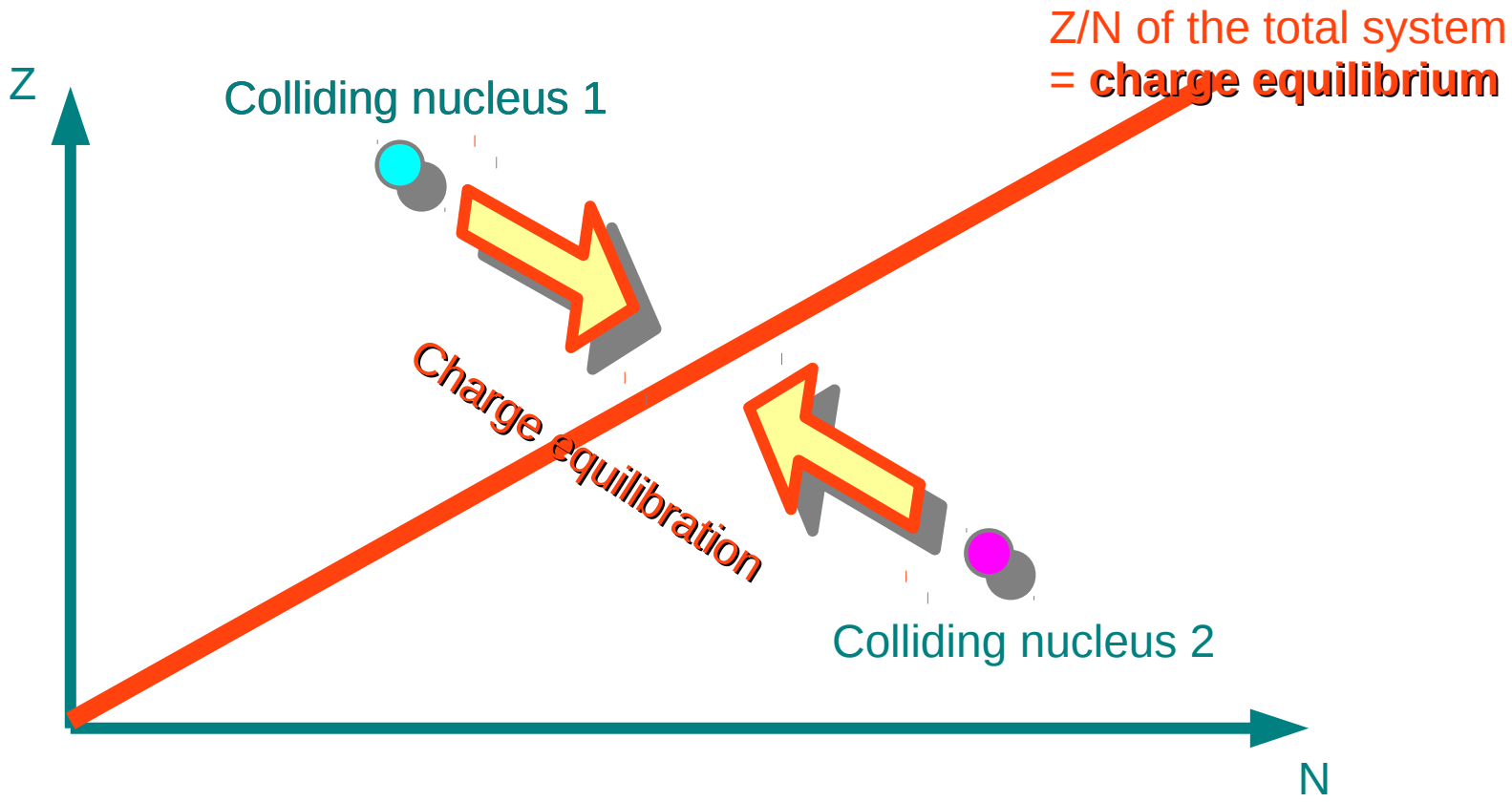
  = zero sound propagation (collective dynamics ~ mean-field effect)

Iwata, JMP (2012); ArXiv:1204.3723

Iwata-Otsuka *et al.*, PRL (2010)

Charge equilibration is dominant at the early stage of low-energy heavy-ion reactions

Appearance of charge equilibration SUPPRESS the production of exotic nuclei

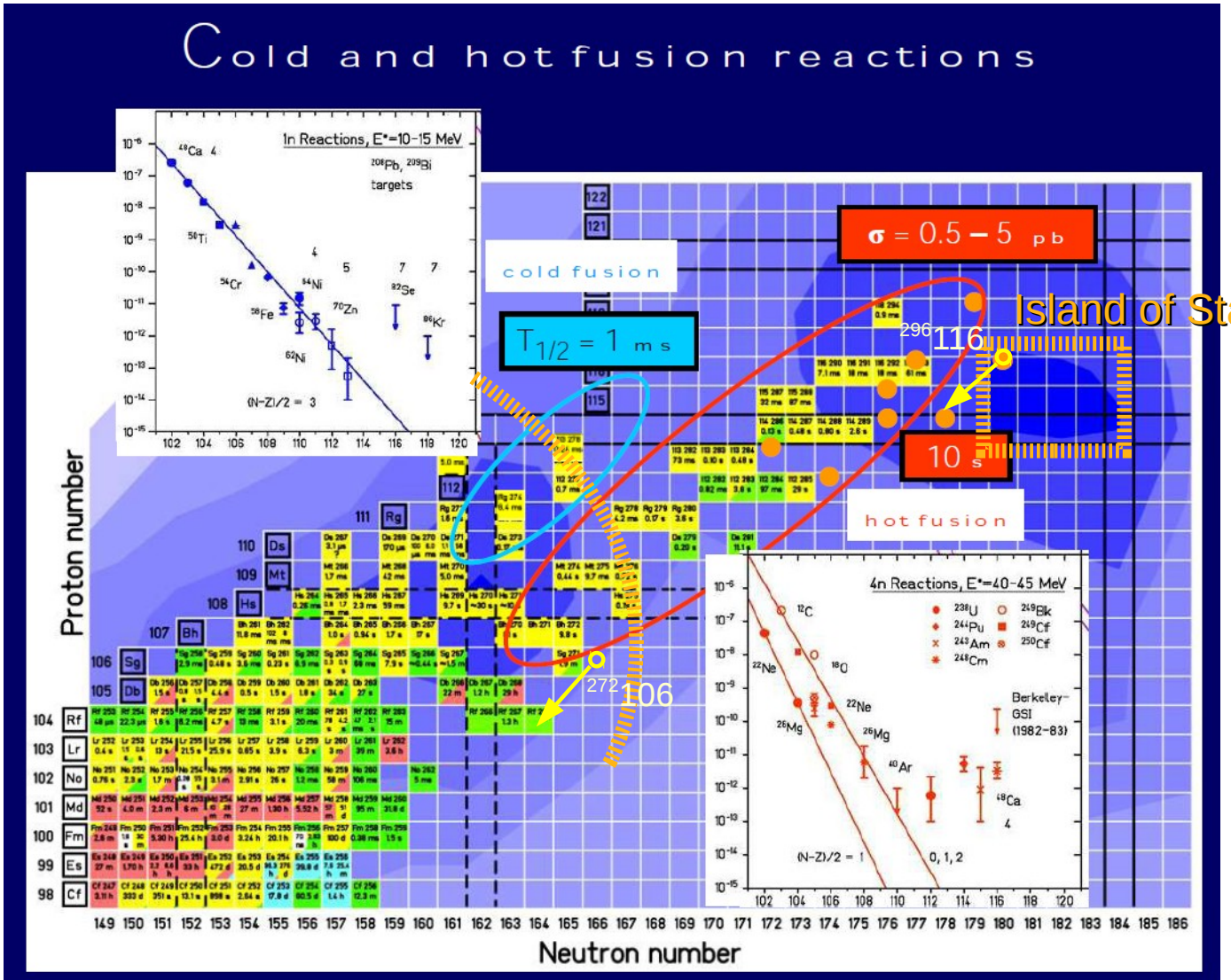


As the most probable quantum dynamics, the TDDFT results predict that it is difficult/impossible to produce exotic and very heavy nuclei.

Indeed, energy should be higher than the upper-limit energy for exotic production, but final fragments become smaller for higher energies.

Superheay reactions including fission

$^{248}Cm + {}^{48}Ca \longrightarrow {}^{296}116^*$ is calculated;



New element around 120 by hot or cold fusion

The ending point of r-process is expected to be around the island (recycle loop)

Our calculation for

$^{238}U + {}^{238}U$ (transfer)
$^{238}U + {}^{248}Cm$ (transfer)

will come soon !

Motivation:

Theoretical prediction of possibility

Producing neutron-rich and heavy nuclei

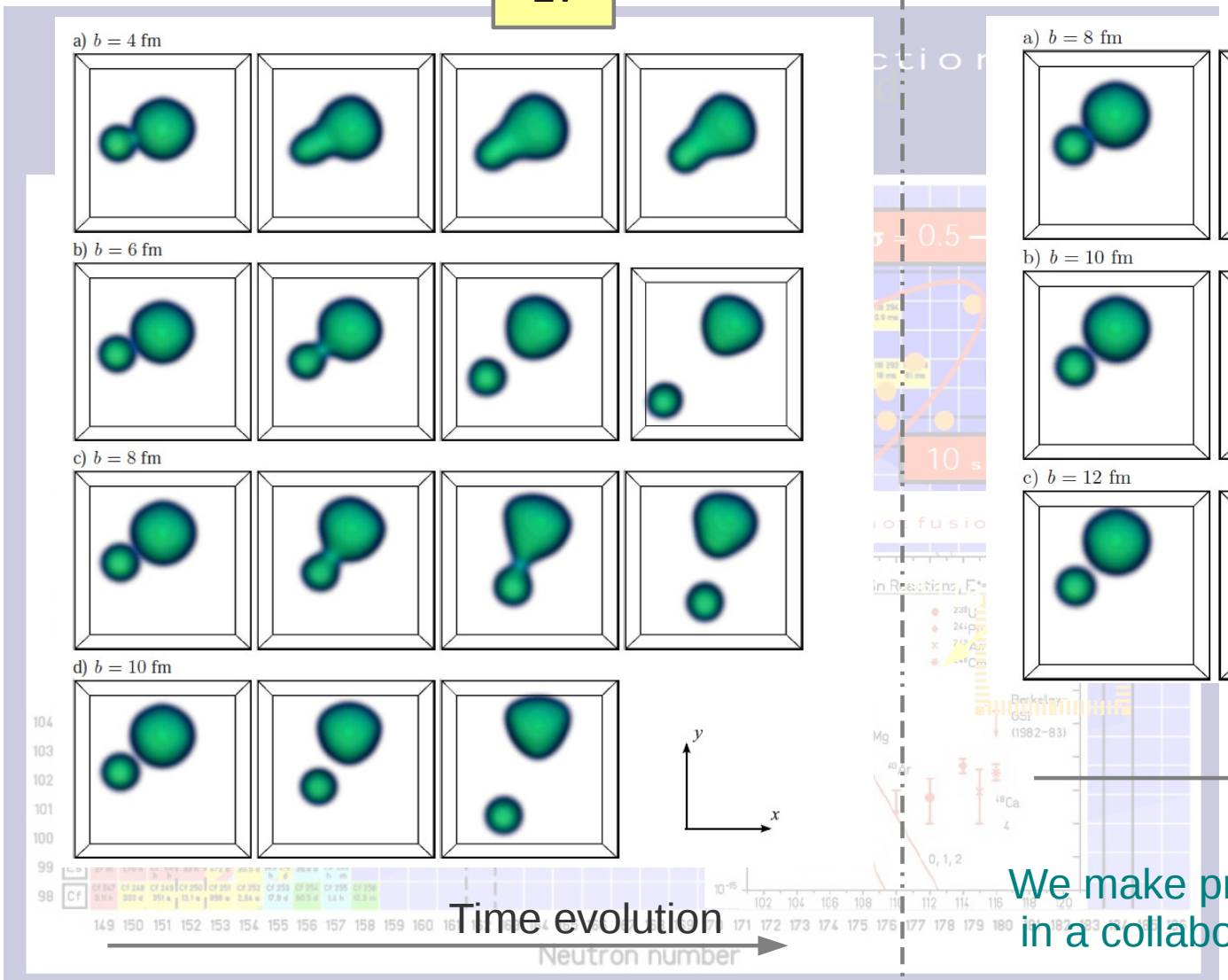
$^{248}Cm + {}^{48}Ca \rightarrow (\ ^{296}116\ )$ is calculated;

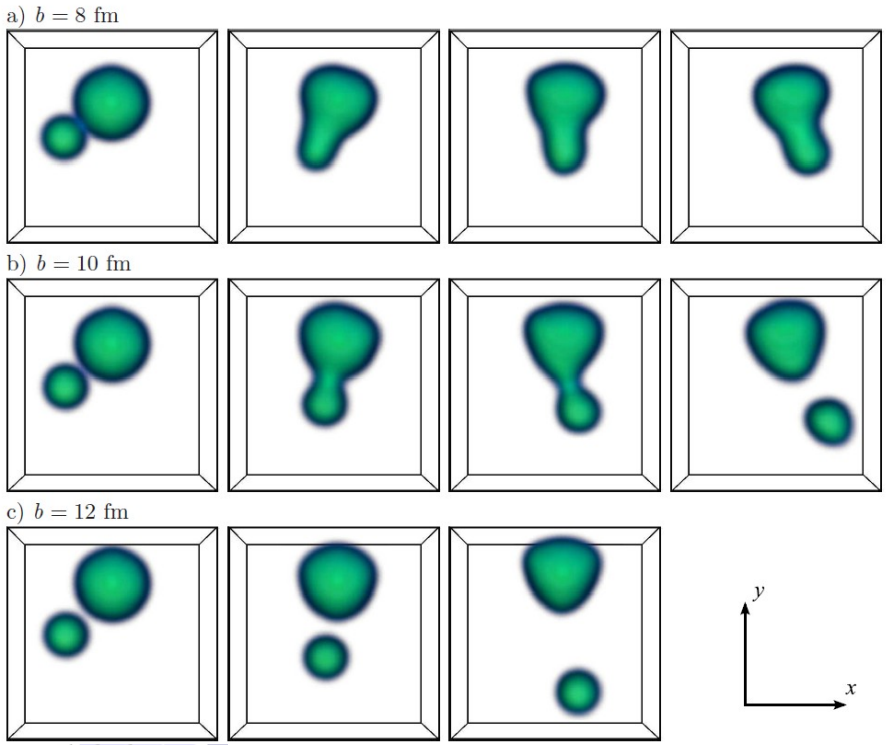
cf.) island of stability

E = 268 MeV

Lv

E = 352 MeV



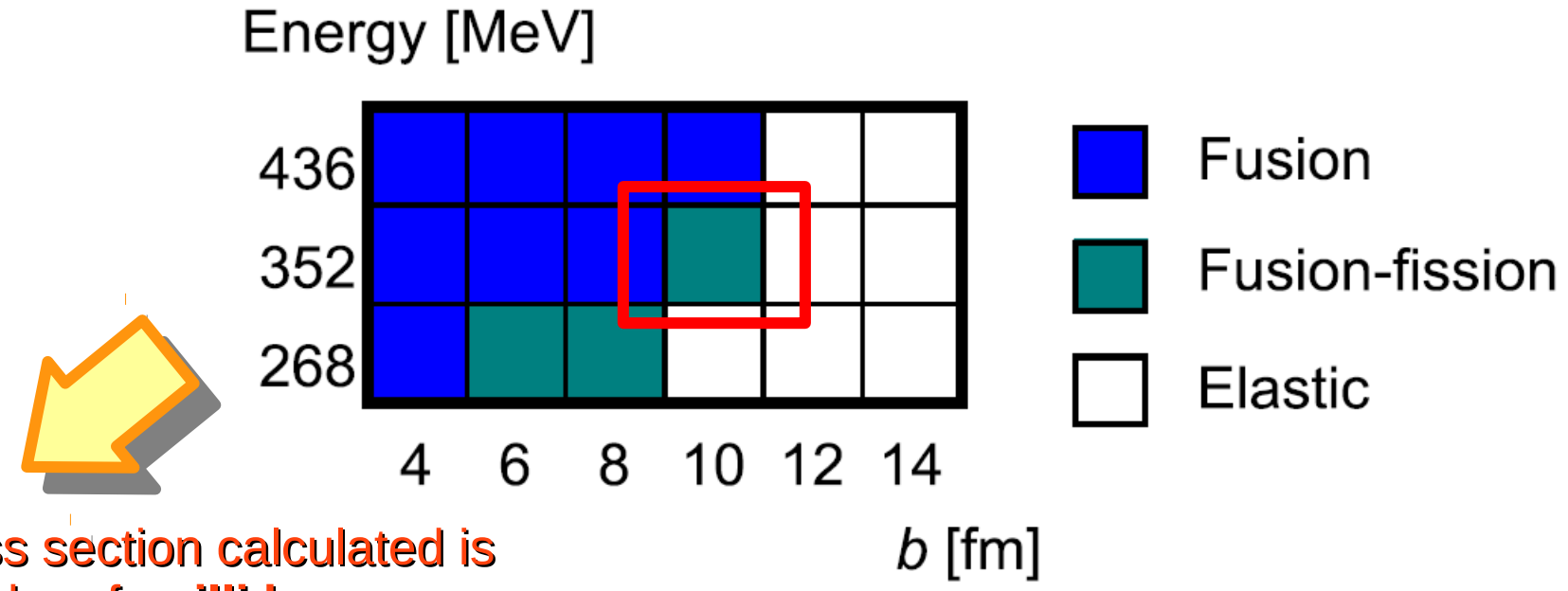


We make progresses
in a collaboration with GSI experiments.

Superheavy synthesis reaction

Recent Progress of computer technology
makes us possible to treat heavy system in a systematic way.

Iwata-Heinz, JPCS (2012)



The cross section calculated is
at the order of **milli barn**

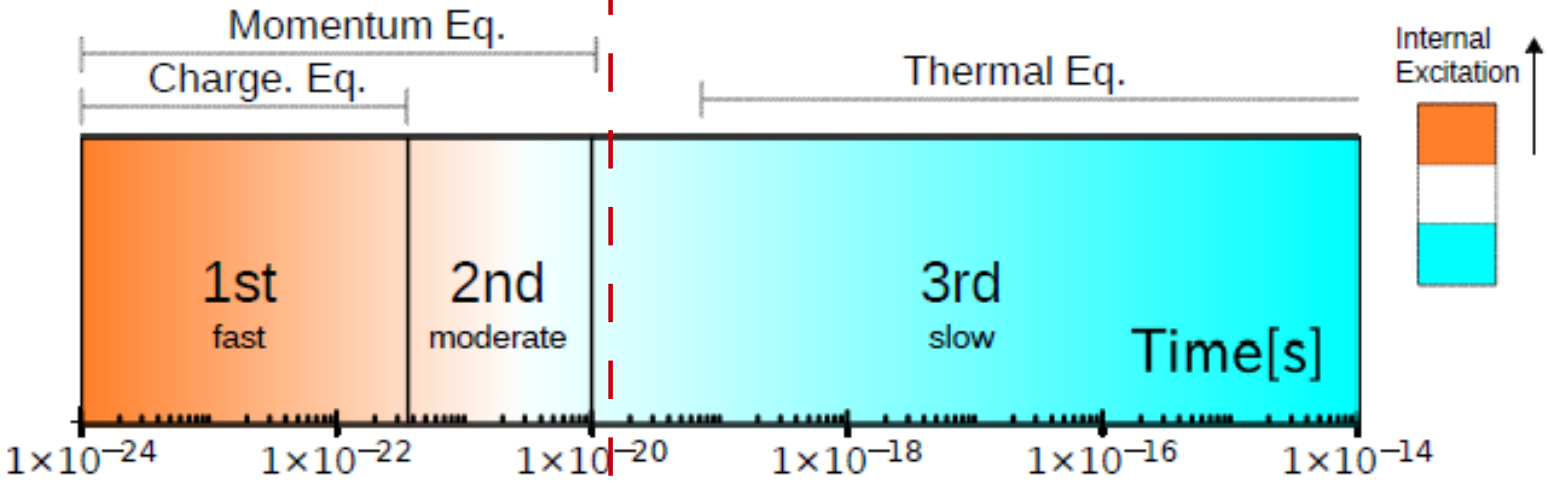
superheavy experiments
~~> **pico barn**

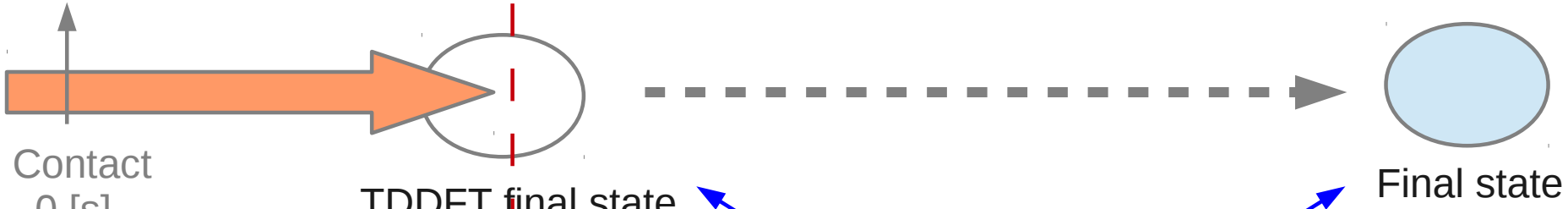
Quite different from the experiments

In order to have better predictability (to compensate for shortcomings of the TDDFT),
The additional thermal treatment is necessary.

Before going into the additional treatment,
the reason is simply summarized here

Iwata JPCS, to appear





Described by TDDFT

These two states are quite different !

In addition to the time scale difference, thermal equilibration cannot be fully treated in the TDDFT

$^{248}Cm + {}^{48}Ca \longrightarrow (\ ^{296}116\ )$ is calculated;

Lv

Evaporation residue cross section:

$$\sigma_{ER}(E_{cm}) = \sum_J \sigma_{CP}(E_{cm}, J) \times P_{CN}(E_{cm}, J) \times P_{SV}(E_{cm}, J)$$

Capture Compound fom. prob. Survival prob.

~ 1 for light system

TDDFT theorists have not known the importance of thermal treatment for a long time (until now);
only light nuclear systems are considered, e.g., $^{40}Ca + {}^{40}Ca$.

Thermal property

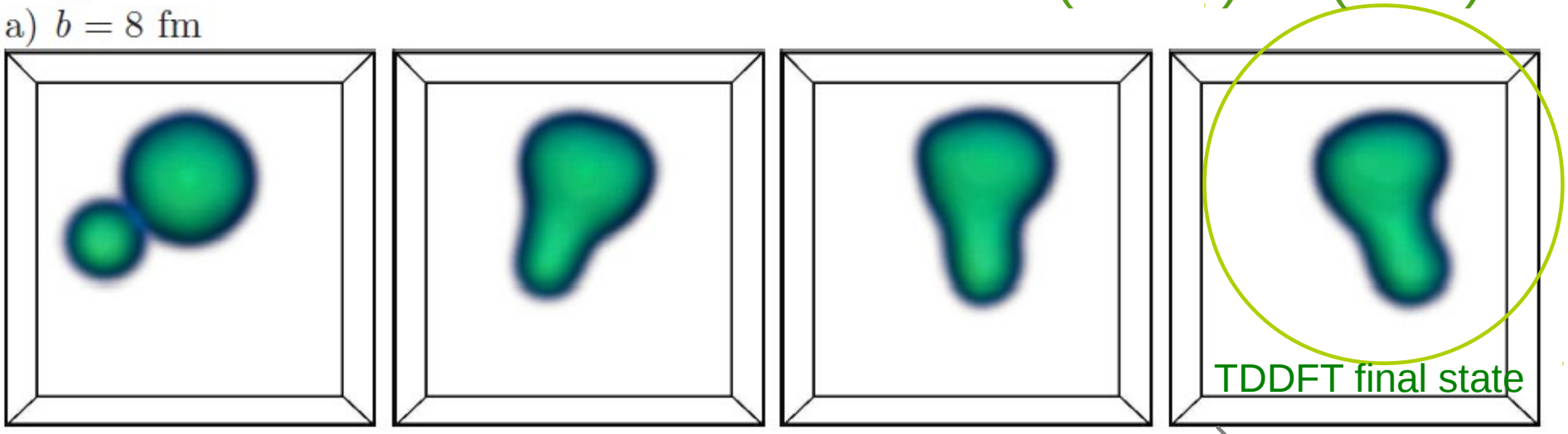
Correct treatment of the thermal instability of the compound nuclei

Before going into the additional treatment, the reason is simply summarized here

Iwata JPCS, to appear

E = 268 MeV

$(^{296}116)^* = (^{296}Lv)^*$



Comparing with the binding energy of HF state (^{296}Lv)

Contact
0 [s]

TDDFT final state

Compound nucleus;
Going into a stable fused system in TDDFT

Described by TDDFT

A Z E*

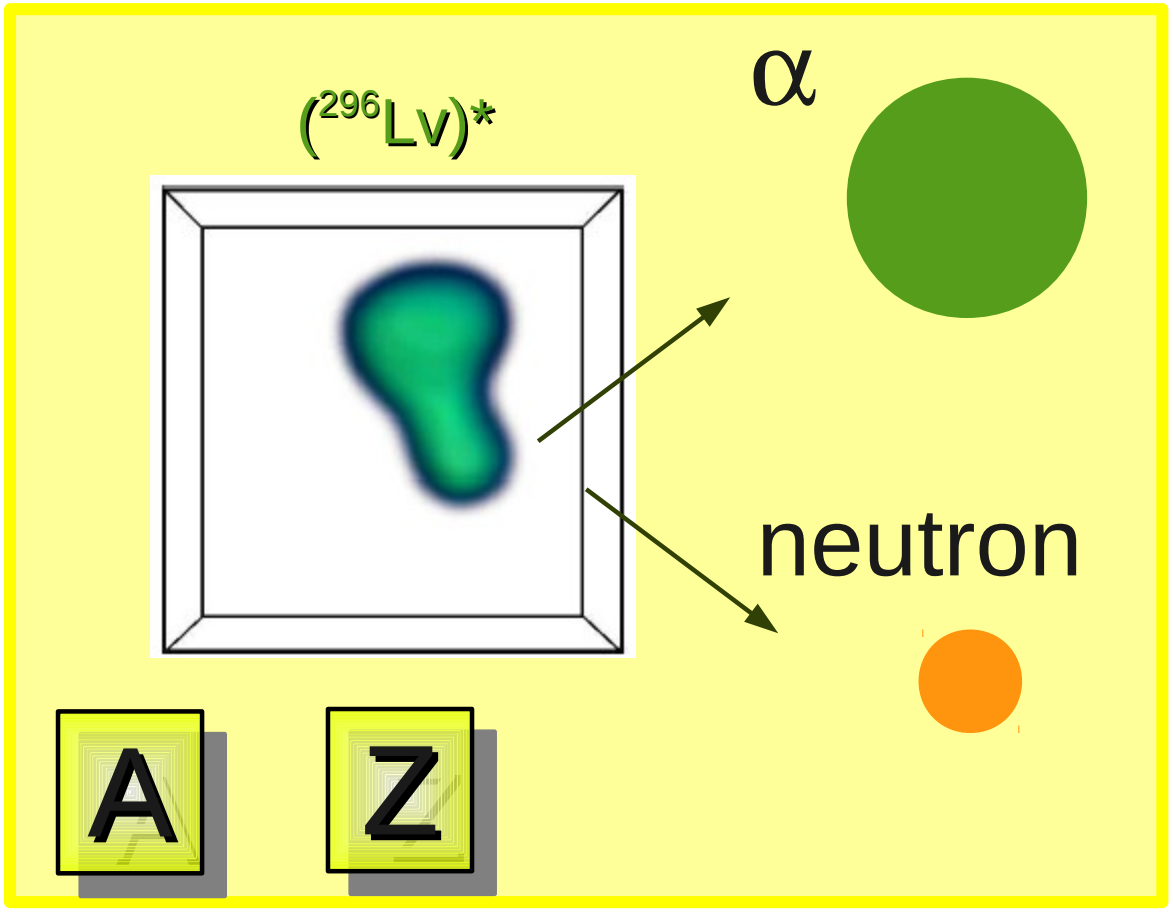
1) obtain TDDFT fragments (A_i and Z_i) with excitation (E_i^*) and kinetic (K_i) energies;

Cooling due to alpha and neutron emission

2) for each fragment calculate evaporation energy:

$$\begin{cases} E_{i,\alpha,evap} = E_{i,1\alpha,evap} + E_{i,\alpha,kin}, \\ E_{i,n,evap} = E_{i,1n,evap} + E_{i,n,kin}, \end{cases}$$

where $E_{i,\alpha,evap}$ and $E_{i,n,evap}$ are the cooling energies due to one alpha-particle and one neutron emissions, respectively, and $E_{i,\alpha,kin}$ and $E_{i,n,kin}$ denotes the kinetic energy of alpha-particle and neutron, respectively (cf. Boltzmann distribution);



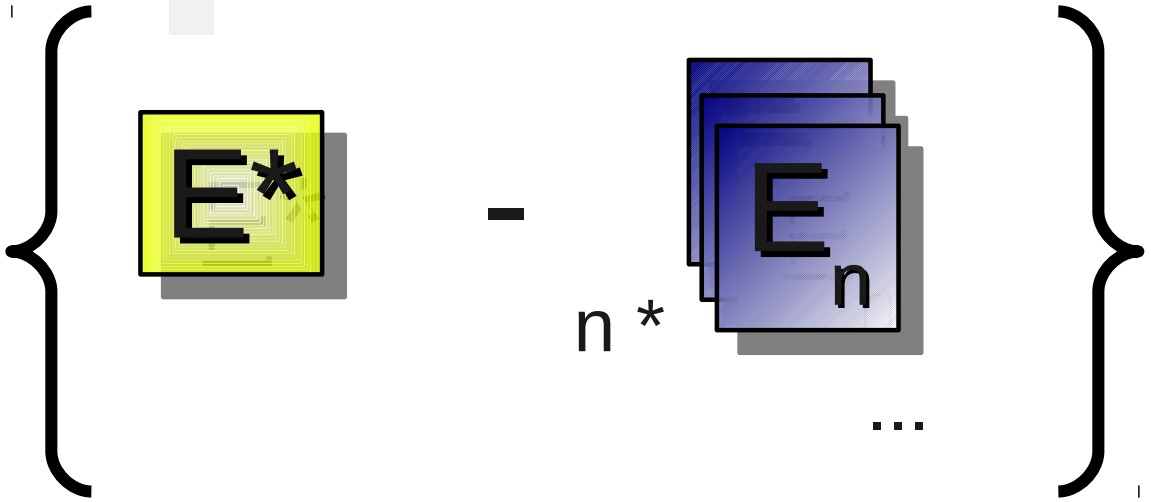
<<< cooling
(1 alpha separation energy)

<<< cooling
(1 neutron separation energy)

Evaporation prescription (3/3)

Cooling due to alpha and neutron emission

For *n* neutron emission channel, calculate the remaining energy



In this talk ...

As a trial calculation for the most probable process,

We fix *n* by
1) calculate maximum *m*
E* - *m* Ea > 0
2) calculate maximum *n*
E* - *m* Ea - *n* En > 0

Comparing with

Single alpha emission

we can obtain the alpha-decay chain

Result of SHE reaction (example)

Based on the prescriptions, for example, we have obtained the following alpha-decay chain depending on the impact parameter

Calculation for the cross section is not yet !

as well as the possible (incl. possibility) fission dynamics of each fragment

$$E = 268\mathrm{MeV},$$

$$^{248}\mathrm{Cm} + ^{48}\mathrm{Ca} \rightarrow {}^{292}\mathrm{Lv} + 4n$$

We want to know the fission property (fission dynamics) of obtained product after alpha and neutron emission

$$\rightarrow \quad \mathrm{Cn} + 2\alpha + 4n$$

$$\rightarrow {}^{280}\mathrm{Ds} + 3\alpha + 4n, \quad (b \leq 4\ \mathrm{fm})$$

$$^{248}\mathrm{Cm} + ^{48}\mathrm{Ca} \rightarrow {}^{246}\mathrm{Cf} + ^{47}\mathrm{Ar} + 3n$$

$$\rightarrow {}^{242}\mathrm{Cm} + ^{47}\mathrm{Ar} + \alpha + 3n$$

$$\rightarrow {}^{238}\mathrm{Pu} + ^{47}\mathrm{Ar} + 2\alpha + 3n, \quad (b = 6\ \mathrm{fm})$$

$$^{248}\mathrm{Cm} + ^{48}\mathrm{Ca} \rightarrow {}^{245}\mathrm{Bk} + ^{48}\mathrm{K} + 3n$$

$$\rightarrow {}^{241}\mathrm{Am} + ^{48}\mathrm{K} + 1\alpha + 3n$$

$$\rightarrow {}^{237}\mathrm{Np} + ^{48}\mathrm{K} + 2\alpha + 3n, \quad (b = 8\ \mathrm{fm})$$

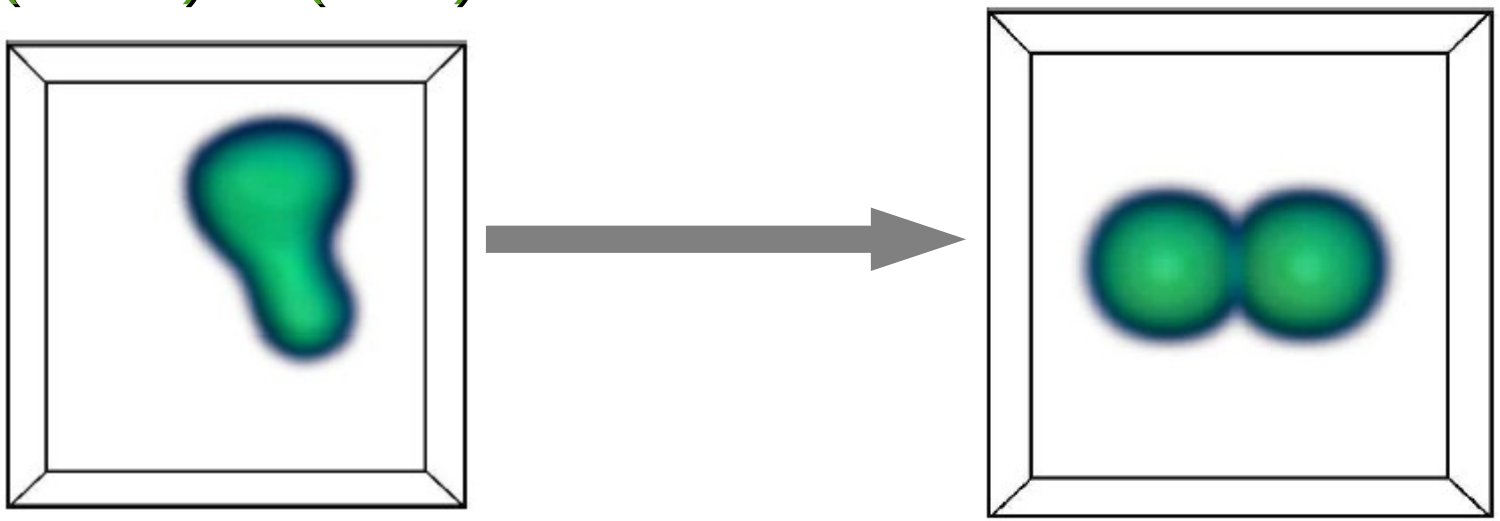
$$^{248}\mathrm{Cm} + ^{48}\mathrm{Ca} \rightarrow {}^{248}\mathrm{Cm} + ^{48}\mathrm{Ca}, \quad (b \geq 10\ \mathrm{fm});$$

Fission dynamics

After the alpha and neutron emissions,
The compound nucleus is still hot …; we prepare a new initial state

$(^{296}116)^* = (^{296}Lv)^*$

Ex)



E* [MeV]

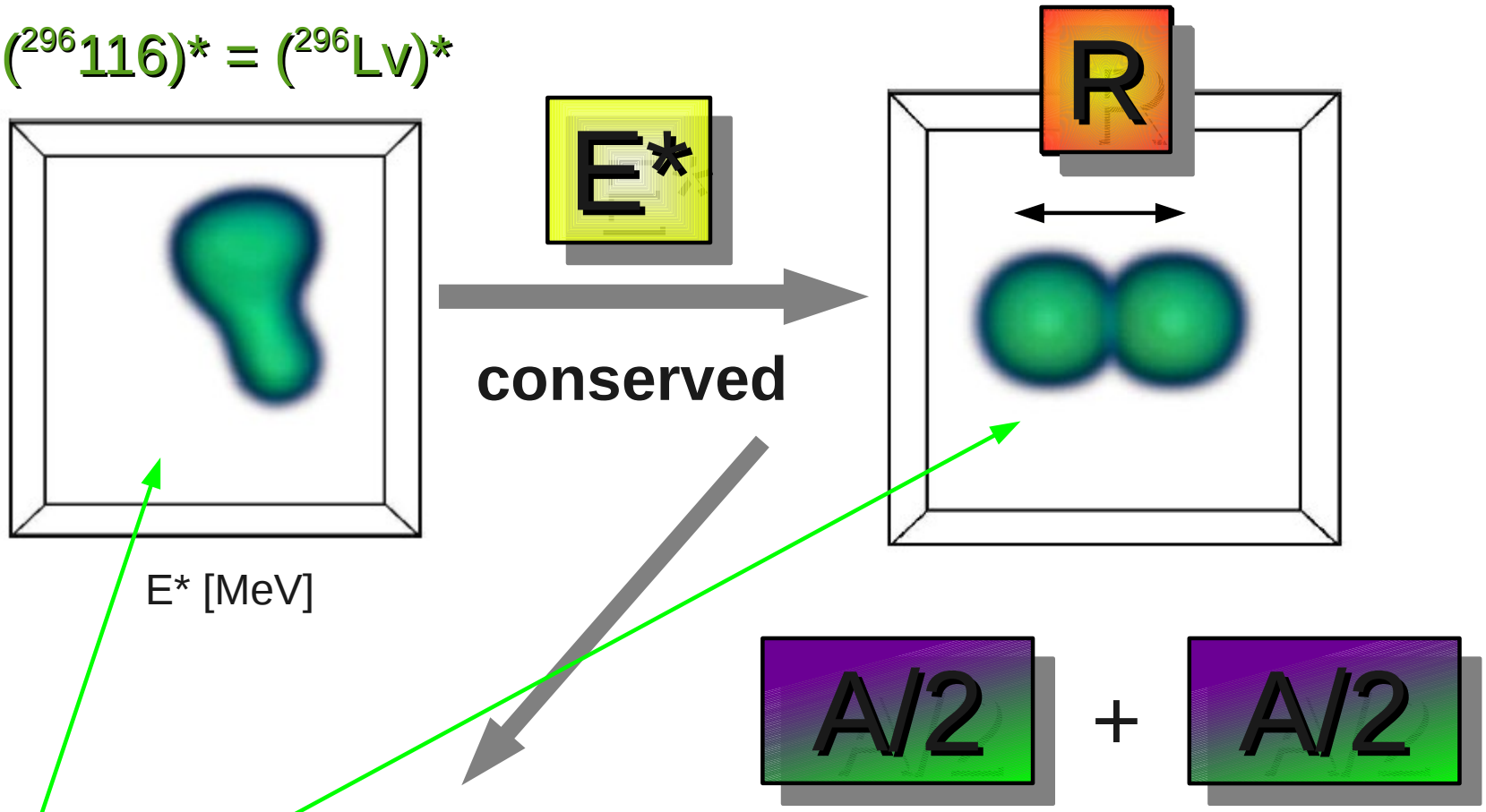
Compound nucleus;
Going into a stable fused system in TDDFT

Note that, **including us**,
all TDDFT trials for calculating fission dynamics failed.
It is due to the difficulty of preparing good initial condition.

Here ...

For simplicity we take $A_1 = A_2$

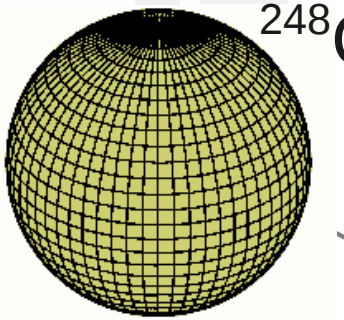
Following the TDDFT property, the total energy is conserved



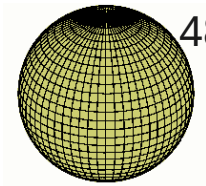
The distance between two nuclei is “uniquely” determined by the excitation energy

The relation between these two states are understood by calculating the overlap between the two states (now ongoing), which corresponds also to the calculation of the probability:

the symmetric fission of ^{296}Lv* (compound)
E_{cm} = 268 MeV (the energy is strictly conserved)



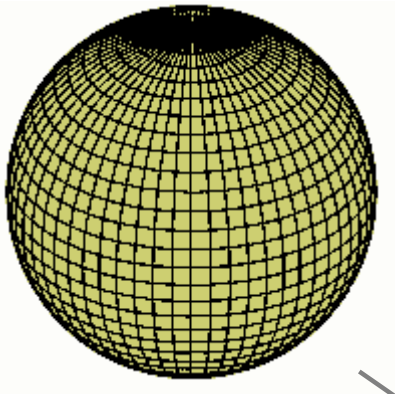
^{248}Cm



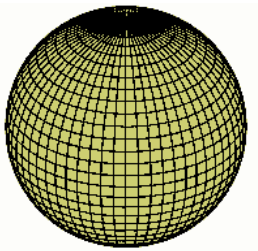
^{48}Ca

Fusion

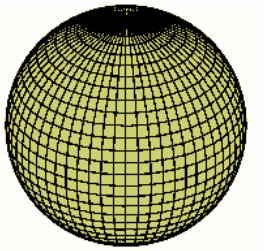
^{296}Lv*



Fission



^{148}Ce



^{148}Ce

^{248}Cm + ^{48}Ca → (^{296}116)* TDDFT 1

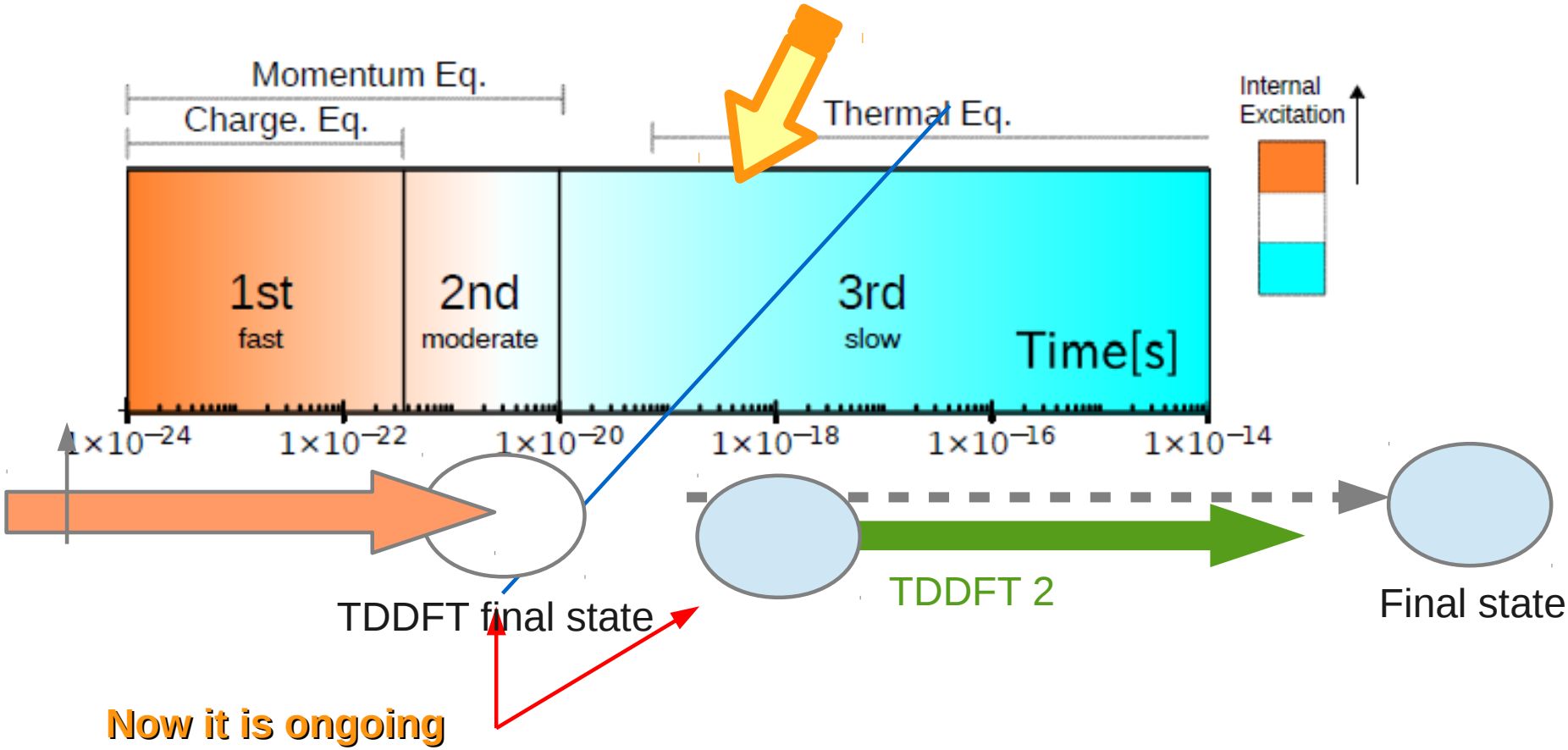
→ ^{148}Ce + ^{148}Ce TDDFT 2

The problem is “how to” connect these two calculations !

People do not know that such kind of fission process can appear purely by the mean-field description

Before going into the additional treatment,
the reason is simply summarized here

Note: more terms in modern EDF



Now it is ongoing

These two calculations can be connected by the additional treatment;
i.e., the relation between the final state of TDDFT1 and the initial state of TDDFT2 can be quantitatively obtained by calculating the correlation function.

What does TDDFT fission dynamics tell us ?

Physical pieces of fission:

- Collectivity
- Localization = clustering (single particle “excitation” effect)
- Thermal effect (beyond the eq. of motion)

……

- Probability and so on ...

1) The fission dynamics actually appears purely by the TDDFT dynamics (after preforming):

single particle degree of freedom might be important to the preforming stage
pairing (level crossing) plays a role in the preforming stage (but other effects is also necessary)
thermal equilibration effect might be important; adiabatic approach should not be ultimate.

2) The duration time of fission dynamics is rather short than we have expected; which is actually about 10^{-21} s:

once an ideal state is formed, fission is completed quickly (by collective motion)
Preforming (clustering) stage might consume incomparably long time (10^{-18} to 10^{-15}s at least)

Summary

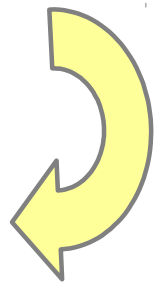
- The present status of the TDDFT is shown.

- Now TDDFT confront difficulties with respect to

  treatment of heavy system

  treatment of fission, fragmentation (late processes)

  = reduced to the treatment of thermal property !



Evaporation residue cross section:

~1 (light systems)

$$\sigma_{ER}(E_{cm}) = \sum_J \sigma_{CP}(E_{cm}, J) \times P_{CN}(E_{cm}, J) \times P_{SV}(E_{cm}, J)$$

Capture Compound fom. prob. Survival prob.

Summary

As a way of overcoming some difficulties,

we have proposed a sequence of method

evaporation prescription to calculate (Iwata-Heinz)

fission dynamics by preparing a new initial state (Iwata-Heinz)

by calculating the correlation function,
the physical meaning of the new initial state is clarified (Iwata-Otsuka)

where difficulties mostly arise from the difference of the time scales.