Fusion and quasifission dynamics in the synthesis of superheavy elements

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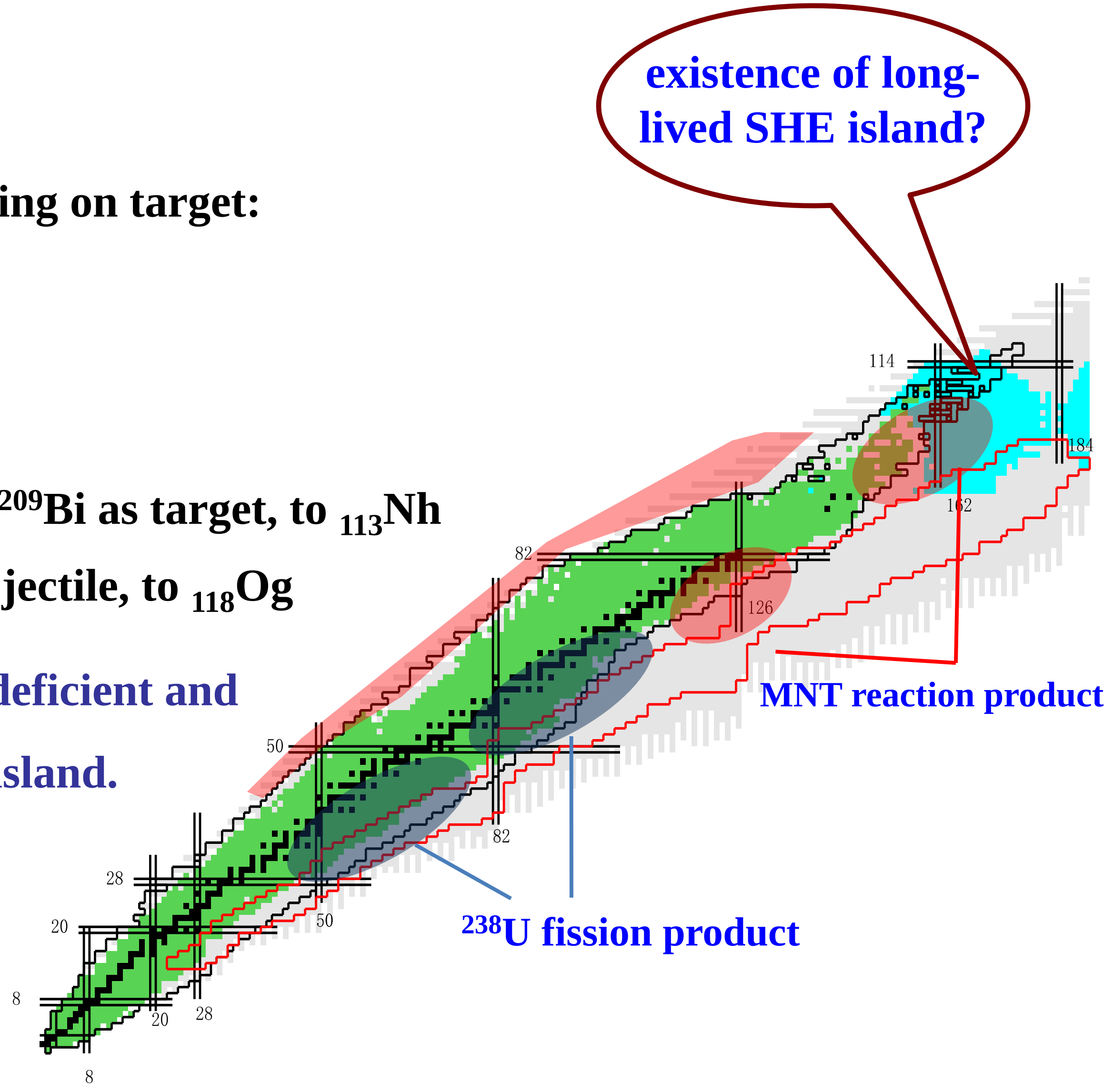
Synthesis of SHE

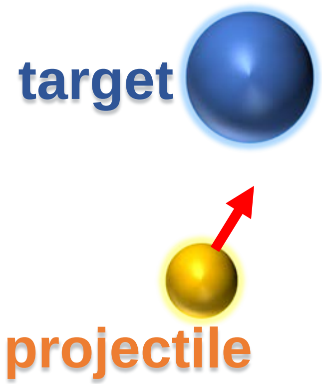
Ways to synthesize heavy and superheavy elements:

- **neutron capture:**
  $_{94}Pu$---$_{100}Fm$;
- **light ions (^1H, ^2H, ^3H, He) colliding on target:**
  heaviest to $_{101}Md$
- **multi-nucleon transfer (MNT)**
- **fusion reactions**
  - **cold fusion: with ^{208}Pb and ^{209}Bi as target, to $_{113}Nh$**
  - **hot fusion: with ^{48}Ca as projectile, to $_{118}Og$**

The synthesized SHE are neutron-deficient and far from the predicted stable SHE island.



HIC with heavy nuclei



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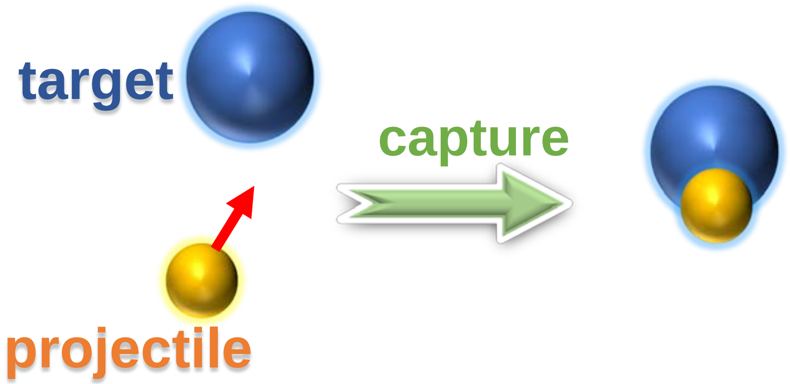

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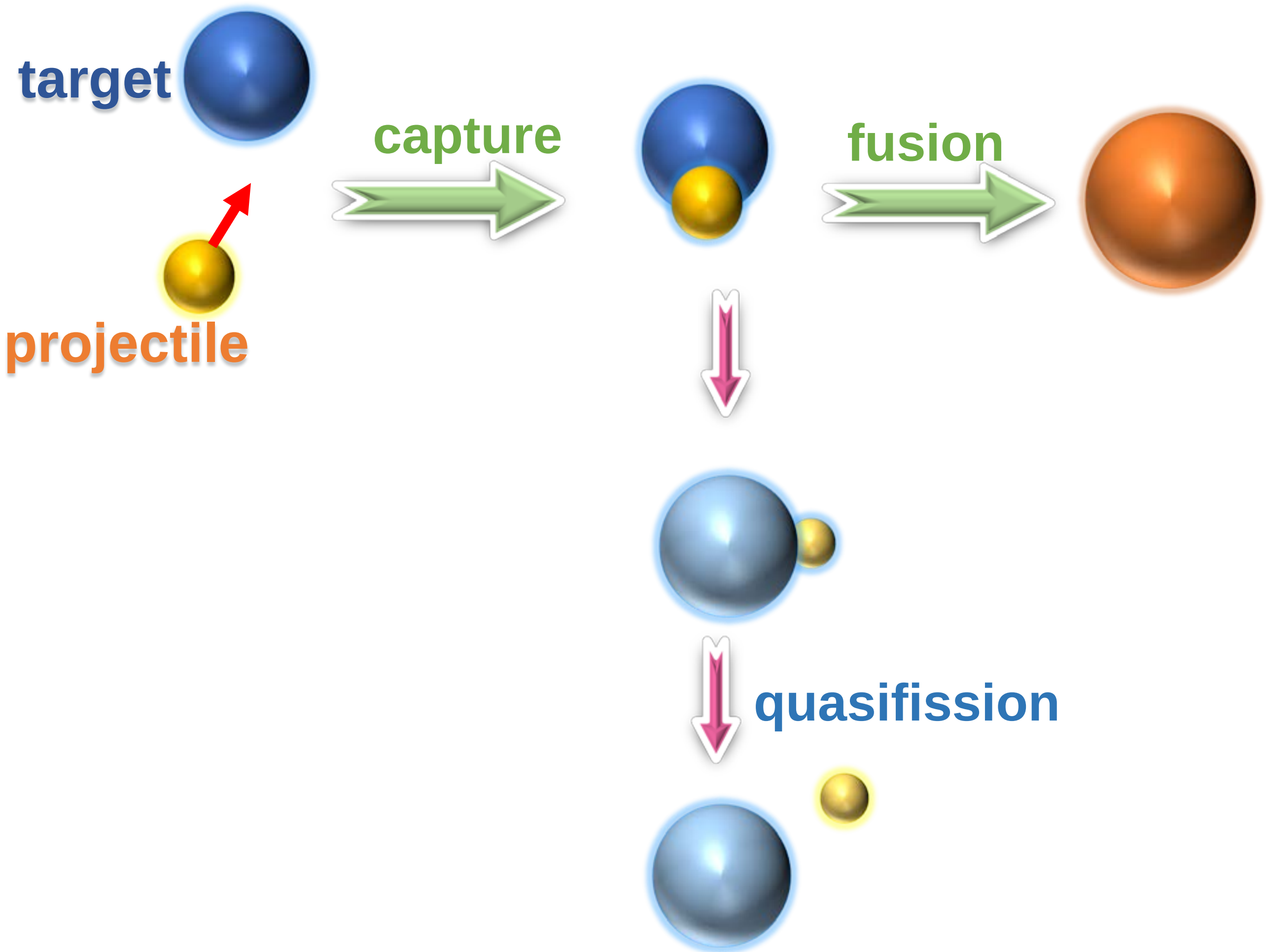

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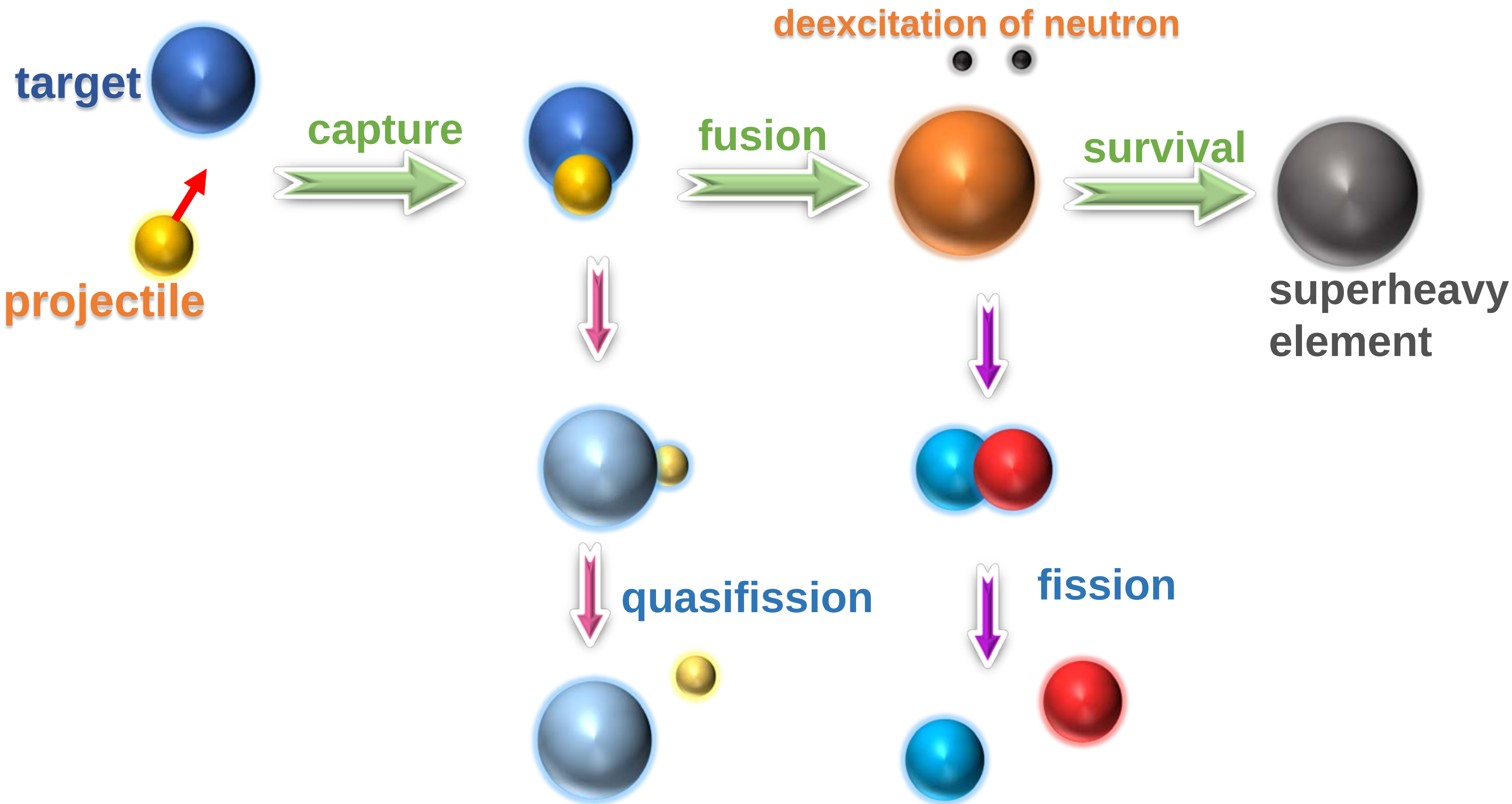
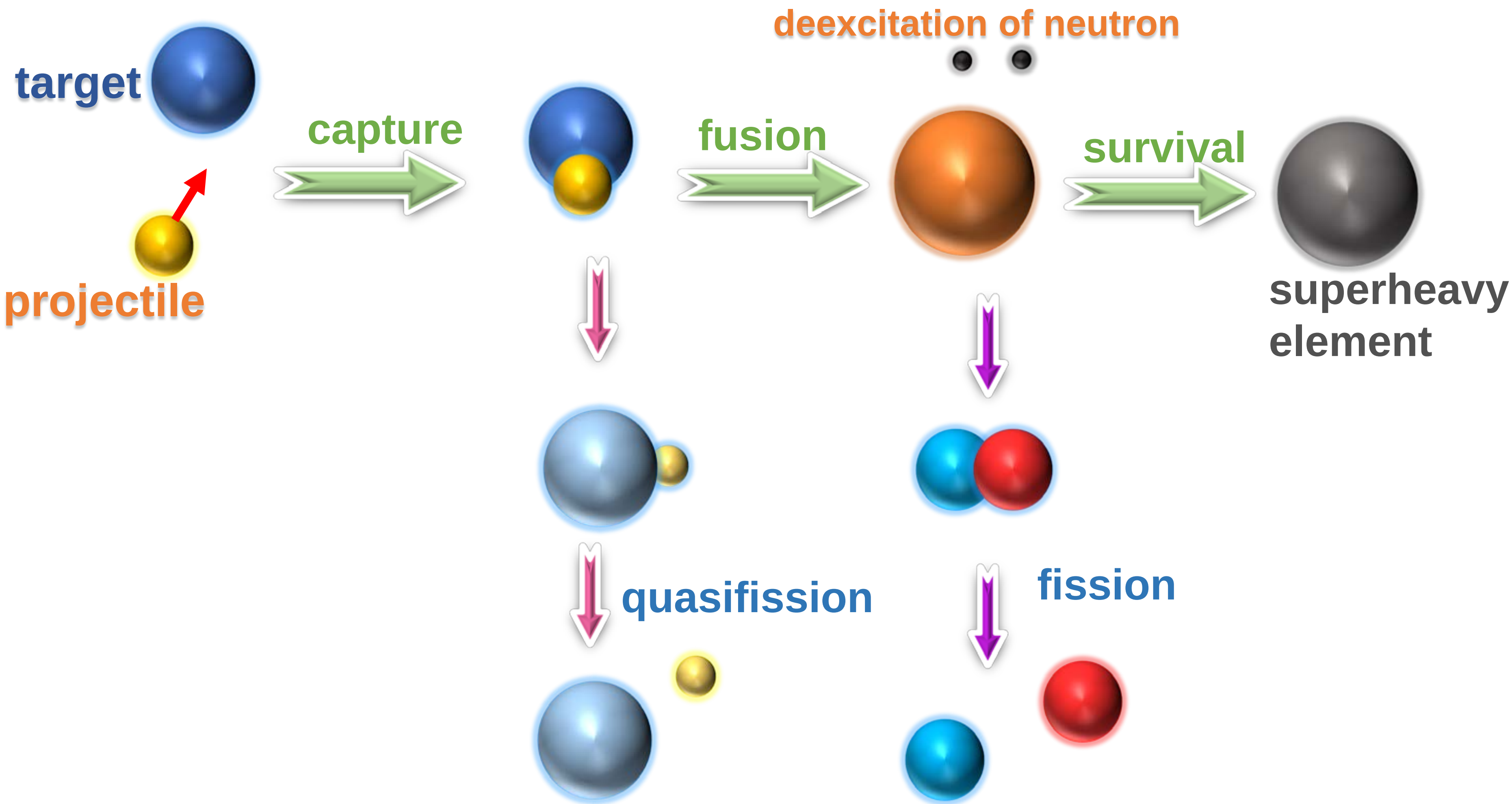


the time for quasifission ~10^{-20}s, fusion-fission ~10^{-20} ~10^{-16}s

Quasifission is the primary mechanism to prevent the formation of superheavy elements.

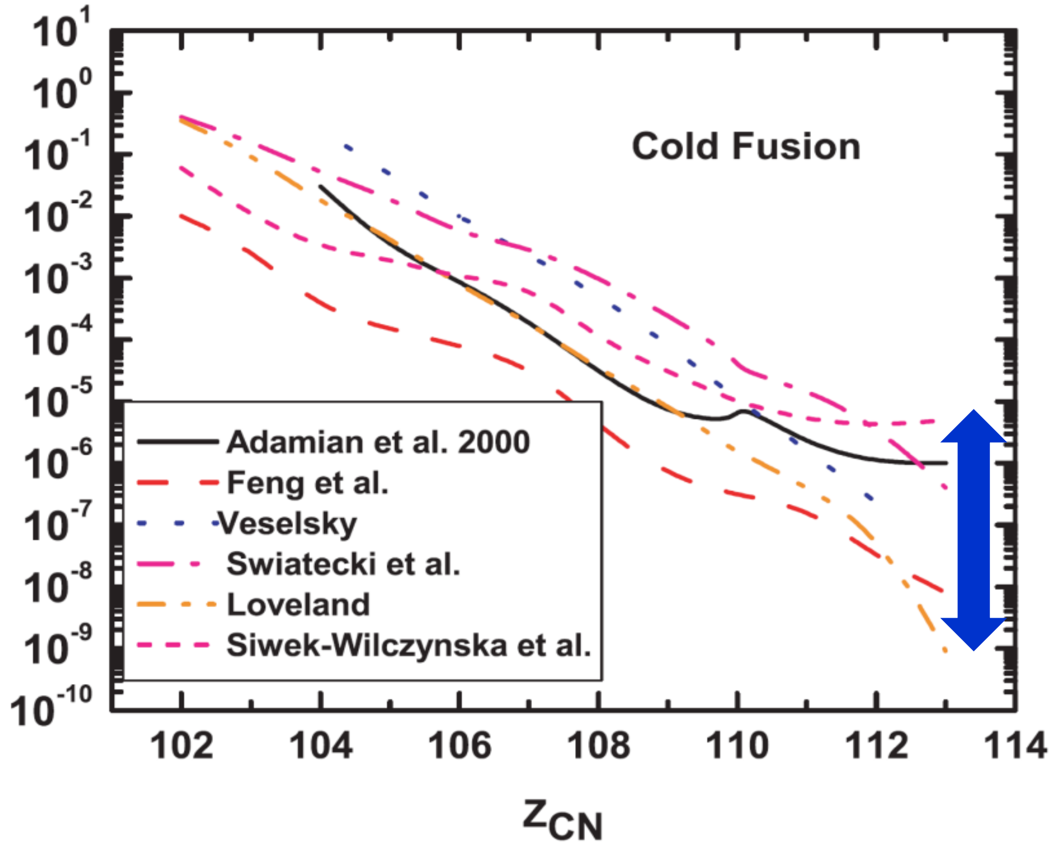
HIC with heavy nuclei



$$\sigma_{\mathrm{EVR}} = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{capture}}(E_{\mathrm{c.m.}}, J) P_{\mathrm{CN}}(E^*, J) W_{\mathrm{sur}}(E^*, J)$$

Fusion probability

- Phenomenological model
  - DNS
  - Langevin-type equation
  - fusion by diffusion model
  - Grazing model
  - ......
- Microscopic model
  - QMD
  - TDHF
  - ......



- The P_{CN} given by phenomenological model is different by several order;
- The P_{CN} can't be measured directly in experiments;
- Microscopic model would be better;

Time-dependent Hartree-Fock theory

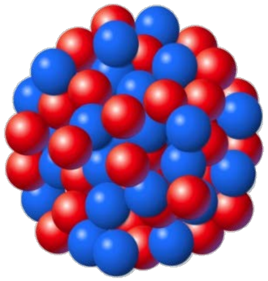
time-dependent Hartree-Fock (TDHF) theory

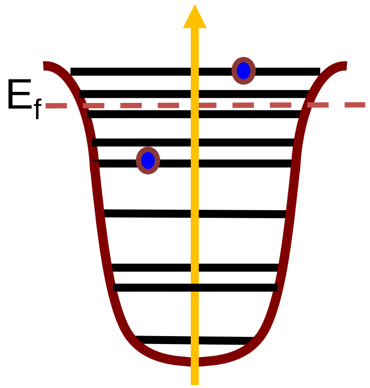
$$S = \int_{t_1}^{t_2} \langle \Psi(t) | H - i\hbar\partial_t | \Psi(t) \rangle \, dt,$$

$$H = \sum_{i=1}^{A} t_i + \sum_{i<j}^{A} v_{ij}$$

$$\Psi(\mathrm{r}_1, r_2, \cdots, r_A, t) = \frac{1}{\sqrt{A!}} \det |\varphi_\lambda(r_i, \mathrm{t})|,$$

$$i\hbar \frac{\partial \varphi_\lambda}{\partial t} = h\varphi_\lambda$$





Advantages:

- **Fully microscopic, parameter-free theory in heavy-ion collisions;**
- **Nuclear structure and reactions in a unified framework (same EDF);**
- **Dynamical and quantum effects are automatically incorporated**;

Limitations:

- **Only one-body dissipation;**
- **tunneling effect is missing;**

TDHF EDF in fusion dynamics

☐ Energy density functional (EDF)

Both time-even and time-odd EDF have been included

$$\mathcal{H} = \mathcal{H}_0 + \sum_{\mathrm{t}=0,1} \Big\{ A_{\mathrm{t}}^{\mathrm{s}} \mathbf{s}_{\mathrm{t}}^2 + \left(A_{\mathrm{t}}^{\Delta \mathrm{s}} + B_{\mathrm{t}}^{\Delta \mathrm{s}} \right) \mathbf{s}_{\mathrm{t}} \cdot \Delta \mathbf{s}_t + B_t^{\nabla s} (\nabla \cdot \mathbf{s}_t)^2$$

$$+ (A_{\mathrm{t}}^{\mathrm{T}} + B_{\mathrm{t}}^{\mathrm{T}}) \Big(\mathbf{s}_{\mathrm{t}} \cdot \mathbf{T}_{\mathrm{t}} - \sum_{\mu,\nu=x}^{z} J_{\mathrm{t},\mu\nu} J_{\mathrm{t},\mu\nu} \Big)$$

$$+ B_t^F \Big[\mathbf{s}_t \cdot \mathbf{F}_t - \frac{1}{2} \Big(\sum_{\mu=x}^{z} J_{t,\mu\mu} \Big)^2 - \frac{1}{2} \sum_{\mu,\nu=x}^{z} J_{t,\mu\nu} J_{t,\nu\mu} \Big] \Big\},$$

H_0 is basic functional used in Sky3D code and most TDHF calculations

$$\mathcal{H}_0 = \sum_{\mathrm{t}=0,1} \Big\{ A_{\mathrm{t}}^{\rho} \rho_{\mathrm{t}}^2 + A_{\mathrm{t}}^{\Delta\rho} \rho_{\mathrm{t}} \Delta \rho_{\mathrm{t}} + A_{\mathrm{t}}^{\tau} \left(\rho_{\mathrm{t}} \tau_{\mathrm{t}} - \mathbf{j}_{\mathrm{t}}^2 \right)$$

$$+ A_{\mathrm{t}}^{\nabla J} \rho_{\mathrm{t}} \nabla \cdot \mathbf{J}_{\mathrm{t}} + A_{\mathrm{t}}^{\nabla J} \mathbf{s}_{\mathrm{t}} \cdot \nabla \times \mathbf{j}_{\mathrm{t}} \Big\}.$$

Quasifission dynamics in experiments

PRL 113, 182502 (2014) PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 20

Interplay between Quantum Shells and Orientation in Quasifission

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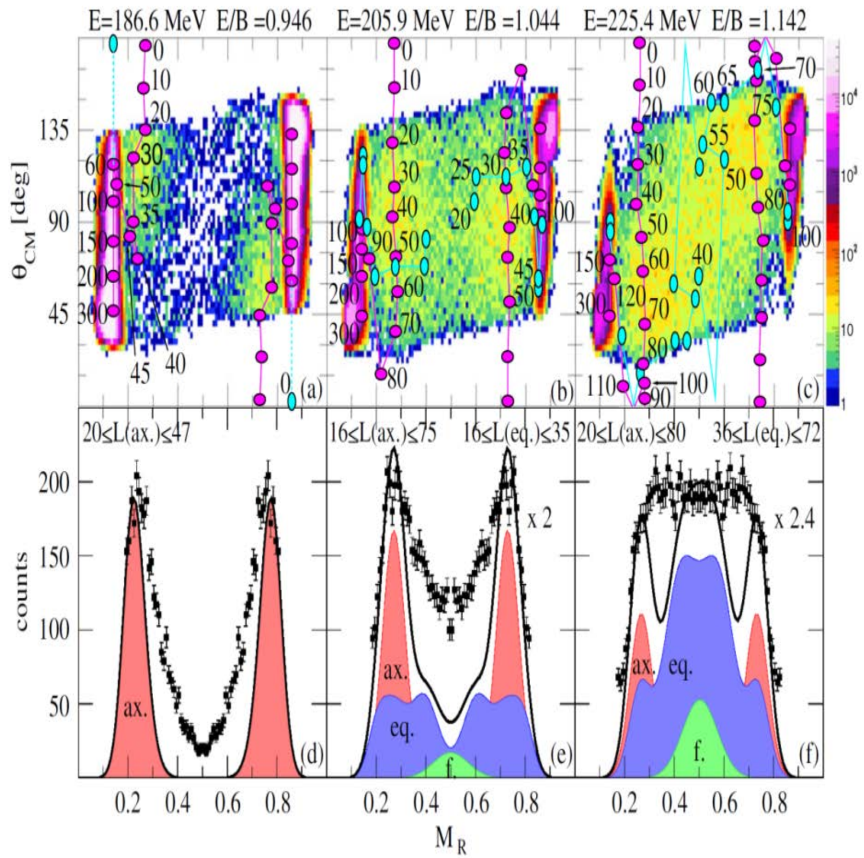
(Received 22 June 2014; revised manuscript received 21 August 2014; published 28 October 2014)

The quasifission mechanism hinders fusion in heavy systems through breakup within zeptoseconds into two fragments with partial mass equilibration. Its dependence on the structure of both the collision partners and the final fragments is a key question. Our original approach is to combine an experimental measurement of the fragments' mass-angle correlations in $^{40}Ca + ^{238}U$ with microscopic quantum calculations. We demonstrate an unexpected interplay between the orientation of the prolate deformed ^{238}U with quantum shell effects in the fragments. In particular, calculations show that only collisions with the tip of ^{238}U produce quasifission fragments in the magic $Z = 82$ region, while collisions with the side are the only ones that may result in fusion.



- An experiment measure the fragment's mass-angle correlations in $^{40,48}Ca + ^{238}U$;
- The studies show an unexpected interplay between the orientation of the prolate deformed ^{238}U with quantum shell effects.

Quasifission dynamics in experiments

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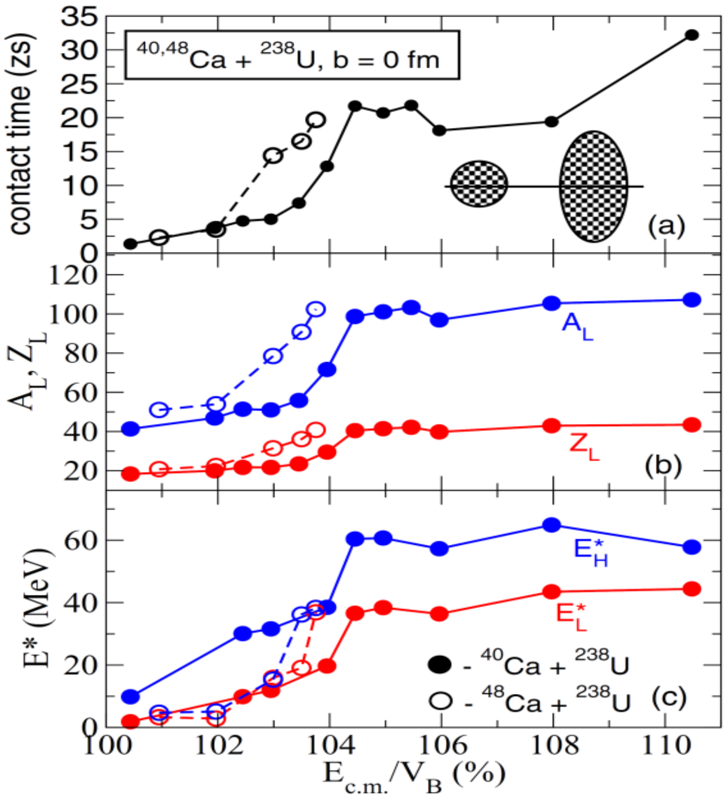

- An experiment measure the fragment's mass-angle correlations in $^{40,48}Ca + ^{238}U$;
- TDHF calculations show that for ^{48}Ca projectiles the quasifission is substantially reduced in comparison to the ^{40}Ca case. This partly explains the success of superheavy element formation with ^{48}Ca beams;

Contents

Experimental Synthesis of SHE 114

PHYSICAL REVIEW C **69**, 054607 (2004)

Measurements of cross sections for the fusion-evaporation reactions $^{244}Pu(^{48}Ca,xn)^{292-x}114$ and $^{245}Cm(^{48}Ca,xn)^{293-x}116$

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Joint Institute for Nuclear Research, 141980 Dubna, Russian Federation

J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, D. A. Shaughnessy, J. M. Kenneally, and R. W. Lougheed

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PRL **105,** 182701 (2010) PHYSICAL REVIEW LETTERS week ending 29 OCTOBER 2010

New Superheavy Element Isotopes: $^{242}Pu(^{48}Ca, 5n)^{285}114$

P. A. Ellison,[1,2] K. E. Gregorich,[2] J. S. Berryman,[2] D. L. Bleuel,[3] R. M. Clark,[2] I. Dragojević,[2] J. Dvorak,[4] P. Fallon,[2] C. Fineman-Sotomayor,[1,2] J. M. Gates,[2] O. R. Gothe,[1,2] I. Y. Lee,[2] W. D. Loveland,[5] J. P. McLaughlin,[1,2] S. Paschalis,[2] M. Petri,[2] J. Qian,[2] L. Stavsetra,[6] M. Wiedeking,[3] and H. Nitsche[1,2]

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Experimental Synthesis of SHE 114

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PHYSICAL REVIEW C **92**, 034609 (2015)

Experiments on the synthesis of superheavy nuclei ^{284}Fl and ^{285}Fl in the $^{239,240}Pu + ^{48}Ca$ reactions

V. K. Utyonkov,[1,*] N. T. Brewer,[2] Yu. Ts. Oganessian,[1] K. P. Rykaczewski,[2] F. Sh. Abdullin,[1] S. N. Dmitriev,[1] R. K. Grzywacz,[2,3] M. G. Itkis,[1] K. Miernik,[2,4] A. N. Polyakov,[1] J. B. Roberto,[5] R. N. Sagaidak,[1] I. V. Shirokovsky,[1] M. V. Shumeiko,[1] Yu. S. Tsyganov,[1] A. A. Voinov,[1] V. G. Subbotin,[1] A. M. Sukhov,[1] A. V. Sabel'nikov,[1] G. K. Vostokin,[1] J. H. Hamilton,[6] M. A. Stoyer,[7] and S. Y. Strauss[8]

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Experimental Synthesis of SHE 114

PHYSICAL REVIEW C **92**, 034609 (2015)

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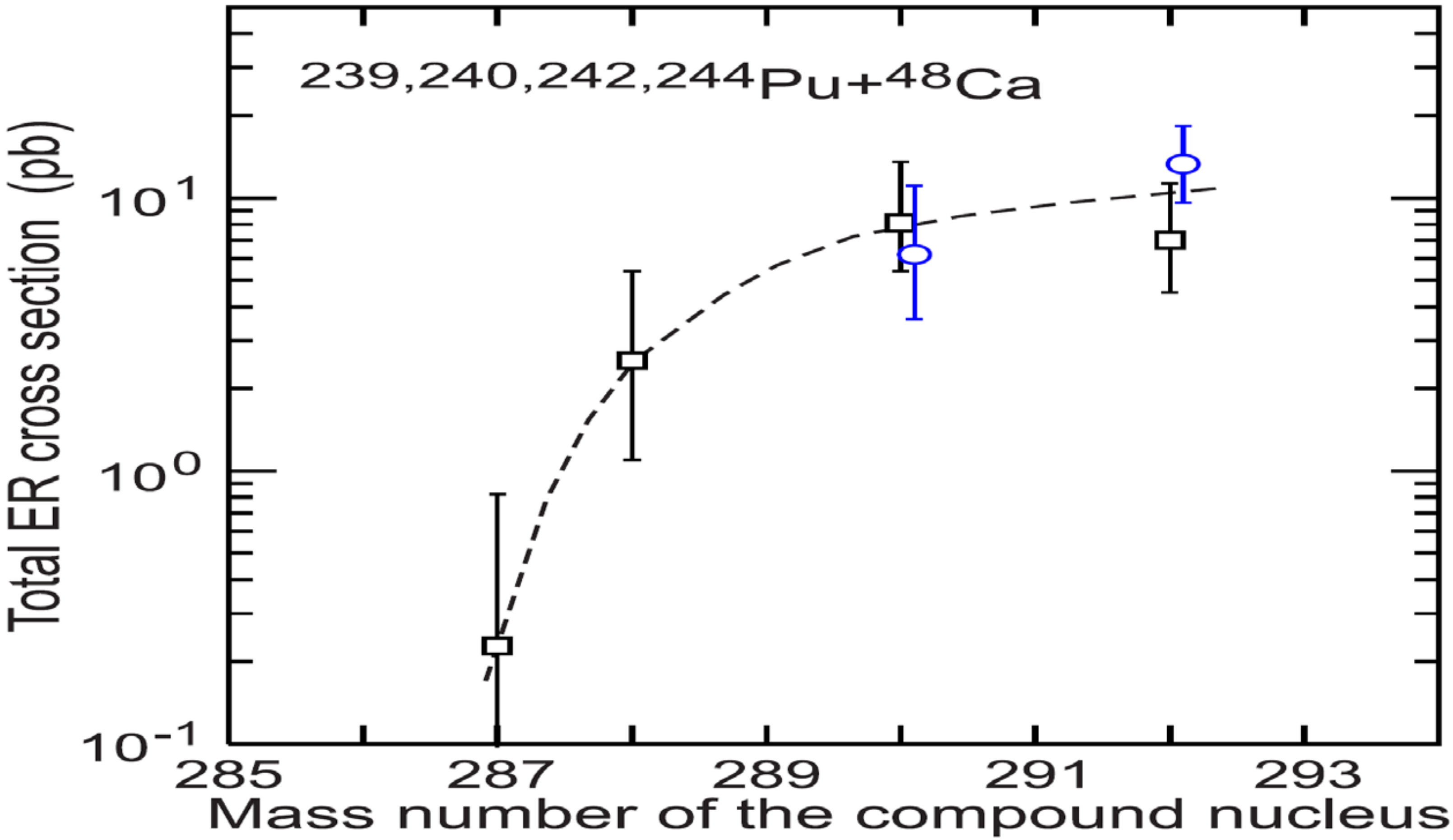
Irradiations of ^{239}Pu and ^{240}Pu targets with ^{48}Ca beams aimed at the synthesis of $Z = 114$ flerovium isotopes were performed at the Dubna Gas Filled Recoil Separator. A new spontaneously fissioning (SF) isotope ^{284}Fl was produced for the first time in the ^{240}Pu + ^{48}Ca (250 MeV) and ^{239}Pu + ^{48}Ca (245 MeV) reactions. The cross section of the ^{239}Pu(^{48}Ca,3n)^{284}Fl reaction channel was about 20 times lower than predicted by theoretical models and about 50 times lower than the maximum fusion-evaporation cross section for the 3n and 4n channels measured in the ^{244}Pu + ^{48}Ca reaction. In the ^{240}Pu + ^{48}Ca experiment, performed at 245 MeV in order to maximize the 3n-evaporation channel, three decay chains of ^{285}Fl were detected. The α-decay energy of ^{285}Fl

Experimental Synthesis of SHE 114



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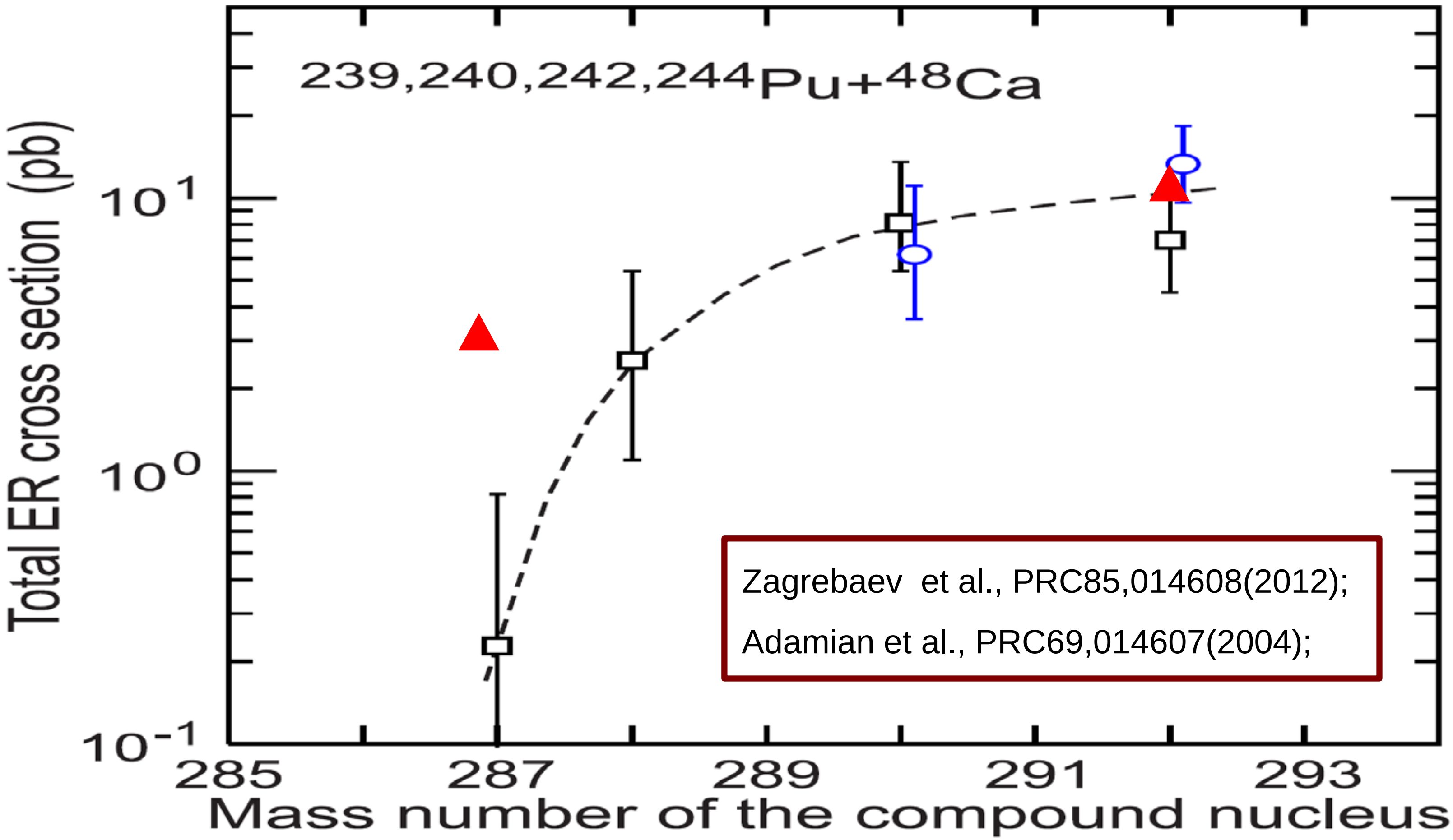

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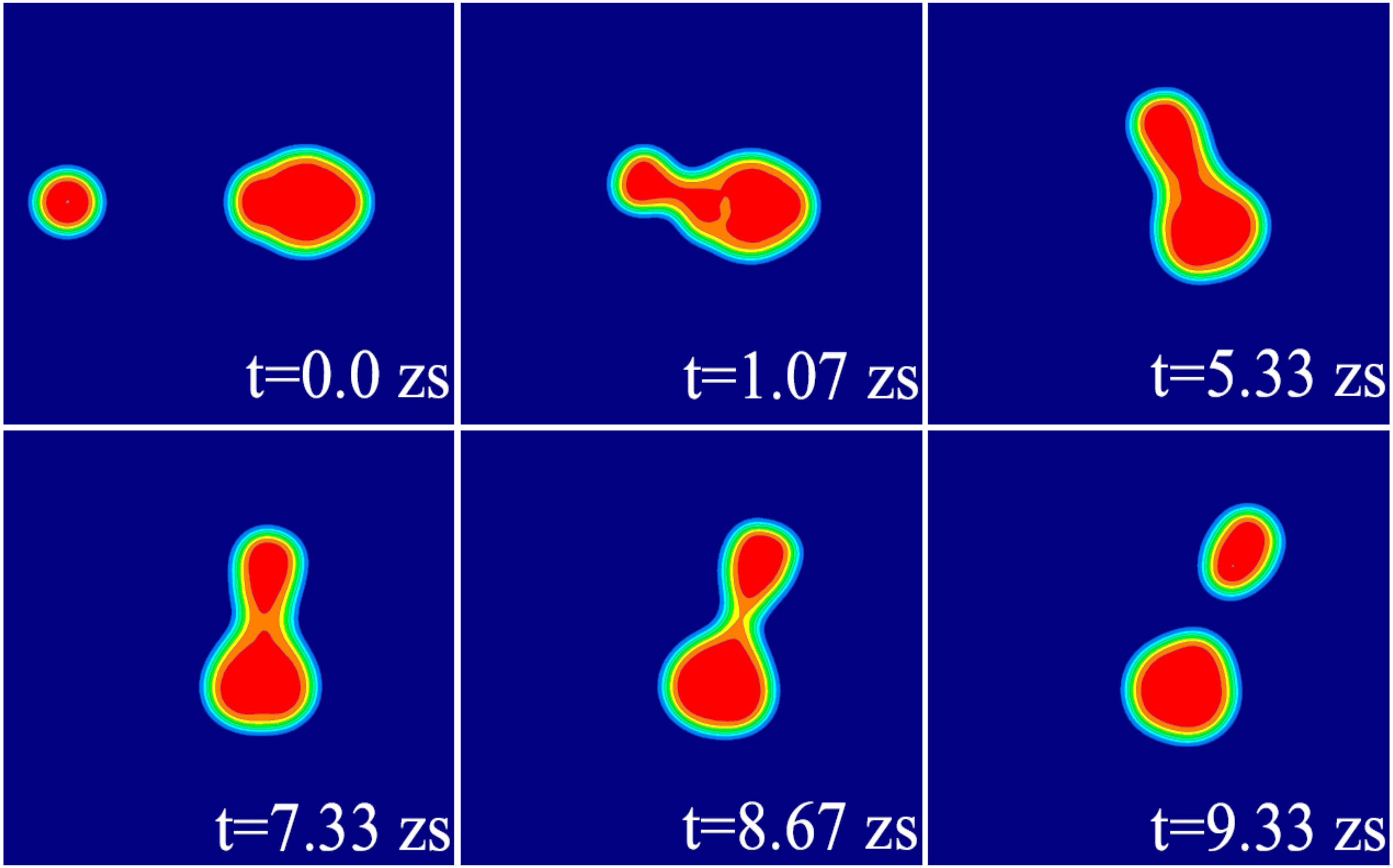
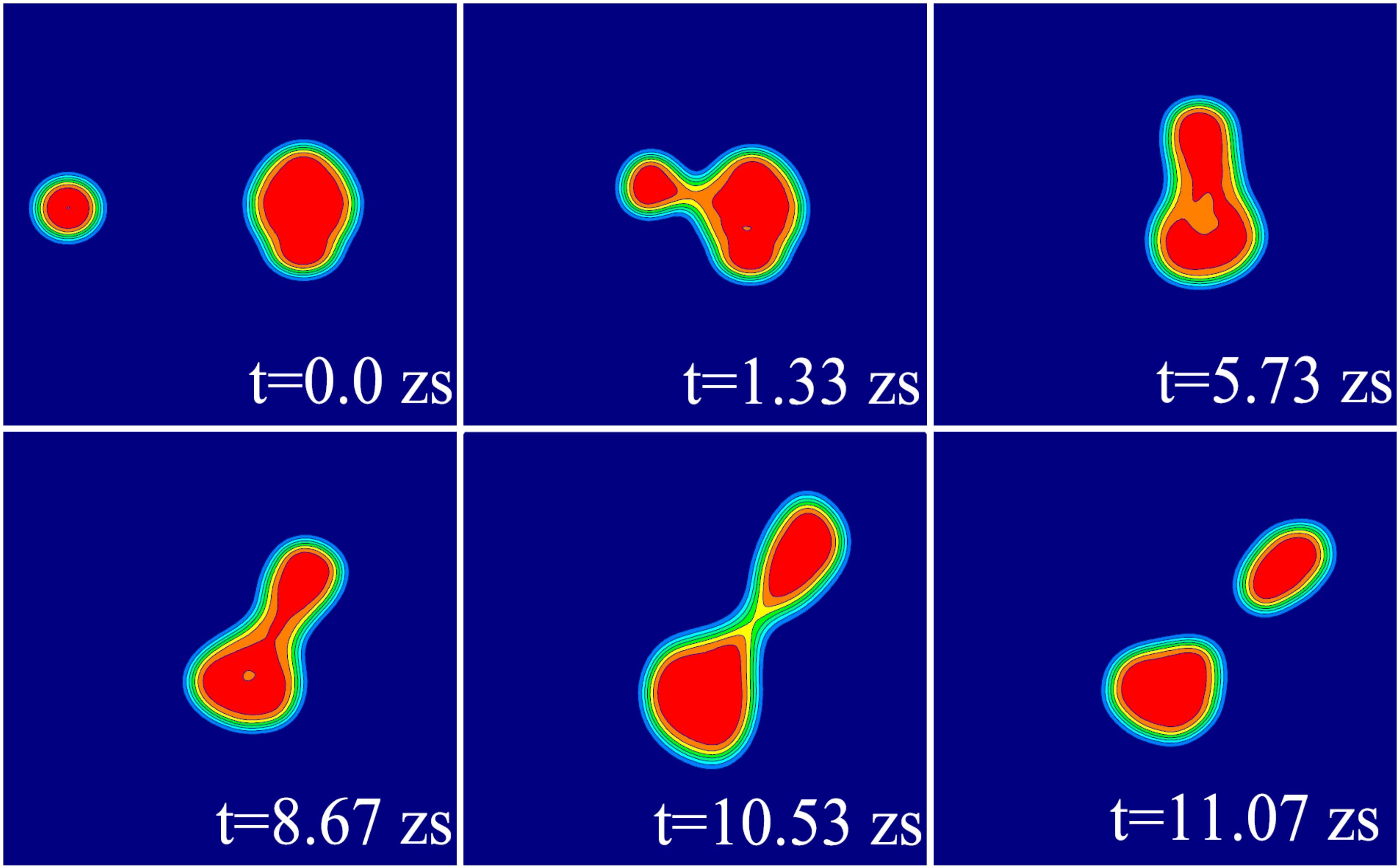
TDHF studies of fusion and quasifission

$^{48}Ca + ^{239}Pu$ with E_{cm}=204.02 MeV, b=2.5 fm



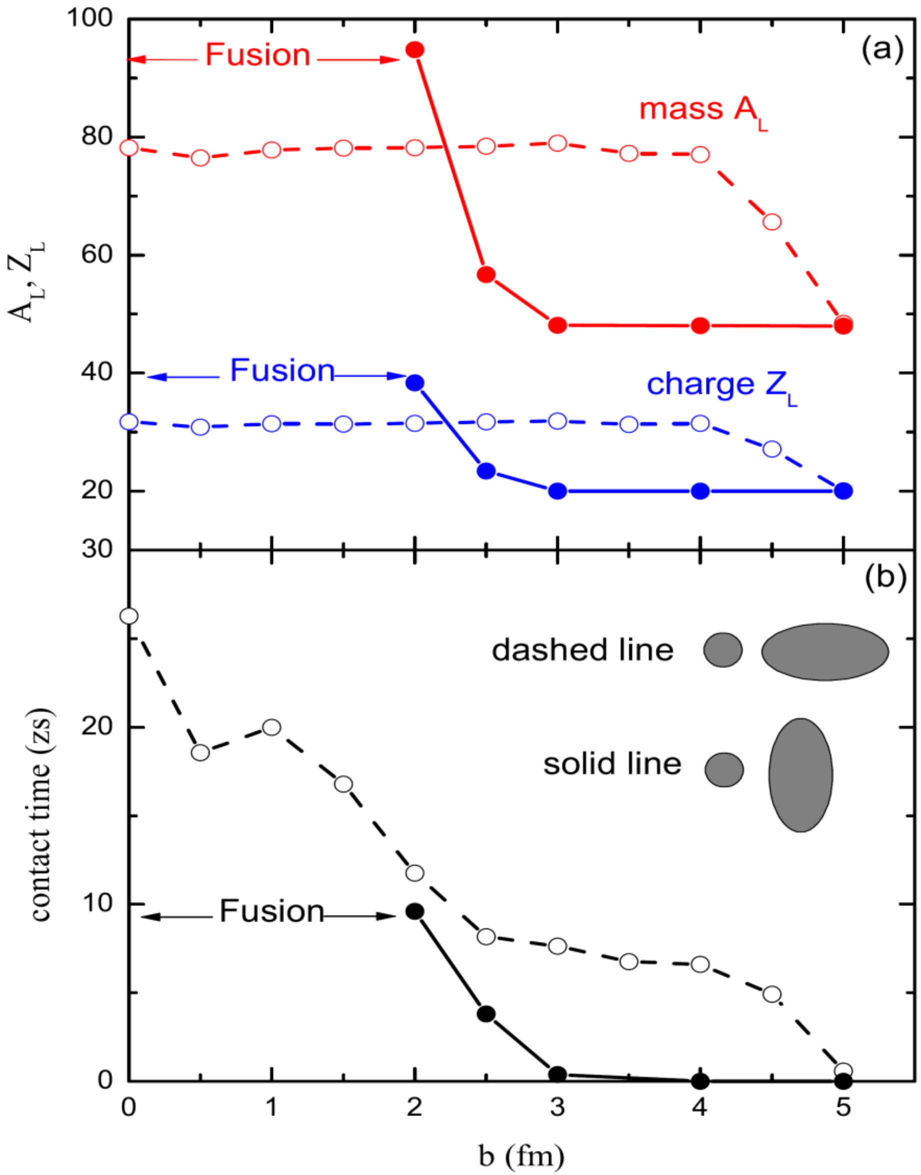
TDHF studies of fusion and quasifission

$^{48}Ca+^{244}Pu$ with E_{cm}=216.76 MeV, b=2.0 fm



TDHF studies of fusion and quasifission

$^{48}Ca+^{239}Pu$



(1) Collisions with the tip of ^{239}Pu produce quasifission fragments, while collisions with the side result in fusion;

(2) contact time decreases as b;

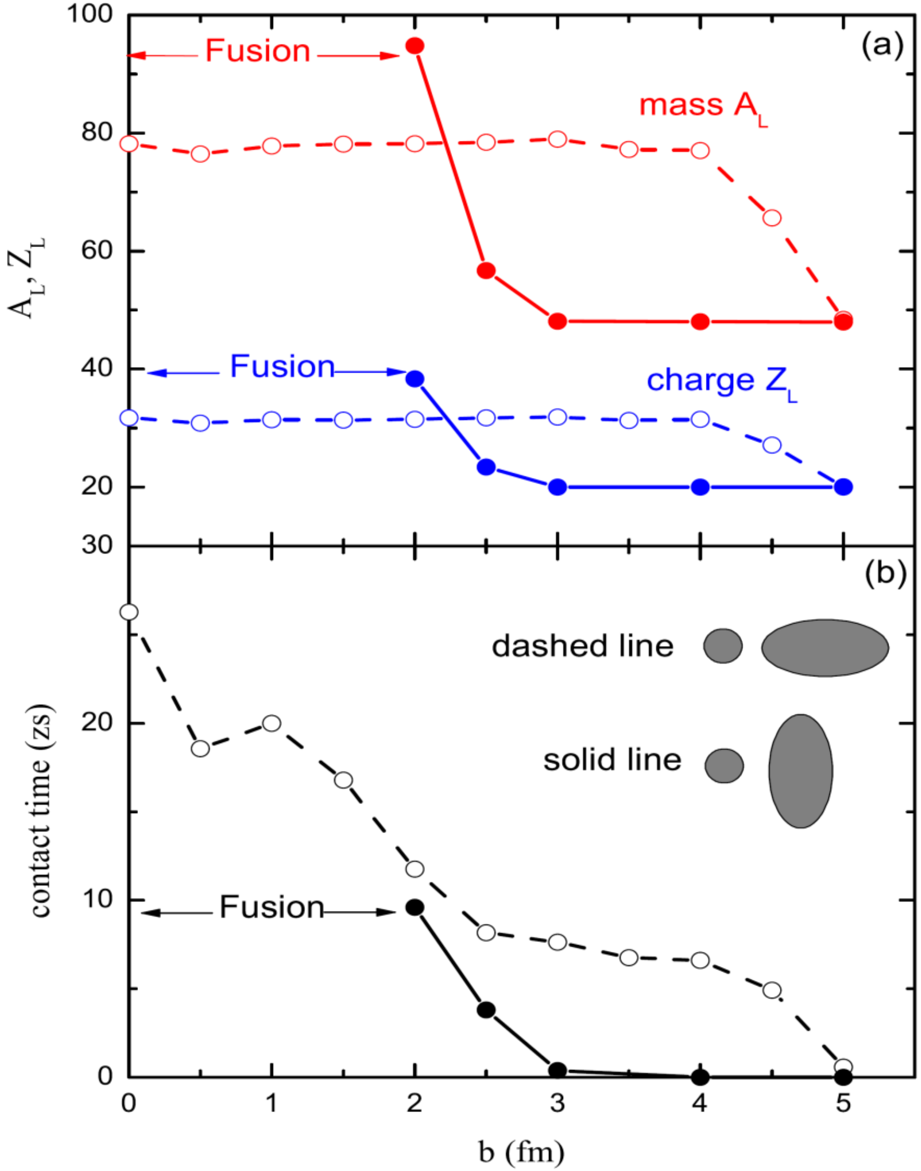
(3) tip: $_{32}Ge+_{82}Pb$

side: $_{40}Zr+_{74}W$;

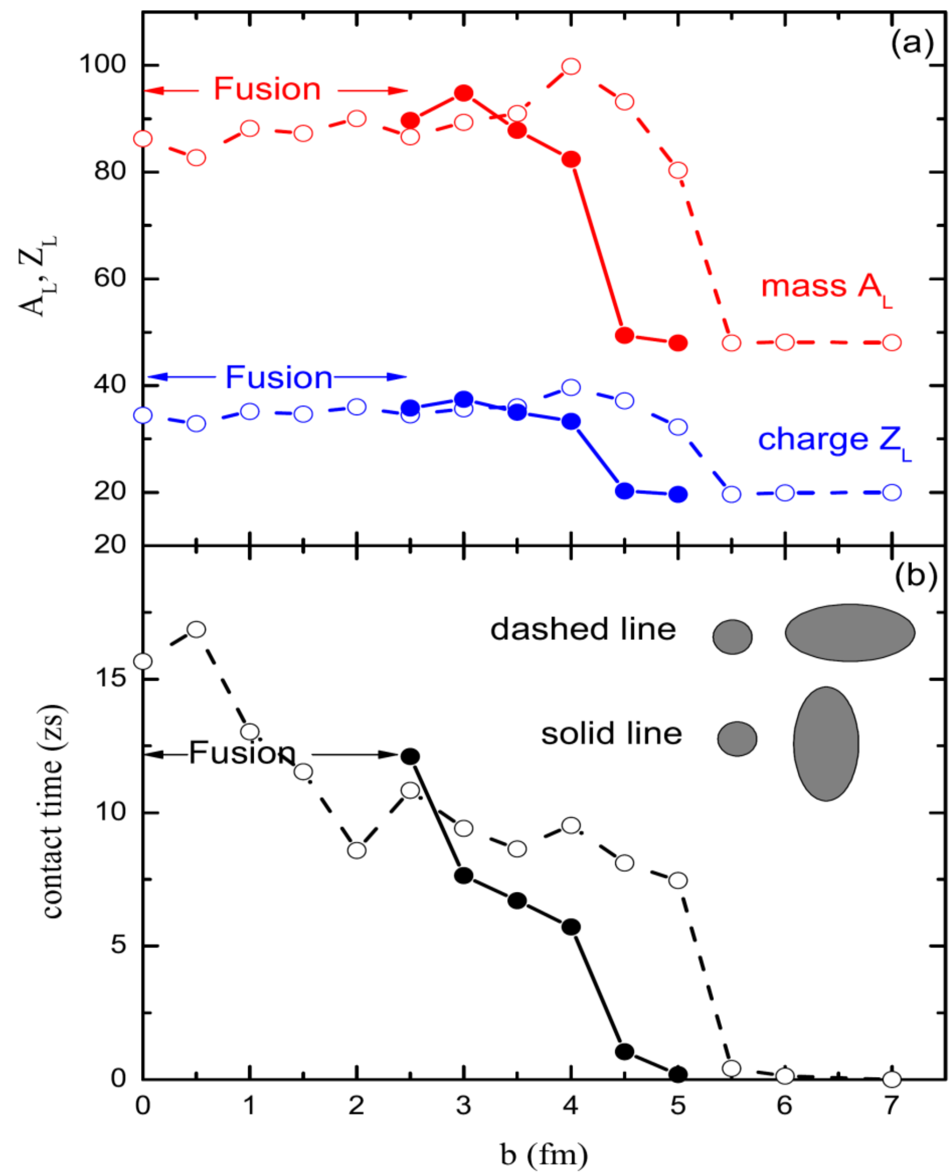
(4) The interplay between quantum shell effect and orientation of deformed nuclei;

TDHF studies of fusion and quasifission

$^{48}Ca+^{239}Pu$



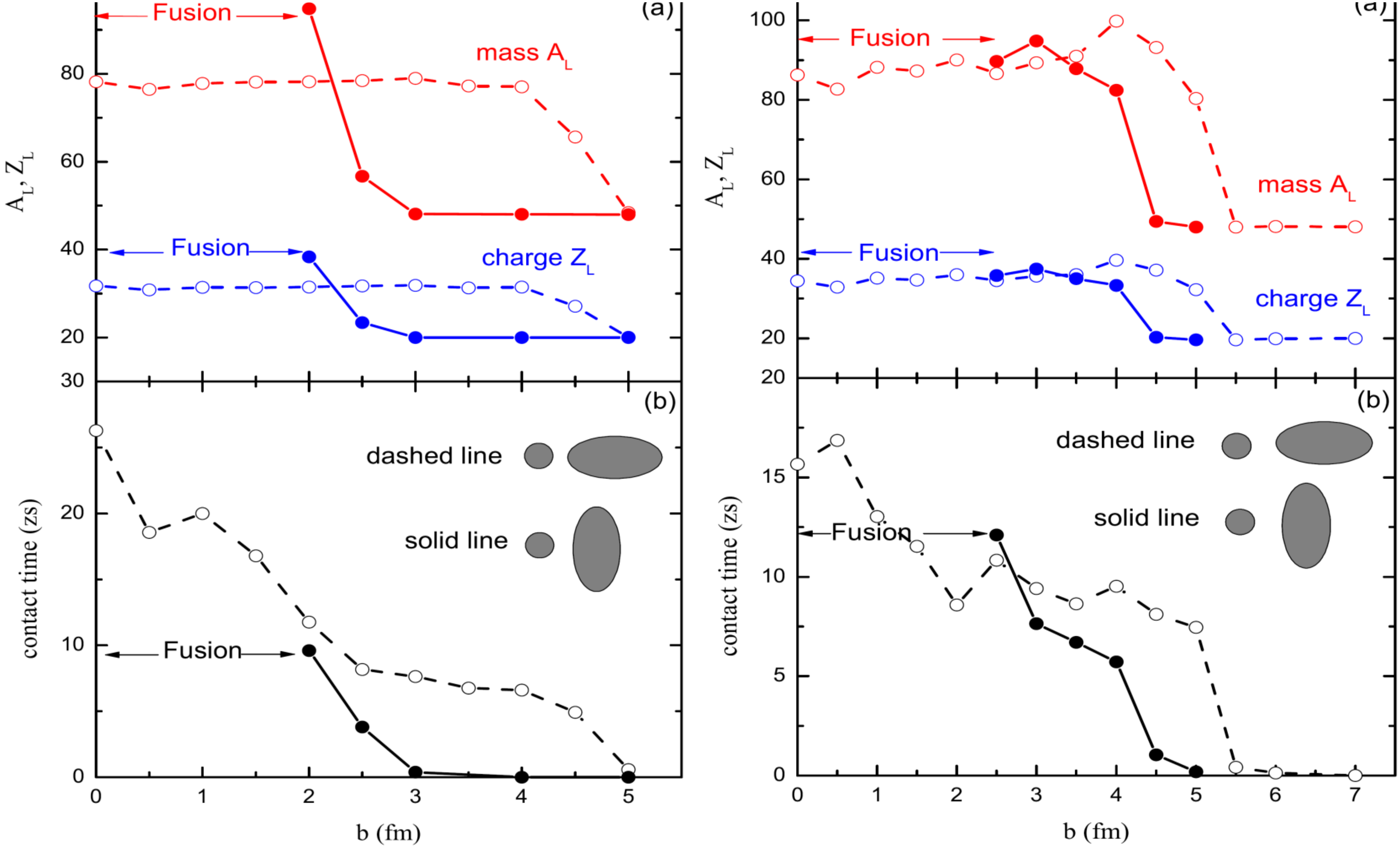
$^{48}Ca+^{244}Pu$



(1) The collision $^{48}Ca+^{239}Pu$is much easier to happen quasifission than $^{48}Ca+^{244}Pu$ (experiment),

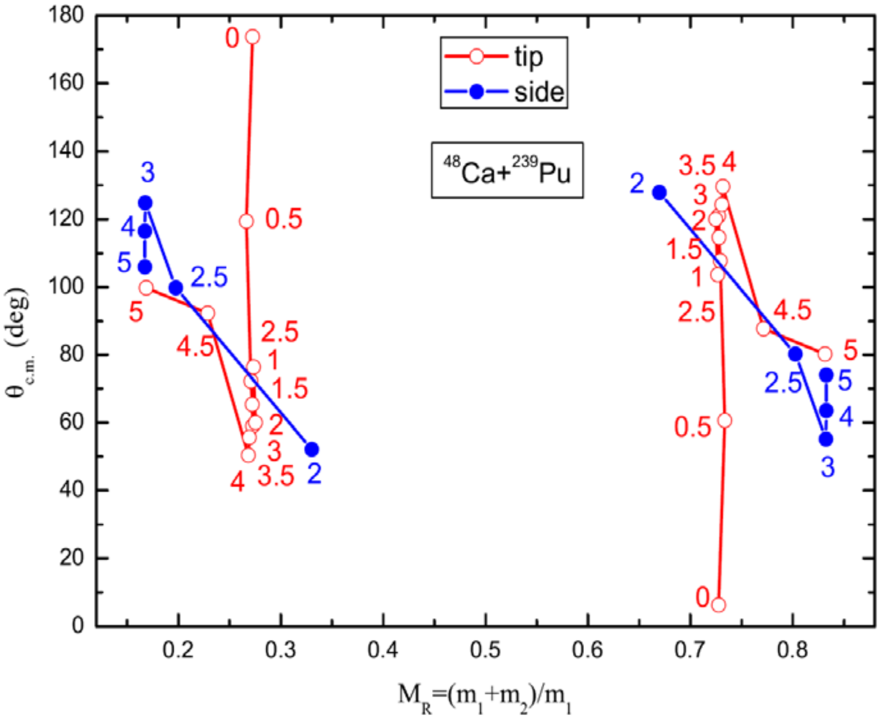
(2) More neutron-rich target nucleus will be helpful in the production of SHE(ANU experiments);

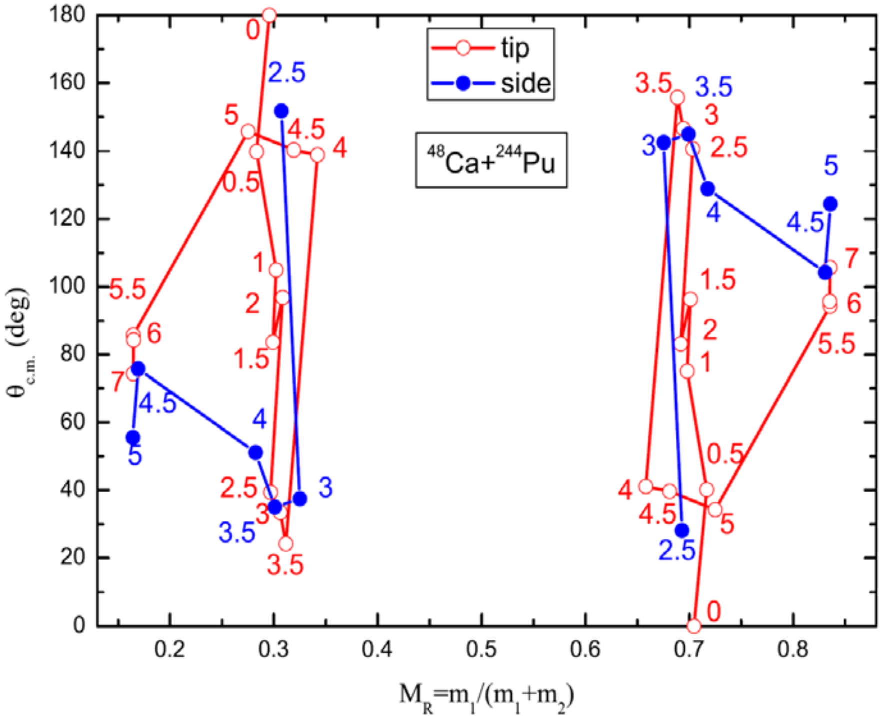
(3) $P_{CN}=\sigma_{fus}/\sigma_{cap}$, P_{CN}=0.2 2($^{48}Ca+^{244}Pu$), P_{CN}=0.14 ($^{48}Ca+^{239}Pu$)---side (first microscopic P_{CN});



TDHF studies of fusion and quasifission

Mass-angle distribution: directly measured by experiments

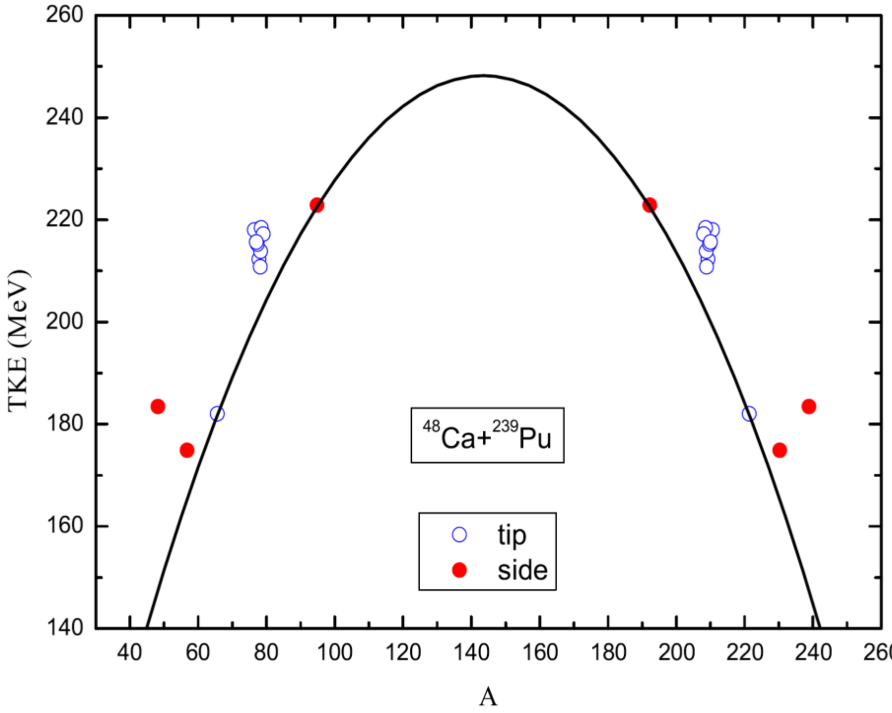


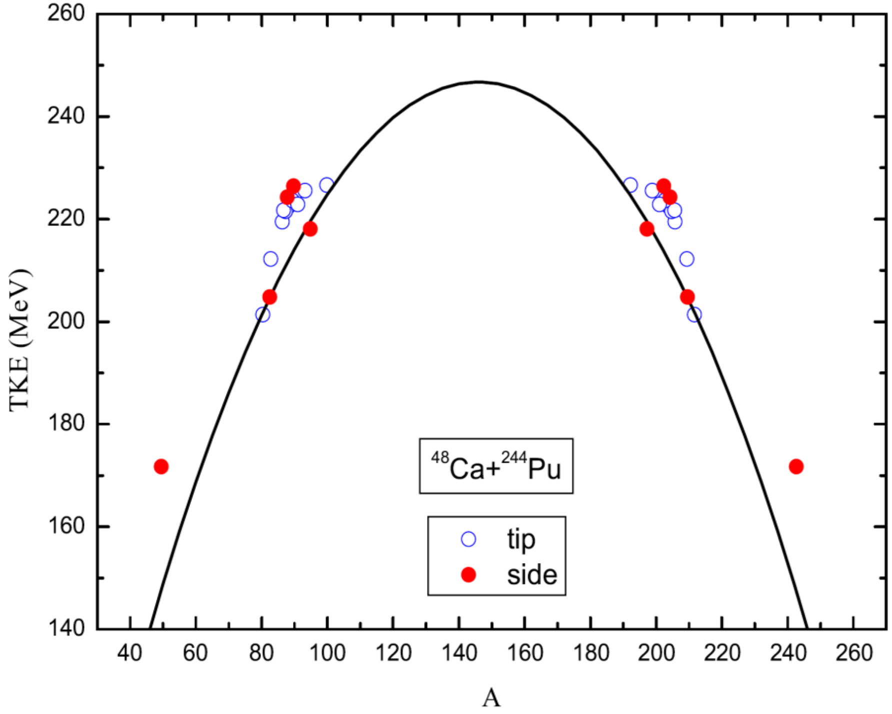


$$\theta = \theta_{in} + \theta_{TDHF} + \theta_{out}$$

TDHF studies of fusion and quasifission

Mass-kinetic distribution: directly measured by experiments





Systematic agreement with the Viola formula;

Quasifission dynamics is a fully damped motion;

Contents

Multi-nucleon transfer reaction

The experiments via multi-nucleon transfer reaction to produce neutron-rich heavy nuclei

PHYSICAL REVIEW C **91**, 064615 (2015)

^{136}Xe + ^{208}Pb reaction: A test of models of multinucleon transfer reactions

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(Received 29 February 2015; published 22 June 2015)

美国Argone

The yields of over 200 projectile-like fragments (PLFs) and target-like fragments (TLFs) from the interaction ($E_{c.m.}$ = 450 MeV) ^{136}Xe with a thick target of ^{208}Pb were measured using Gammasphere and off-line γ-ray

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Three-Particle Exclusive Measurements of the Reactions ^{238}U + ^{238}U and ^{238}U + ^{248}Cm

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PHYSICAL REVIEW C **88**, 054615 (2013)

Reexamining the heavy-ion reactions ^{238}U + ^{238}U and ^{238}U + ^{248}Cm and actinide production close to the barrier

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德国GSI

Recent theoretical work has renewed interest in radiochemically determined isotope distributions in reactions of ^{238}U projectiles with heavy targets that had previously been published only in parts. These data are being reexam-

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Pathway for the Production of Neutron-Rich Isotopes around the $N = 126$ Shell Closure

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日本KEK

Absolute cross sections for isotopically identified products formed in multinucleon transfer in the ^{136}Xe + ^{198}Pt system at ~8 MeV/nucleon are reported. The isotopic distributions obtained using a large

PHYSICAL REVIEW C **86**, 044611 (2012)

Mass distributions of the system ^{136}Xe + ^{208}Pb at laboratory energies around the Coulomb barr A candidate reaction for the production of neutron-rich nuclei at $N = 126$

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俄罗斯DUBNA

Reaction products from the system ^{136}Xe + ^{208}Pb at ^{136}Xe-ions laboratory energies of 700, 870, and 1020 MeV were studied by two-body kinematics and by a catcher-foil activity analysis to explore the theoretically proposed suitability of such reaction as a means to produce neutron-rich nuclei in the neutron shell closure $N = 126$. Cross

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Revisiting the symmetric reactions for synthesis of super-heavy nuclei of $Z \geqslant 120$

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A B S T R A C T

Extensive efforts have been made experimentally to reach nuclei in the super-heavy mass region of $Z = 110$ and above with suitable choices of projectile and target nuclei. The cross sections for production of these nuclei are seen to be in the range of a few picobarn or less, and pose great experimental challenges. Theoretically, there have been extensive calculations for highly asymmetric (hot-fusion) and moderately asymmetric (cold-fusion) collisions and only a few theoretical studies are available for near-symmetric collisions to estimate the cross sections for production of super-heavy nuclei. In the present article, we revisit the symmetric heavy ion reactions with suitable combinations of projectile and target nuclei in the rare-earth region, that will lead to super-heavy nuclei of $Z \geqslant 120$ with measurable fusion cross sections.

$$^{154}\text{Sm} + {}^{150}\text{Nd} \rightarrow 122$$

$$^{154}\text{Sm} + {}^{154}\text{Sm} \rightarrow 124$$

fusion diffusion model

$\sigma \sim 0.6$ pb

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ELSEVIER

No chance for synthesis of super-heavy nuclei in fusion of symmetric systems

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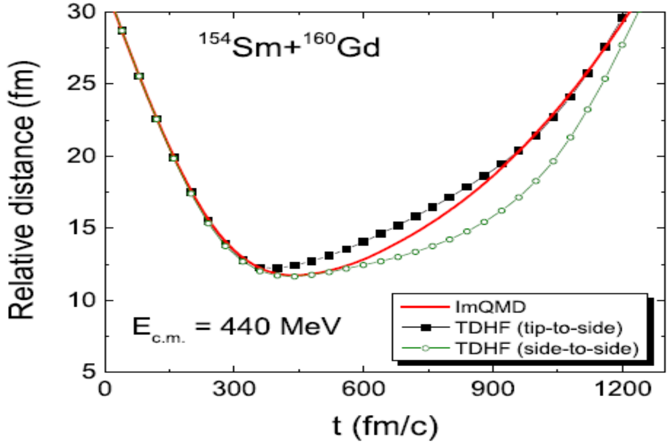
Predictions of relatively large cross sections (of about 1 picobarn) for synthesis of super heavy nuclei of $Z = 122$ and $Z = 124$ in cold fusion (1n) reactions of symmetric ^{154}Sm + ^{150}Nd and ^{154}Sm + ^{154}Sm systems by R.K. Choudhury and Y.K. Gupta (2014) [1] are examined. The authors state that this result had been obtained by using the fusion-by-diffusion (FBD) model. As predictions of the original FBD model of Swiatecki, Cap, Siwek-Wilczyńska and Wilczyński had been definitely pessimistic regarding fusion of more symmetric systems (in comparison with equivalent asymmetric systems), we feel compelled to present excitation functions of the ^{154}Sm(^{150}Nd, 1n)^{303}122 and ^{154}Sm(^{154}Sm, 1n)^{307}124 reactions, calculated within the original fusion-by-diffusion model. In accordance with our earlier predictions of a general trend of fusion hindrance for near-symmetric systems, the cross sections for synthesis of ^{303}122 and ^{307}124 nuclides in fusion of these two symmetric systems are found to be extremely small and probably never reachable: about 10^{-11} pb and 10^{-13} pb, respectively. It is shown that Choudhury and Gupta obtained their results (overestimating the cross sections by 11 and 13 orders of magnitude) as an effect of an arbitrary and physically unjustified interference in the FBD model.

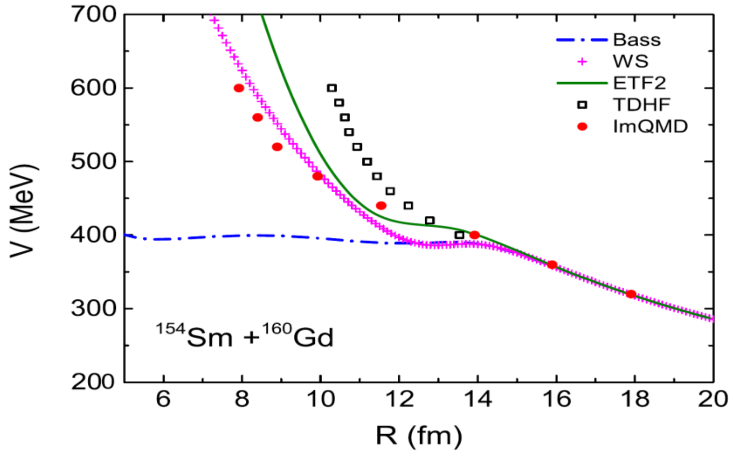
$\sigma \sim 10^{-13}$ pb

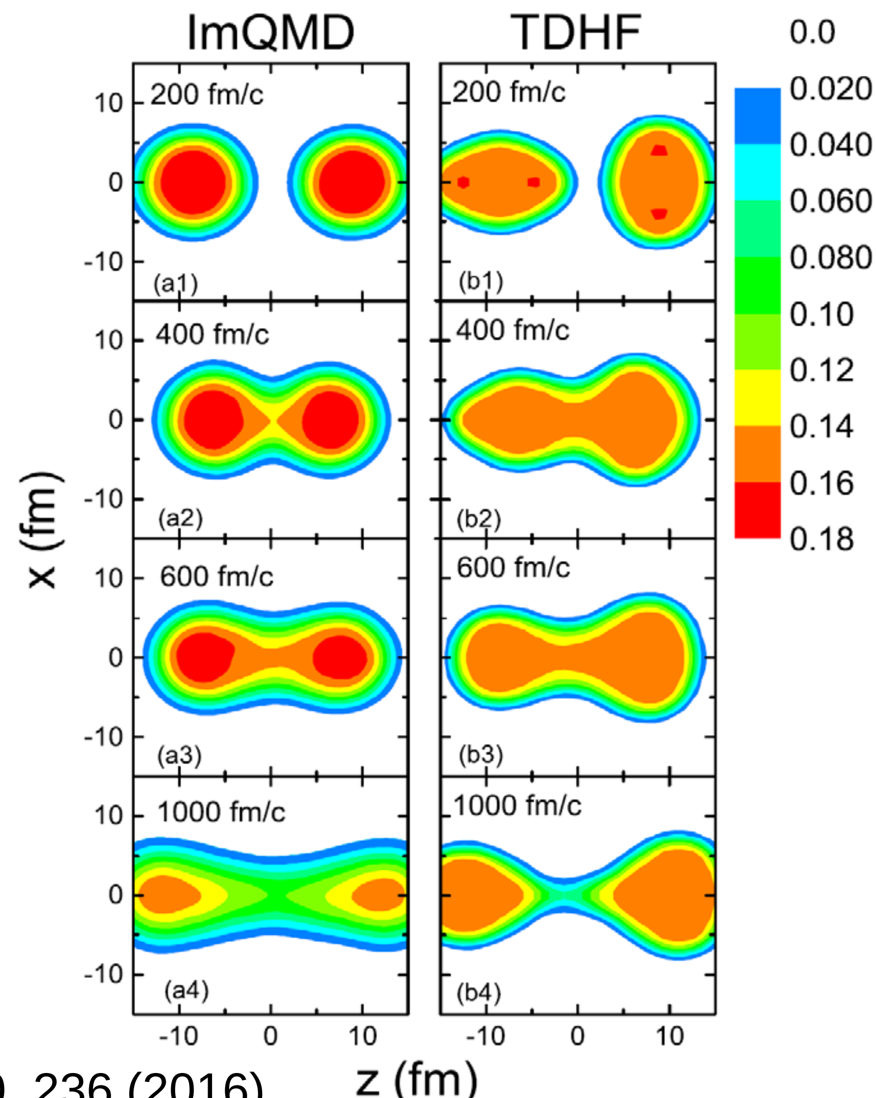
Neutron-rich isotopes production

◻ New neutron-rich isotope production via multi-nucleon transfer

$$^{154}\mathrm{Sm}+^{160}\mathrm{Gd}\ ?\!\to 126$$



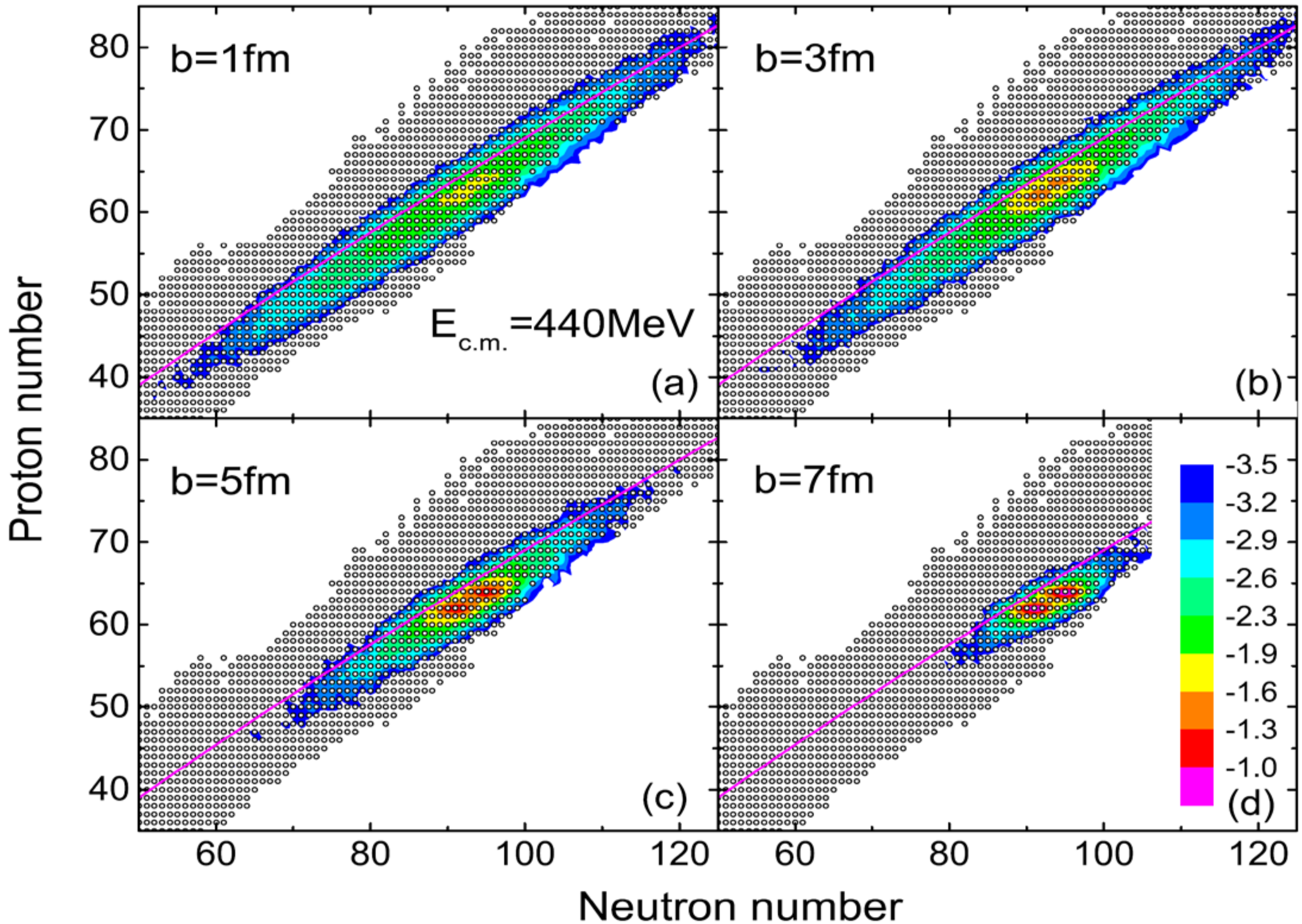




Ning Wang and Lu Guo, Phys. Lett. B760, 236 (2016).

Neutron-rich isotopes production

Isotope distribution at different impact parameters



Ning Wang and Lu Guo, Phys. Lett. B760, 236 (2016).

Summary

- Three-dimensional TDHF with full Skyrme functional and without any symmetry restrictions;
- The fusion and quasifission dynamics in $^{48}Ca+^{239}Pu$ and $^{48}Ca+^{244}Pu$; Our results qualitatively explains the experimental observations;
- Multi-nucleon transfer reactions produce the new neutron-rich nuclei;

Summary

- Three-dimensional TDHF with full Skyrme functional and without any symmetry restrictions;
- The fusion and quasifission dynamics in $^{48}Ca+^{239}Pu$ and $^{48}Ca+^{244}Pu$; Our results qualitatively explains the experimental observations;
- Multi-nucleon transfer reactions produce the new neutron-rich nuclei;

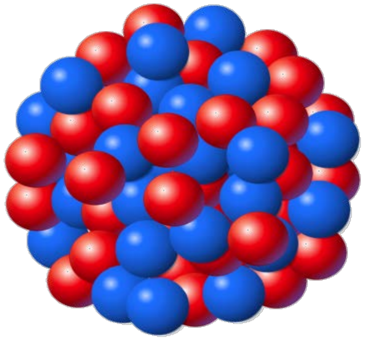
Thank you for your attention!

Quantum Molecular Dynamics Model

Quantum Molecular dynamics (QMD)

$$\phi_i(r) = \frac{1}{\left(2\pi\sigma_r^2\right)^{3/4}} \exp\left[-\frac{\left(r-r_i\right)^2}{4\sigma_r^2} + \frac{i}{\hbar} r \cdot p_i\right]$$

$$\dot{r}_i = \frac{\partial H}{\partial p_i}, \qquad \dot{P}_i = -\frac{\partial H}{\partial r_i}$$

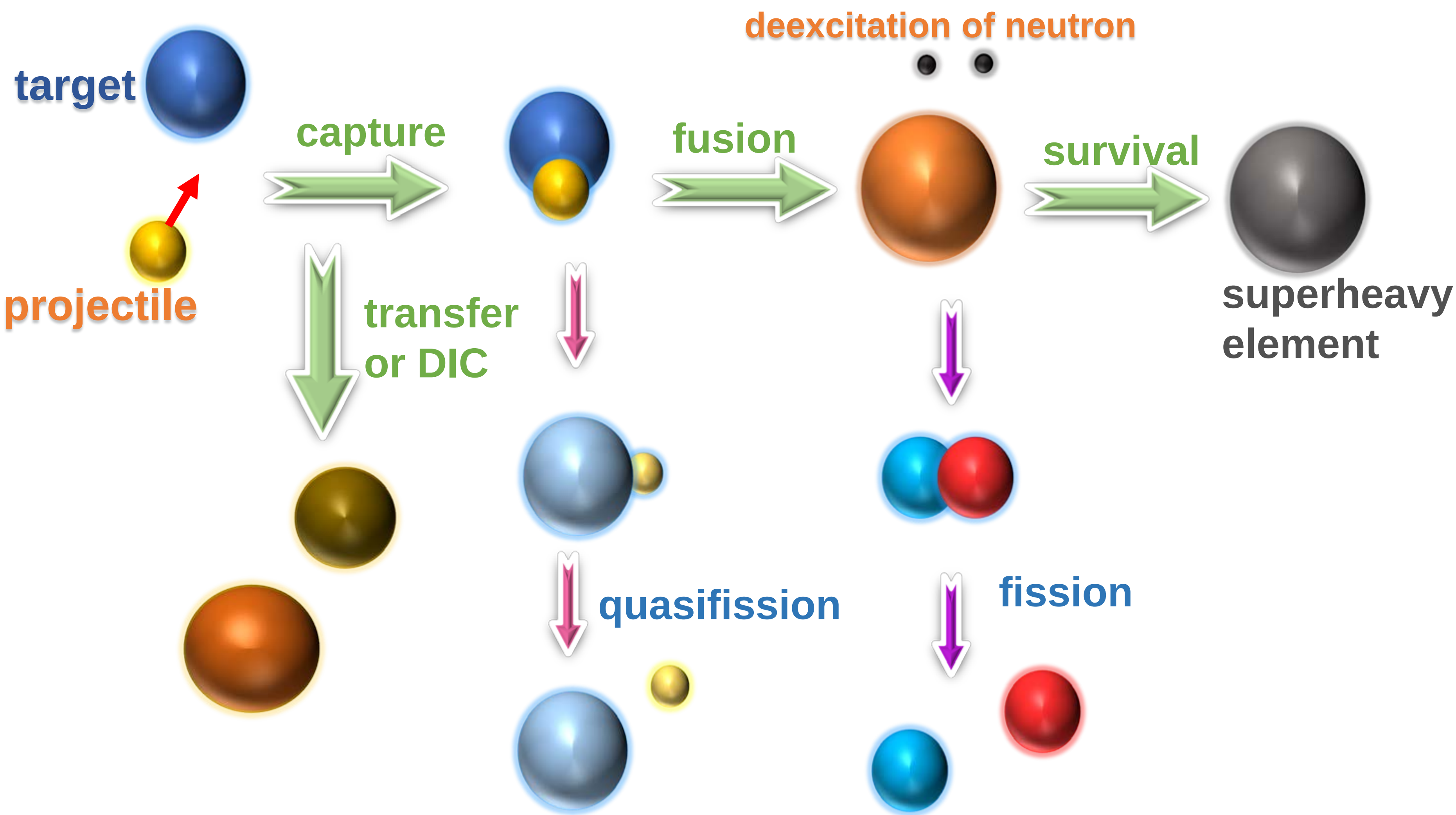


Advantages

- Microscopic theory in heavy-ion collisions;
- Both mean field and collision terms inlcuded;

Limitations

- Pauli principle
- Shell effects
- antisymmetrization of wave functions



deexcitation of neutron
target
capture
fusion
survival
projectile
transfer
or DIC
superheavy
element
quasifission
fission