# Equilibration Dynamics in Nuclear Reactions

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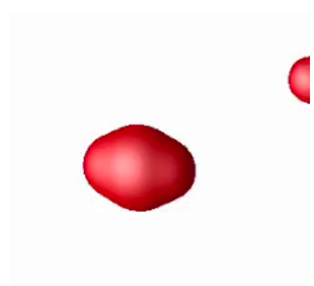
Topics:

Low-energy heavy-ion reactions

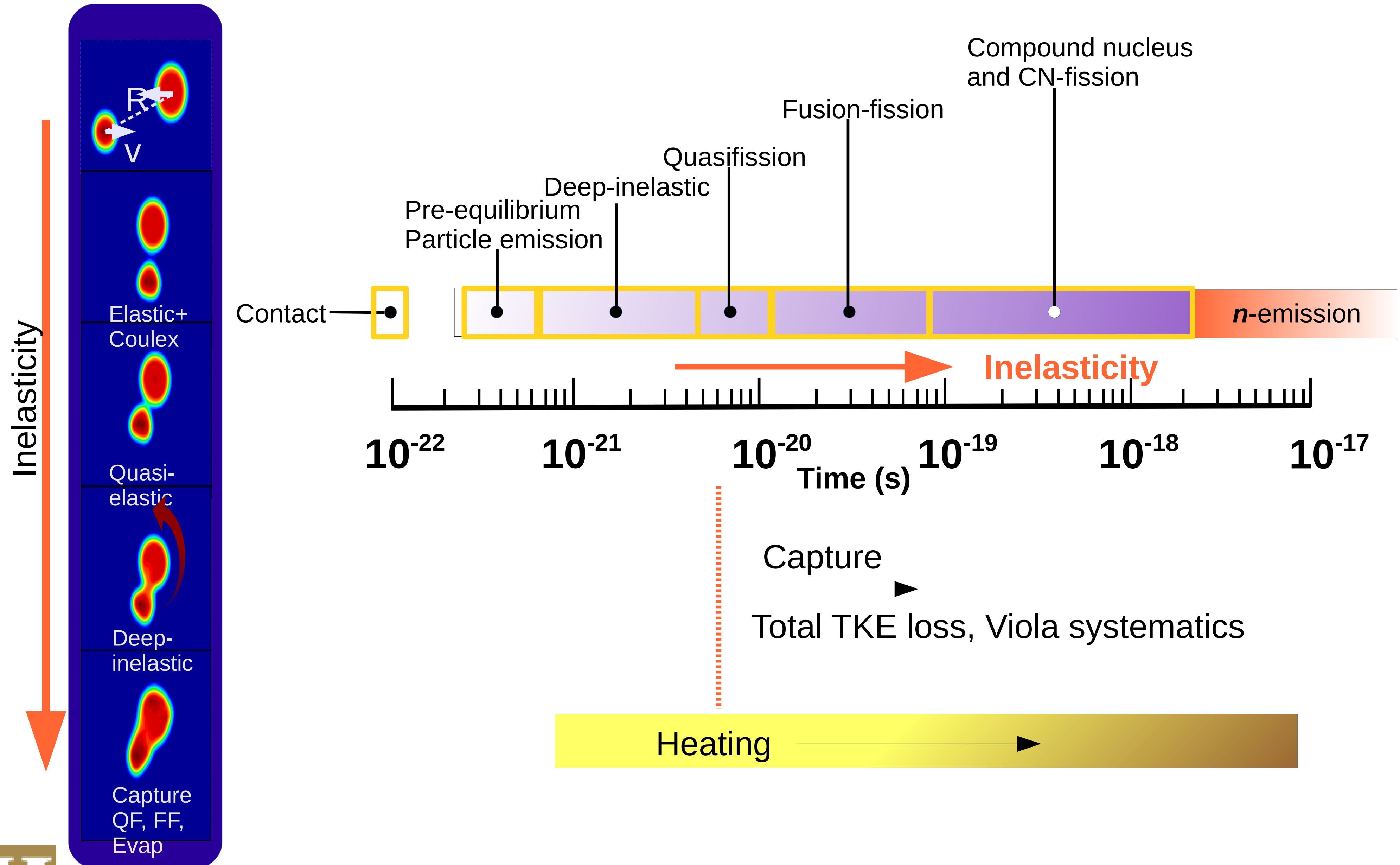
Equilibration dynamics of mass, isospin, energy

Isospin dynamics and fusion barriers



Research supported by: U.S. Department of Energy, Division of Nuclear Physics

# Inelasticity and time scales for nuclear reactions



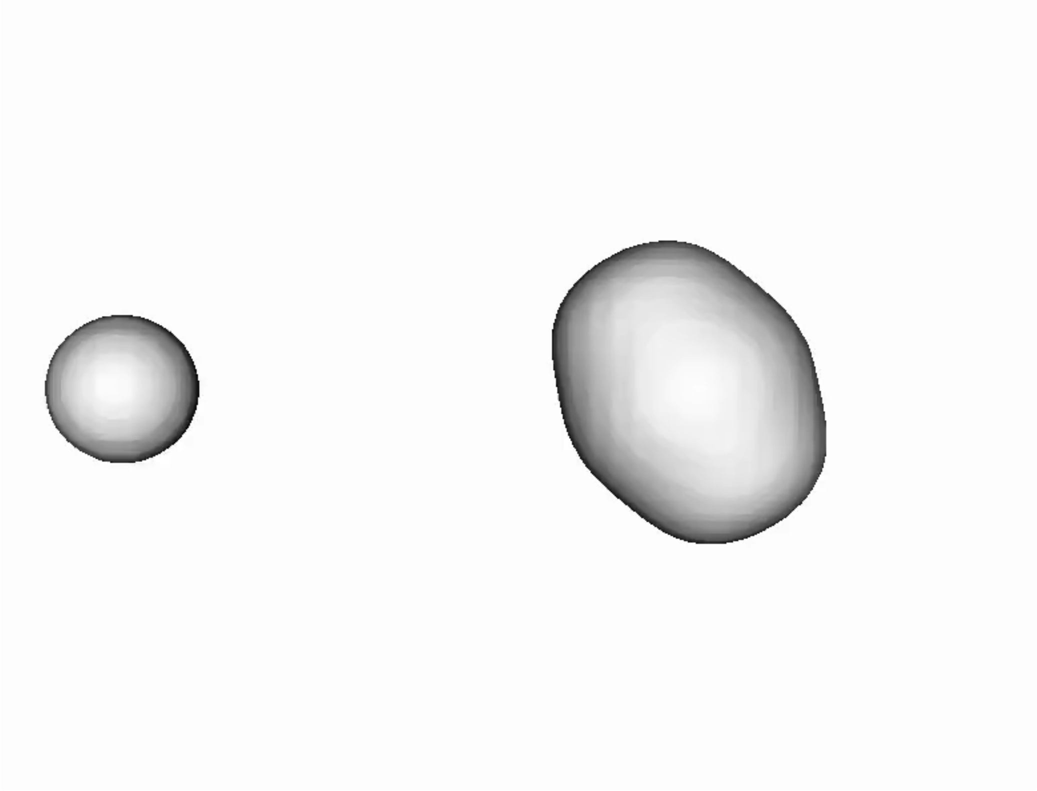

Courtesy of Yu. Ts. Oganessian

# Equilibration dynamics – mass in quasifission

**Equilibration:**
Mass
Isospin
Energy dissipation

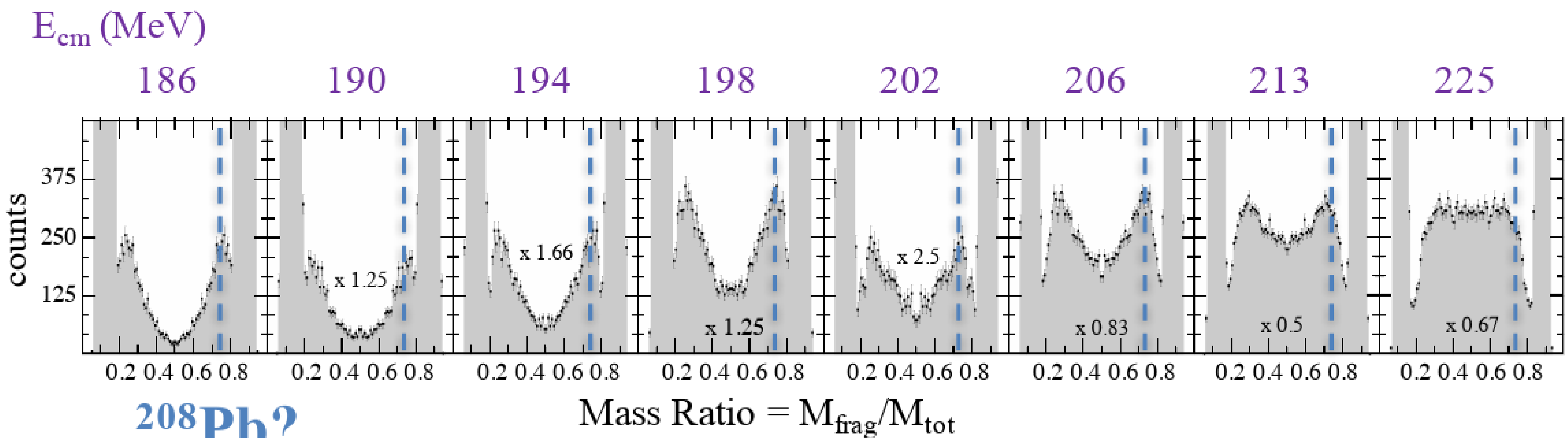
**Dynamics:**
Time scales
Equilibration interrupting mechanisms

**Quantum:**
Shell effects

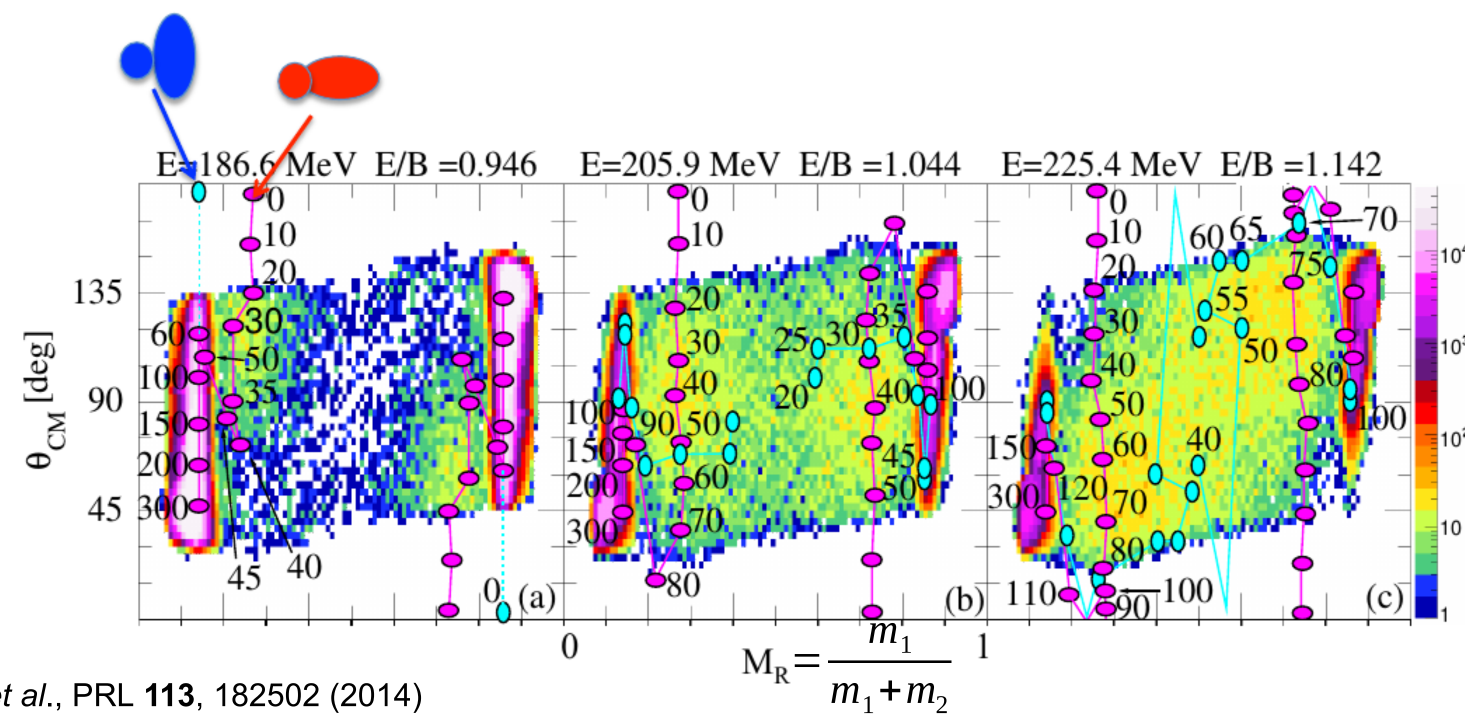


**Theory:**
TDHF is proven to be an excellent diagnostic tool for QF reproducing exp features
Fluctuations can be studied with TDRPA and SMF

# Quasifission – $^{40}Ca$ + $^{238}U$ – shell effects

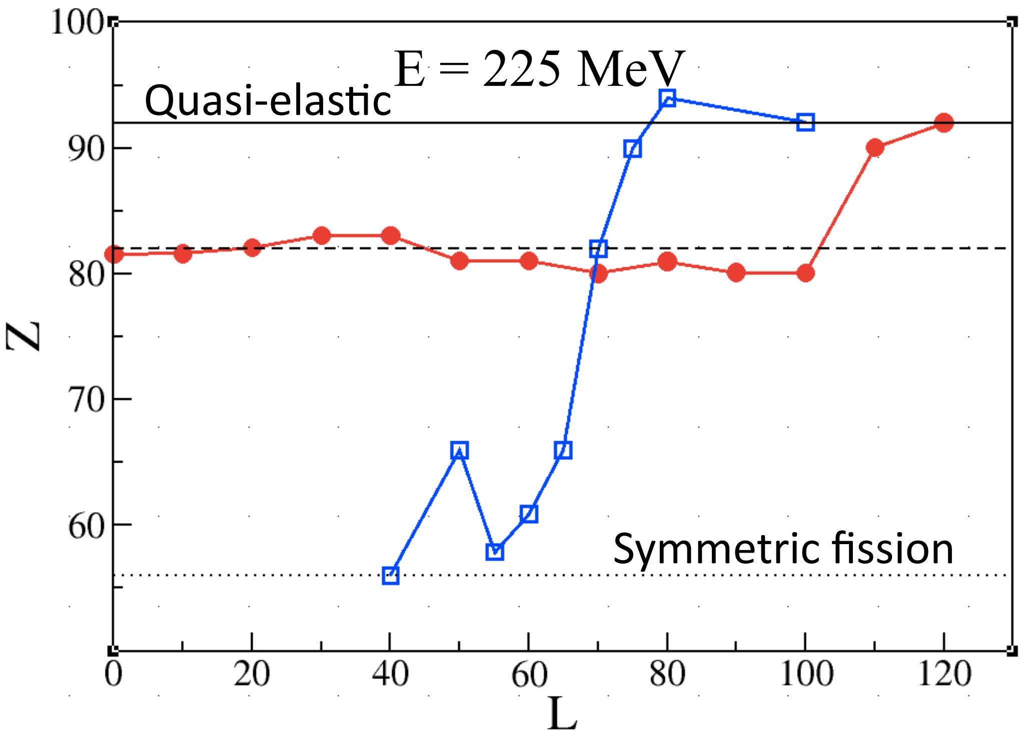


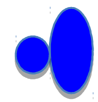

$^{208}$Pb?



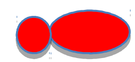

Wakhle *et al*., PRL **113**, 182502 (2014)

# Quasifission – $^{40}$Ca + $^{238}$U – orientation and shell effects



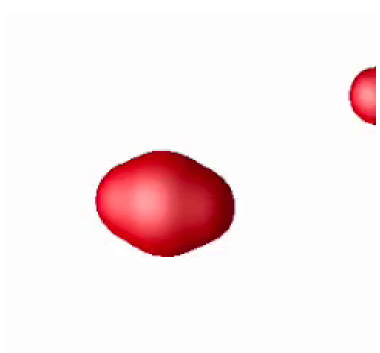
- Fusion and long QF time
- Large mass transfer

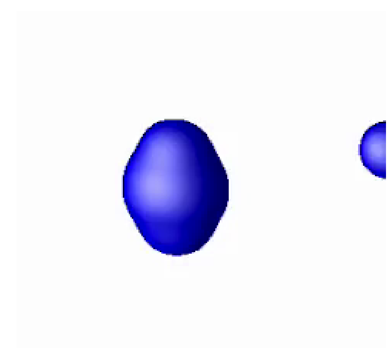


- No fusion, short QF time
- Mass transfer dominated by **quantum shell effects** in the $^{208}$Pb region

**1 zs = 10$^{-21}$ sec**

E=225, L=100 (tip)
Final fragments: $^{78}$Ge, $^{200}$Hg
c. time < 20 zs



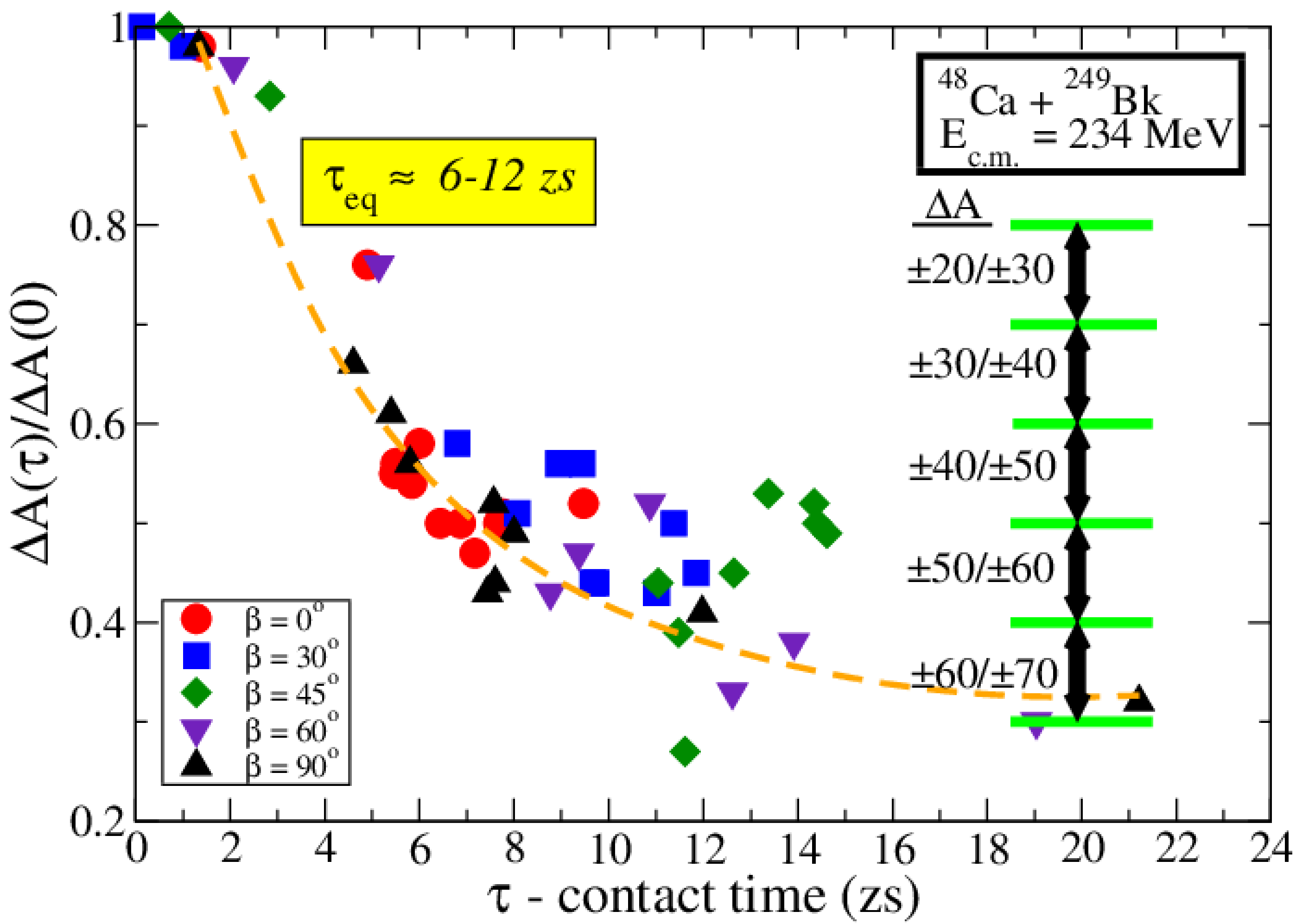


E=225, L=40 (side)
Final framents: $^{140}$Ba, $^{138}$Ba
c. time > 20zs

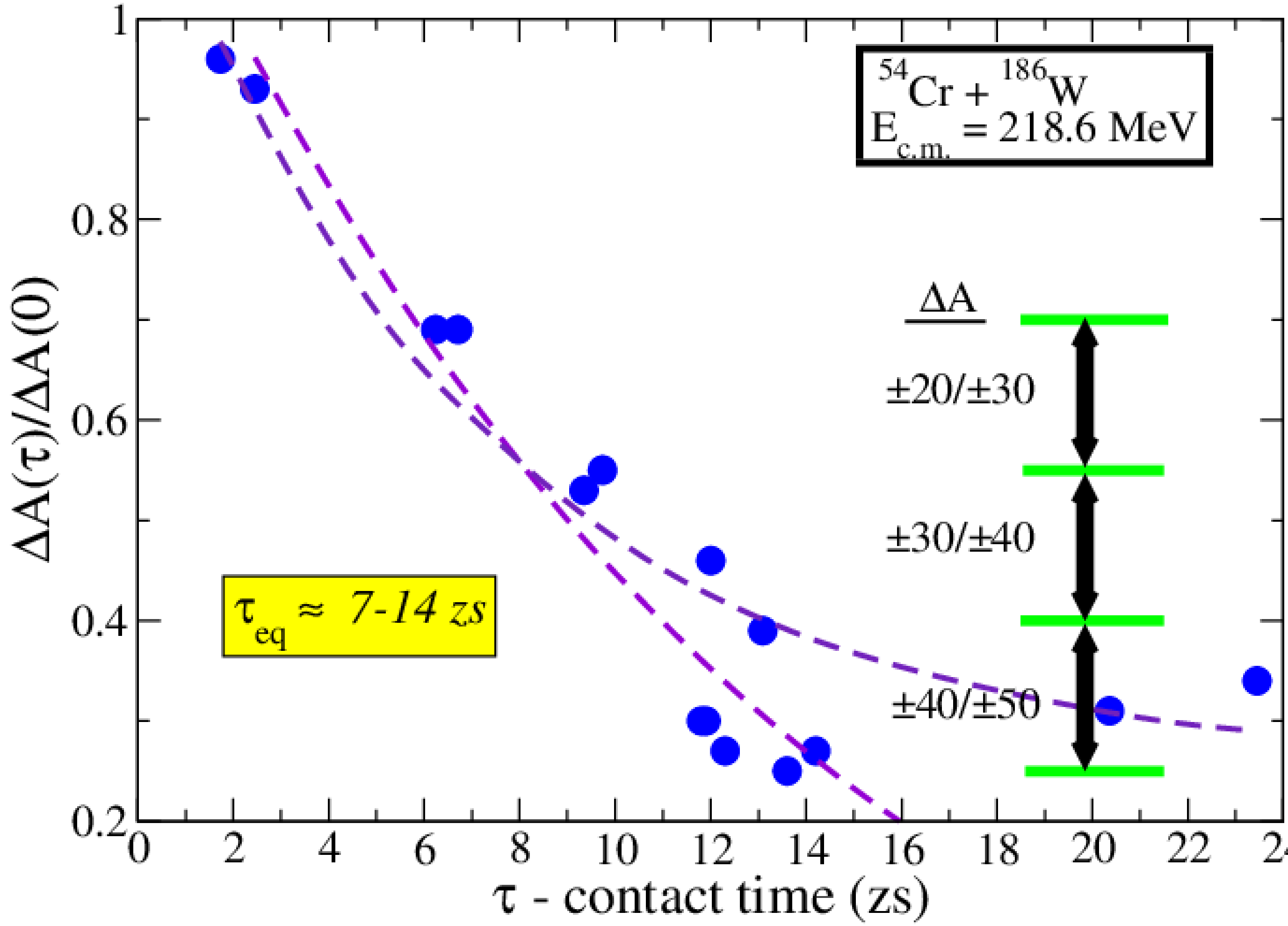
Wakhle *et al.*, PRL **113**, 182502 (2014)

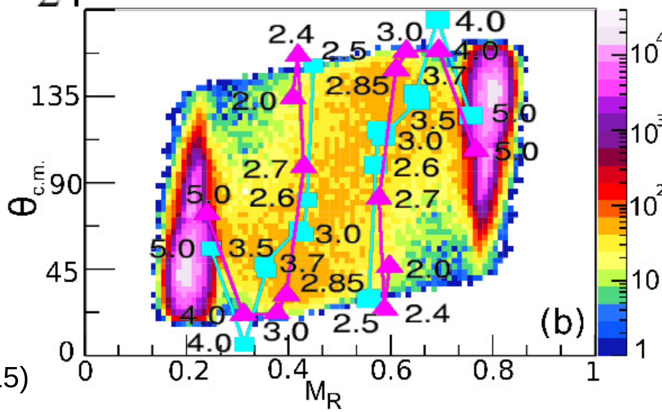
# Quasifission in $^{48}Ca + ^{249}Bk$ – equilibration time

$$\Delta A(t) = A_{TLF}(t) - A_{PLF}(t)$$



# Quasifission in $^{54}Cr + ^{186}W$ – equilibration time




K. Hammerton, *et al.* PRC **91**, 041601(R) (2015)

# Summary for mass equilibration

- ~ **10 zs** to reach mass equilibrium
  (Toke *et al.* PRC 1985, du Rietz *et al.*, PRC 2013)

- Orientation dependence effects time-scales
  - slow QF versus fast QF

First exp. evidence

- Shell effects influence/hinder equilibration (Z=82)
  - 40Ca+238U (Wakhle *et al.* + TDHF)
  - 48Ti + 238U (M. Morjean *et al*. PRL 119, 222502 (2017))

- Other shell effects observed in TDHF
  - preference for neutron rich Zr isotopes (strongly deformed and bound)
  - optimal pair that minimizes energy

# Isospin equilibration

- Connection with symmetry energy, isospin dependence of EoS

- Much faster than mass equilibration: Equilibration ~ exp(**-t/0.3zs**) from experiments at Fermi energy (Jedele *et al.*, PRL 118, 2017)

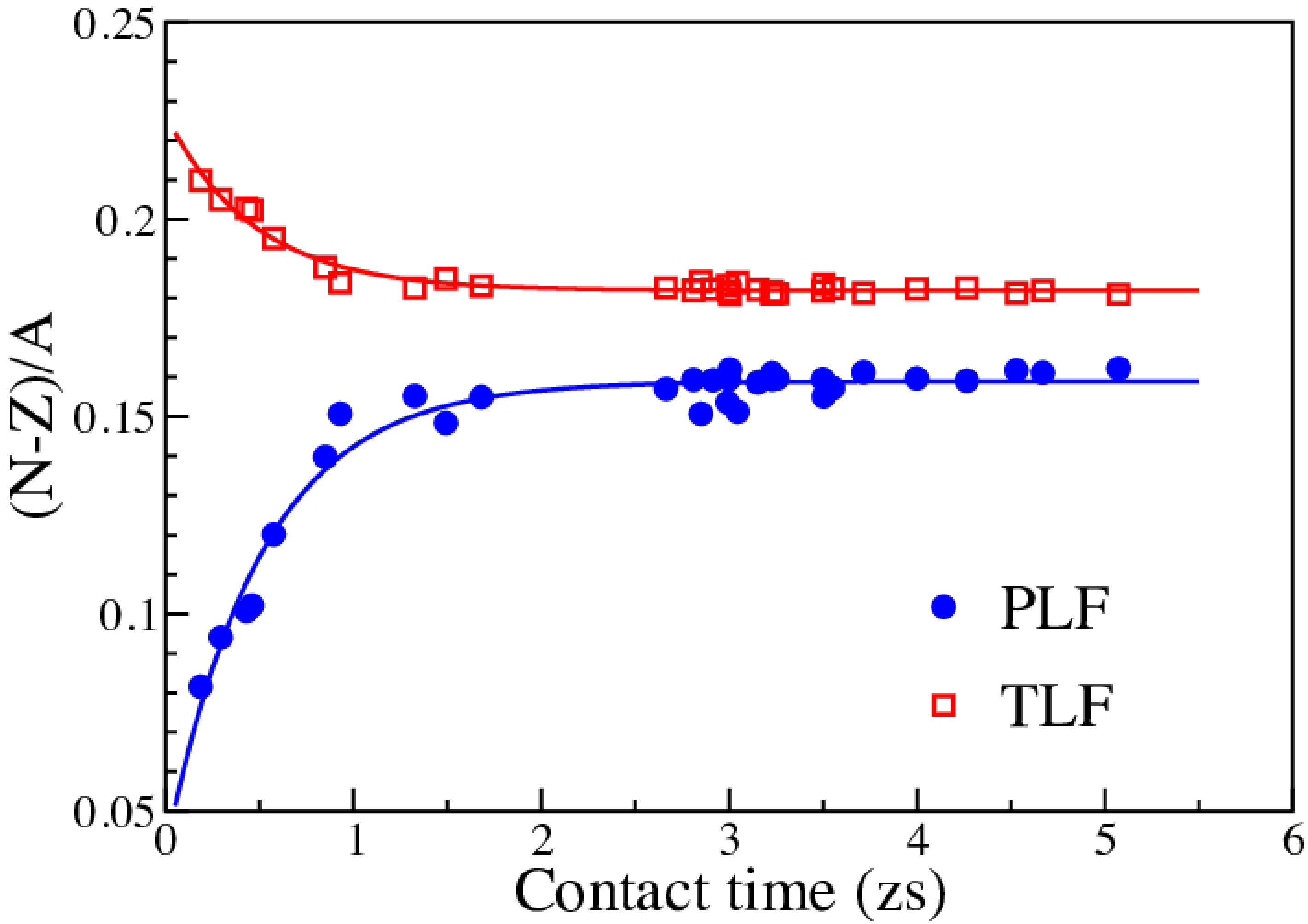
- Needs faster reaction mechanisms than quasifission

- Deep-inelastic collisions
(Planeta *et al.*; deSouza *et al.*, PRC 1988, K. Stiefel *et al*, PRC 2014)

- Will be studied with RIBs

# Isospin equilibration – $^{78}Kr+^{208}Pb$ – 8.5 MeV/A

Umar, Simenel, Ye PRC **96**, 024625 (2017)

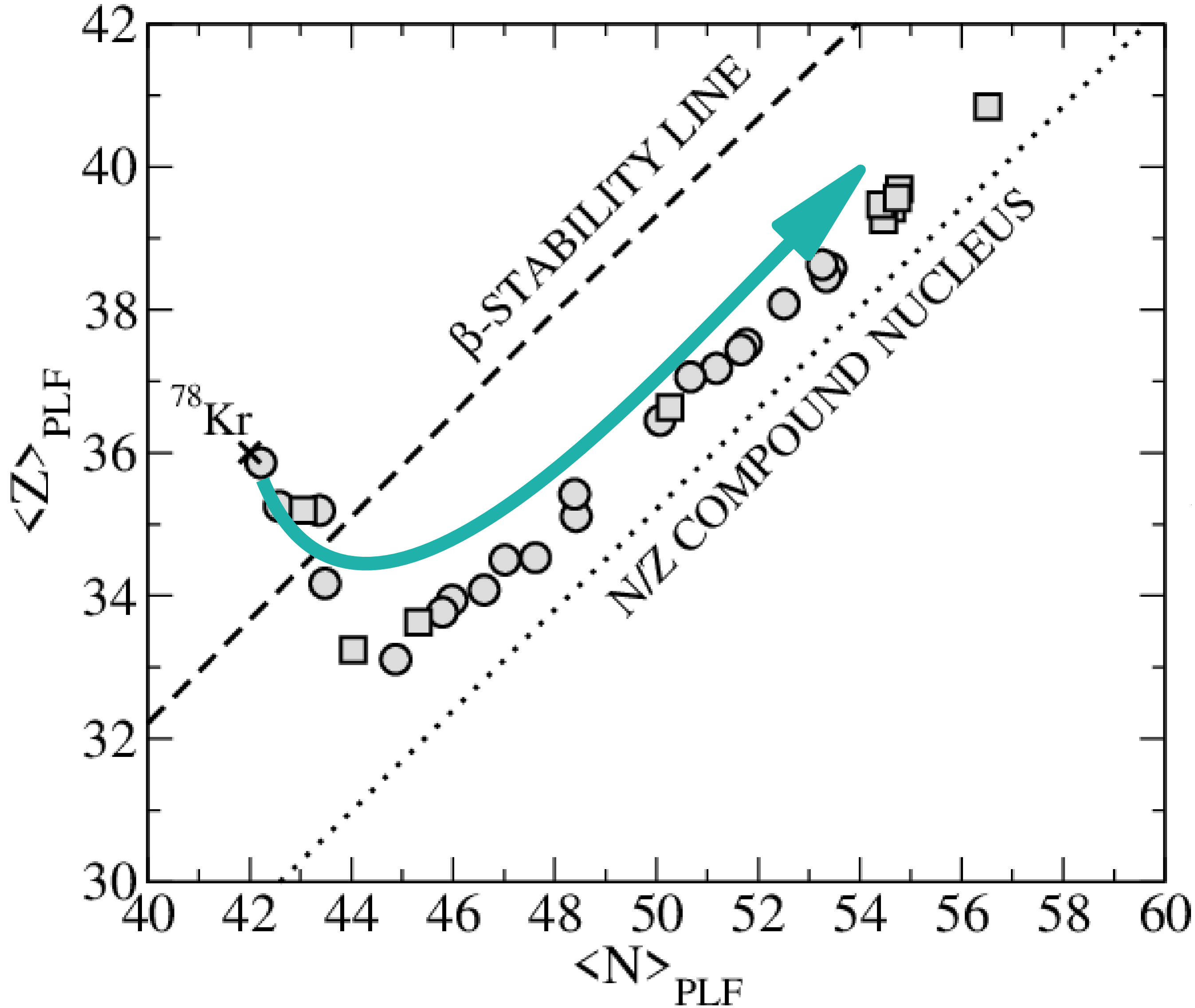



Broad range of fast contact times

~ **1 zs** to reach isospin equilibrium

# Isospin equilibration – $^{78}Kr+^{208}Pb$ – 8.5 MeV/A

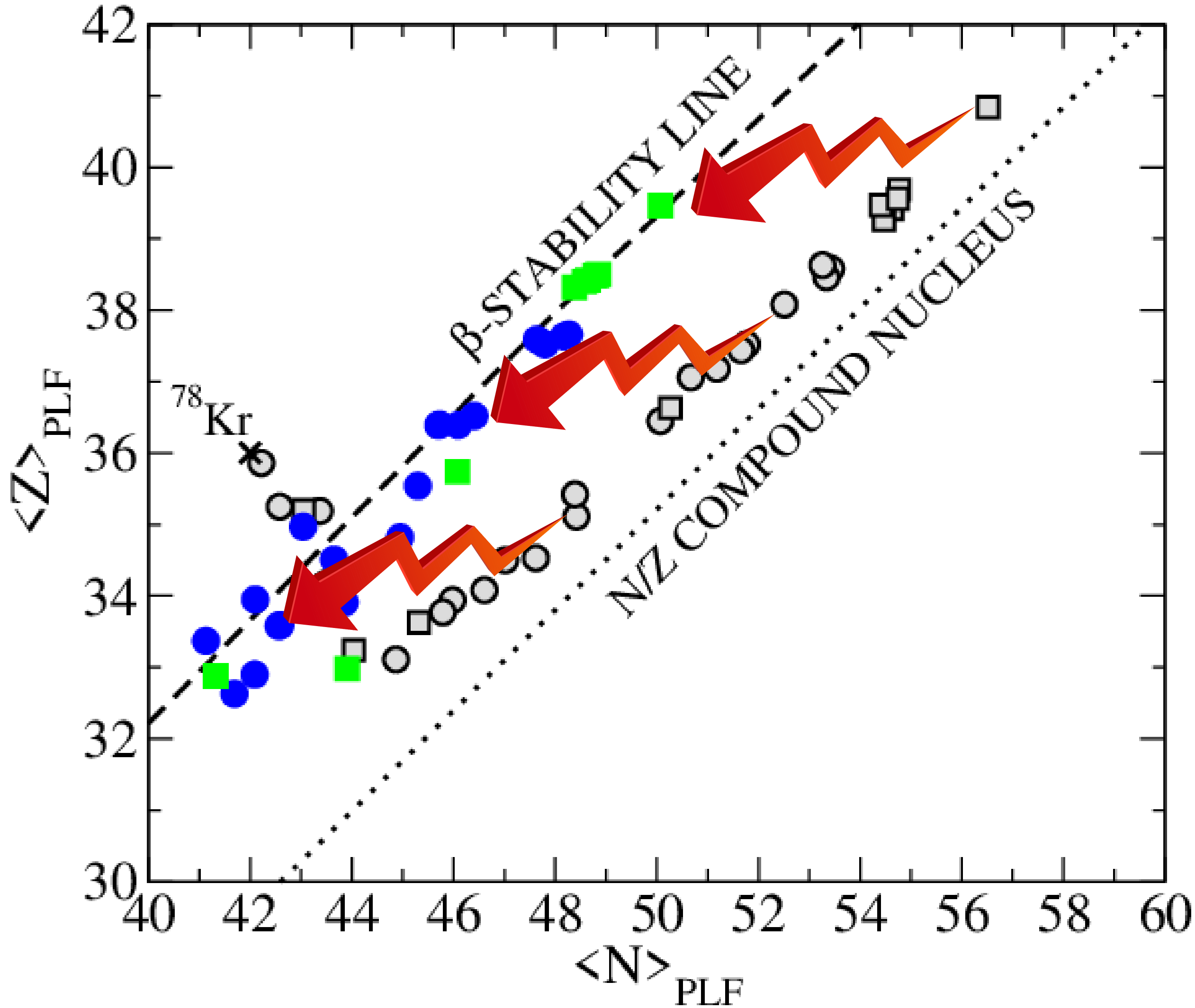
Umar, Simenel, Ye PRC **96**, 024625 (2017)




Isospin and mass equilibration (TDHF)

Need reconstrucution of the primary fragments (statistical codes)

# Isospin equilibration – $^{78}$Kr+$^{208}$Pb – 8.5 MeV/A

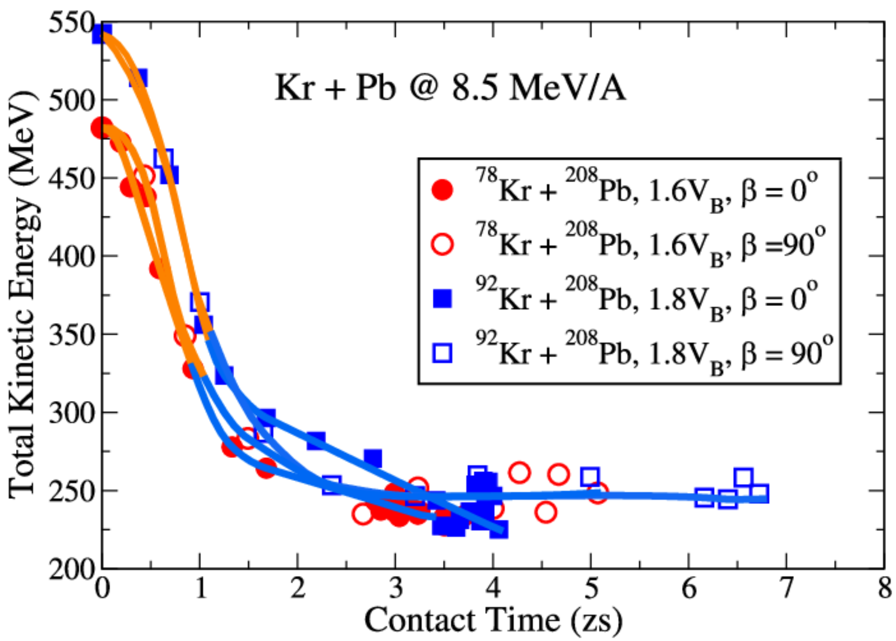



Isospin and mass equilibration (TDHF)

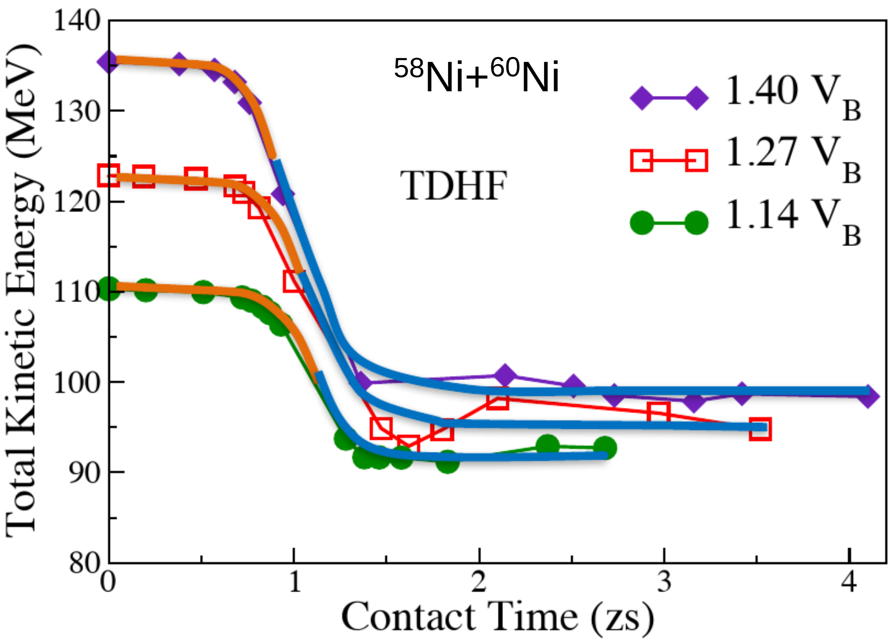
Statistical deexcitation (GEMINI)

# Energy dissipation

Umar, Simenel, Ye PRC **96**, 024625 (2017)




Williams et al., PRL **120**, 022501 (2018)



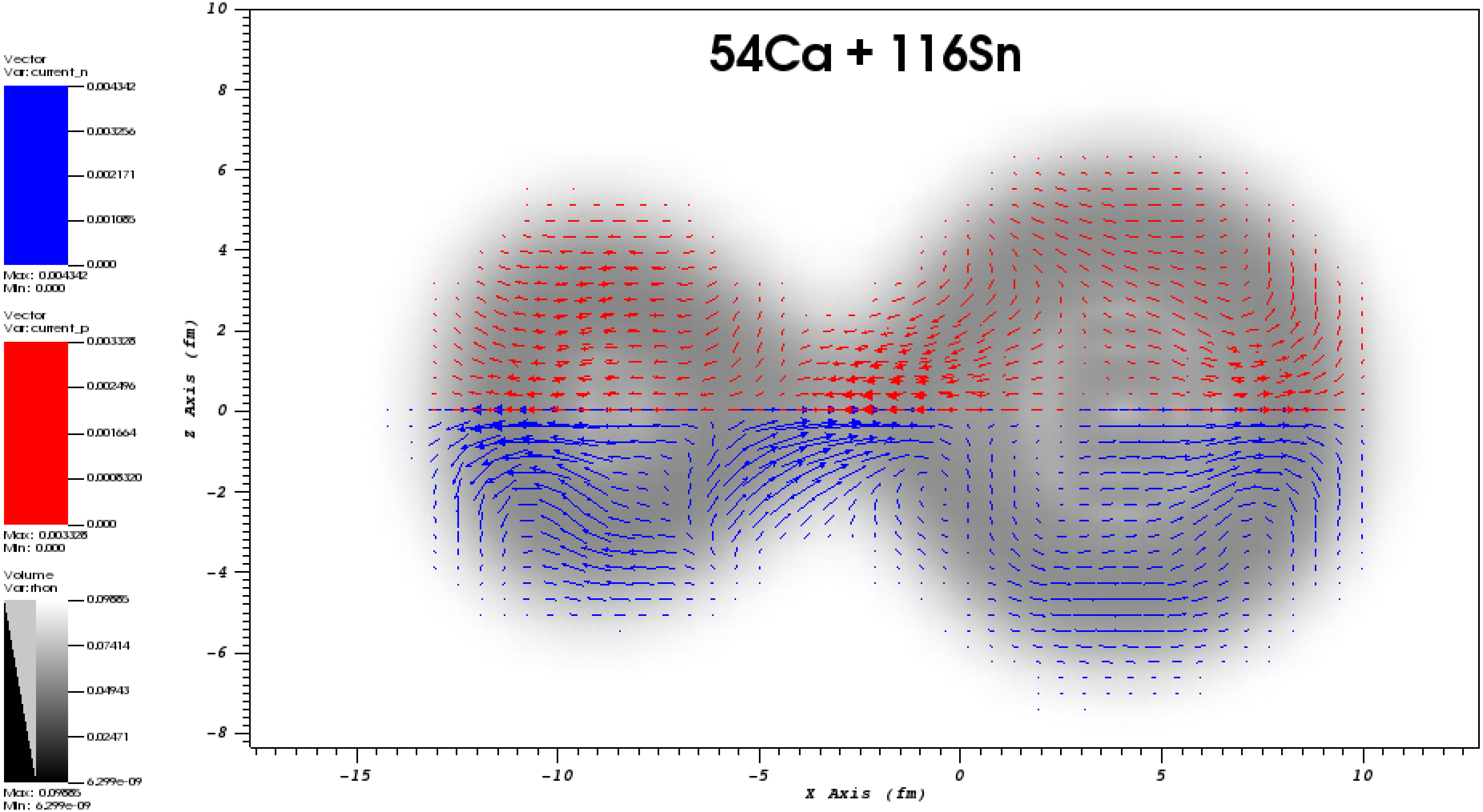

**≈ 1.5zs to reach equilibrium (full energy dissipation)**

# Quantum equilibration dynamics

| | Time to equilibrium | |
|---|---|---|
| **Mass**<br>$^{40,48}Ca+^{238}U,^{249}Bk$<br>Cr+W and many others<br>Slowed by shell effects | **~ 10 zs** | **QF** |
| **Isospin**<br>$^{78}Kr+^{208}Pb$ | **~ 1 zs** | **DIC** |
| **Energy**<br>$^{78}Kr+^{208}Pb$<br>$^{58}Ni+^{60}Ni$ | **~ 1.5 zs** | **DIC** |
| **Mass Fluctuations**<br>$^{58}Ni+^{60}Ni$<br>TDRPA<br>Williams et al., PRL **120**, 022501 (2018) | **~ 3 zs** | **DIC** |

**Need more systematics……..**

# Isospin dynamics and fusion barriers



# TDHF + density constraint (DCTDHF)

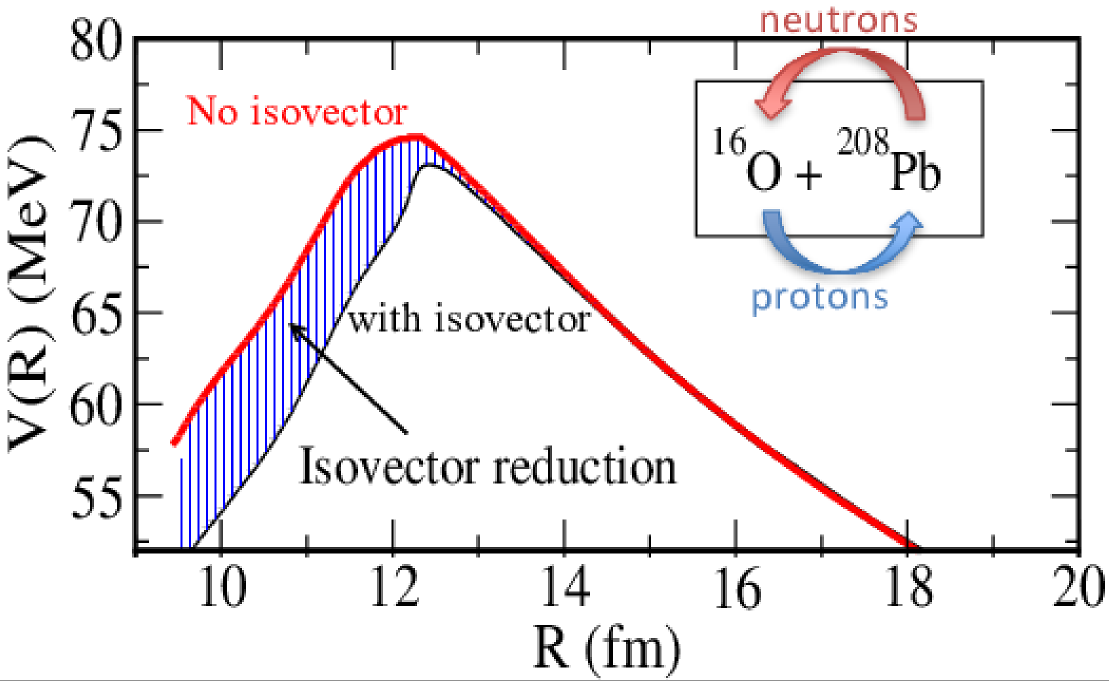
Skyrme EDF

$$\mathcal{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau_0 + \mathcal{H}_{I=0}(\mathbf{r}) + \mathcal{H}_{I=1}(\mathbf{r}) + \mathcal{H}_C(\mathbf{r})$$

Allows for isospin decomposed ion-ion interaction barrier

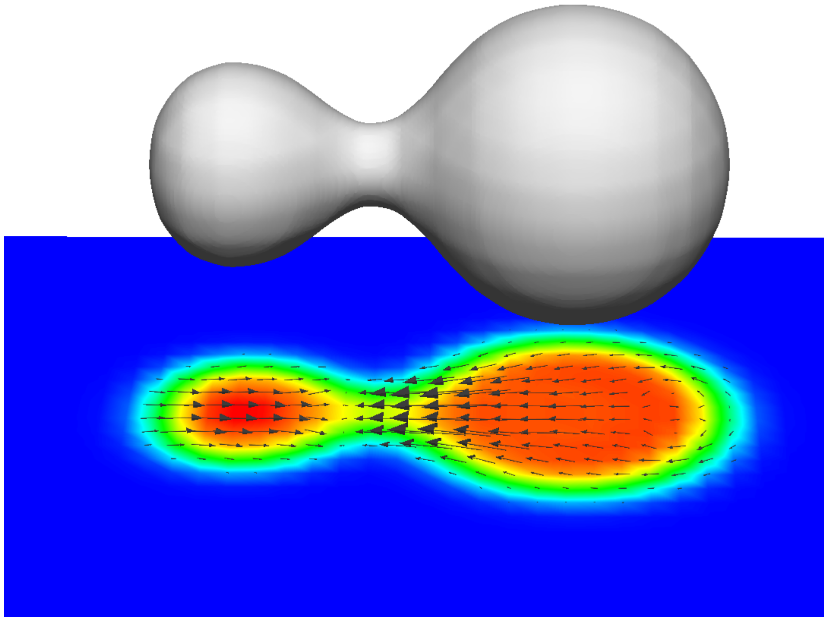
$$\mathrm{V(R)} = \mathrm{V_{I=0}}(R) + V_{\mathrm{I=1}}(R) + V_C(R)$$

- Minimize energy with density constraint during unhindered TDHF
- Microscopic internuclear potential
- Parameter-free, only depends on chosen EDF
- Dynamical, energy-dependent
- Extensively applied to fusion barrier calculations



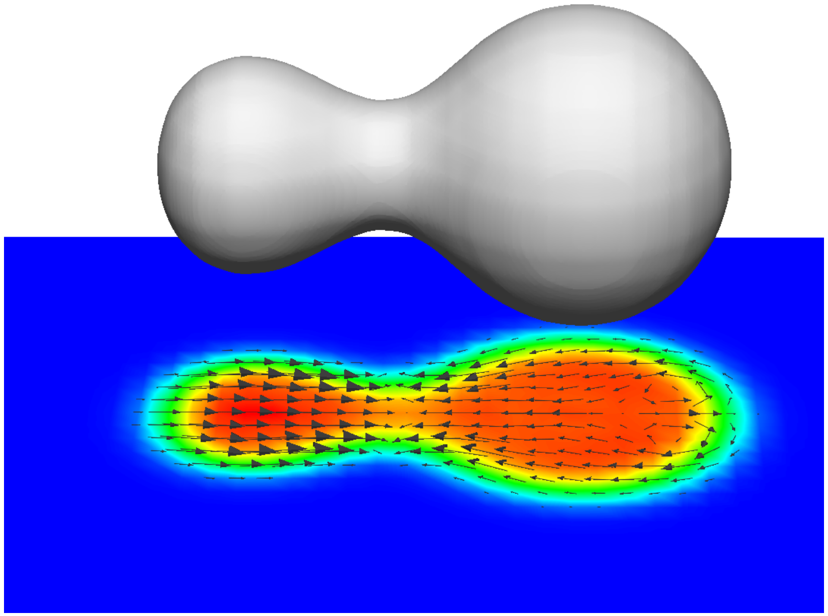
# $^{40}Ca+^{132}Sn$ versus $^{48}Ca+^{132}Sn$

**40Ca + 132Sn**



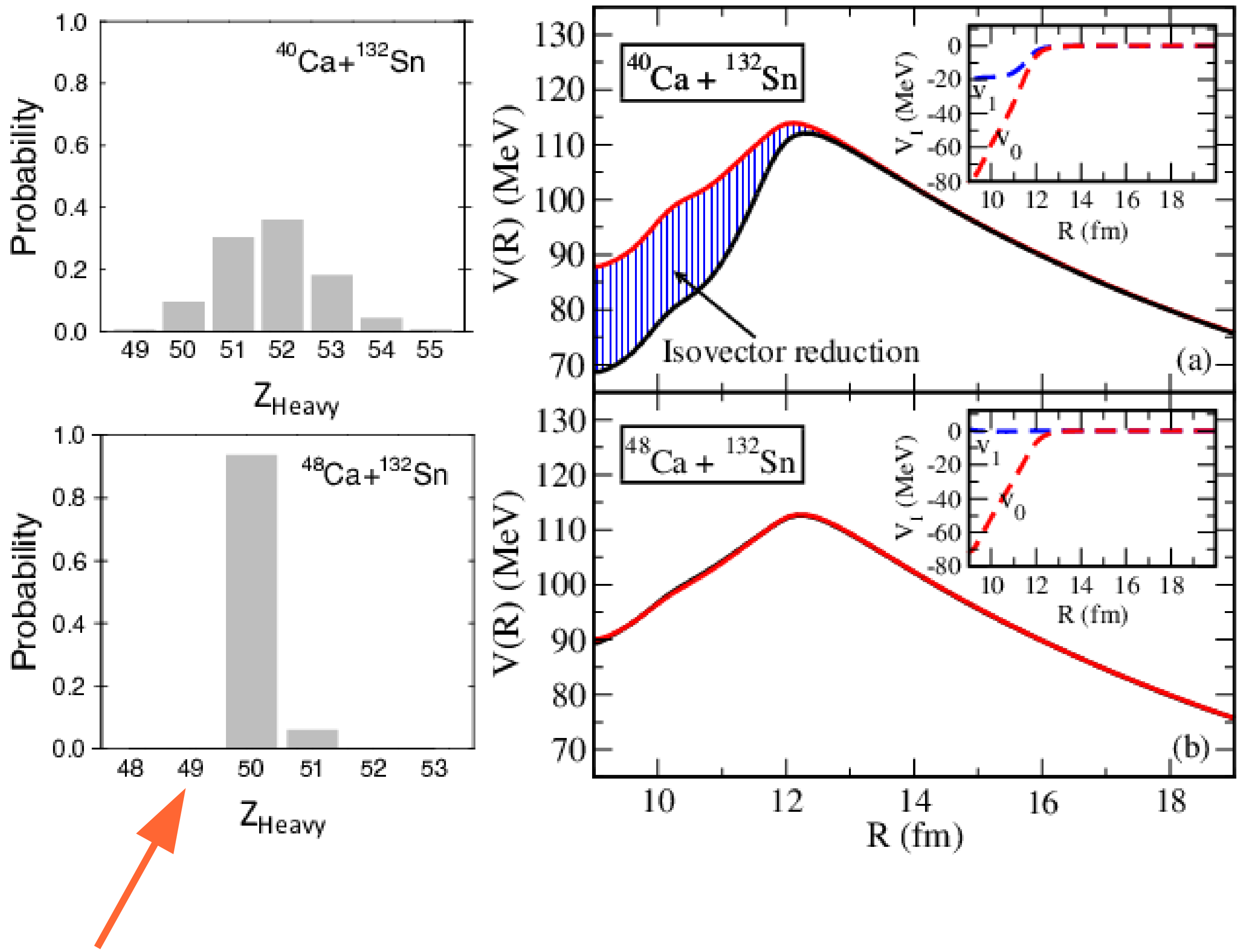
transfer

**48Ca + 132Sn**



No net transfer

# $^{40}Ca+^{132}Sn$ versus $^{48}Ca+^{132}Sn$ – Q-value transfer channels




Particle number projection just below the barrier

# Collaborators

Theory

Experiment

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **95**, 011601(R) (2017)

**Dependence of fusion on isospin dynamics**

K. Godbey[1,*], A. S. Umar[1,†], and C. Simenel[2,‡]

PHYSICAL REVIEW C **96**, 024625 (2017)

**Transport properties of isospin asymmetric nuclear matter using the time-dependent Hartree-Fock method**

A. S. Umar[1,*], C. Simenel[2,†], and W. Ye[3,‡]

PHYSICAL REVIEW C **94**, 024605 (2016)

**Fusion and quasifission dynamics in the reactions $^{48}Ca + ^{249}Bk$ and $^{50}Ti + ^{249}Bk$ using a time-dependent Hartree-Fock approach**

A. S. Umar[1,*], V. E. Oberacker[1,†], and C. Simenel[2,‡]

RAPID COMMUNICATIONS

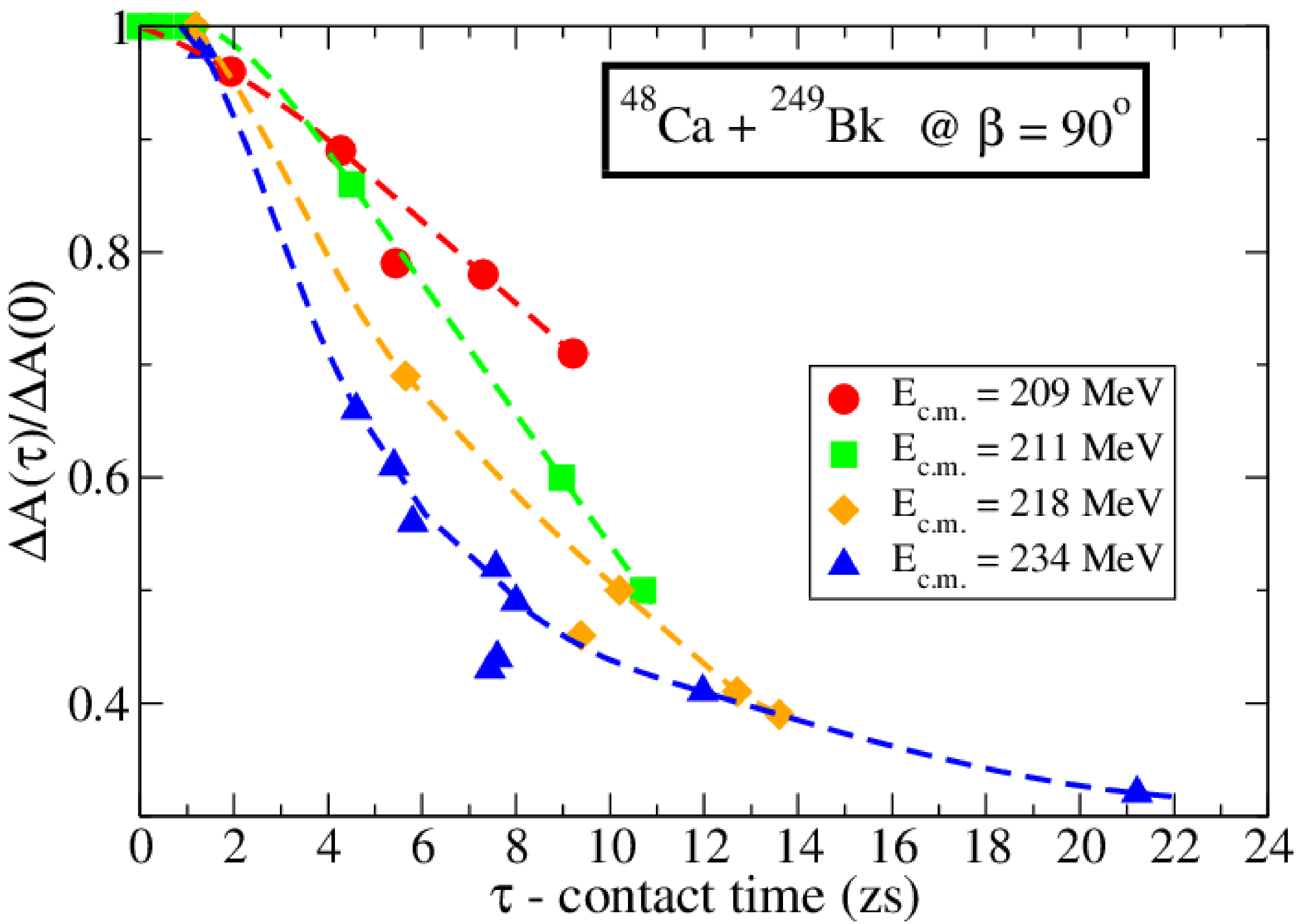
PHYSICAL REVIEW C **95**, 031601(R) (2017)

**How the Pauli exclusion principle affects fusion of atomic nuclei**

C. Simenel[1,*], A. S. Umar[2,†], K. Godbey[2,‡], M. Dasgupta[1], and D. J. Hinde[1]

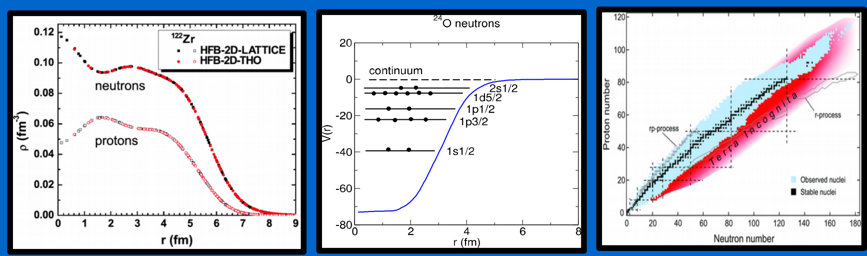
# Supplementary Slides

# Equilibration time E-dependence

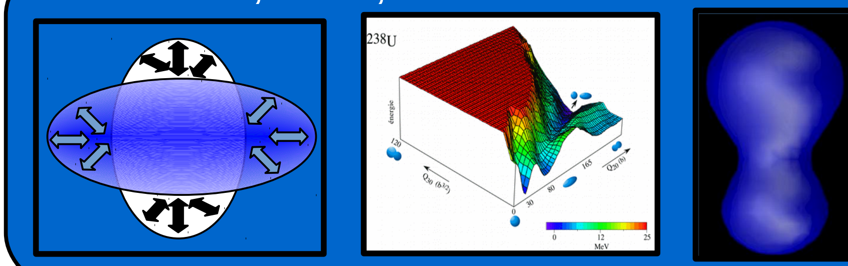


# TDDFT- Study Structure and Reactions in Same Framework

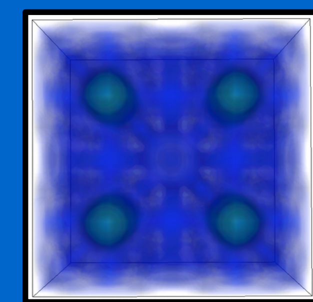
**Structure**

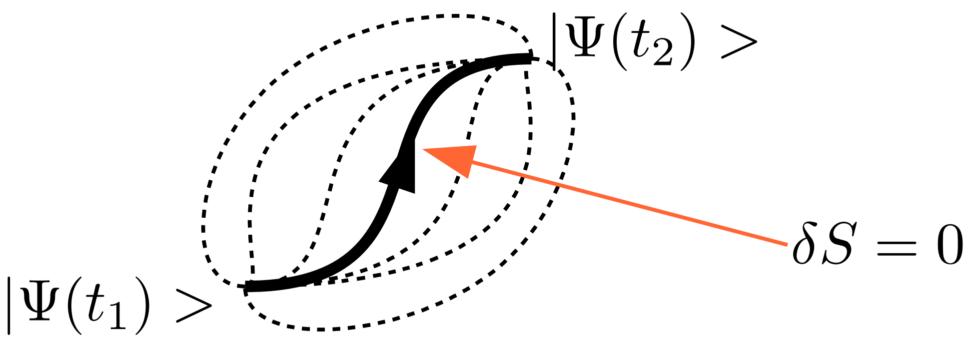



**Oscillations, Fusion, Fission**




**Neutron Star Crust**






- TDDFT is the time-dependent generalization of DFT

$$S = \int_{t_1}^{t_2} dt < \Phi(t)|H - i\hbar\partial_t|\Phi(t) >$$

$$i\frac{\partial}{\partial t}\phi_\alpha = h(\rho, \tau, \mathbf{j}, \mathbf{s}, \mathbf{T}, \mathbf{J}_{\mu\nu}; \mathbf{r})\phi_\alpha$$

self-consistent

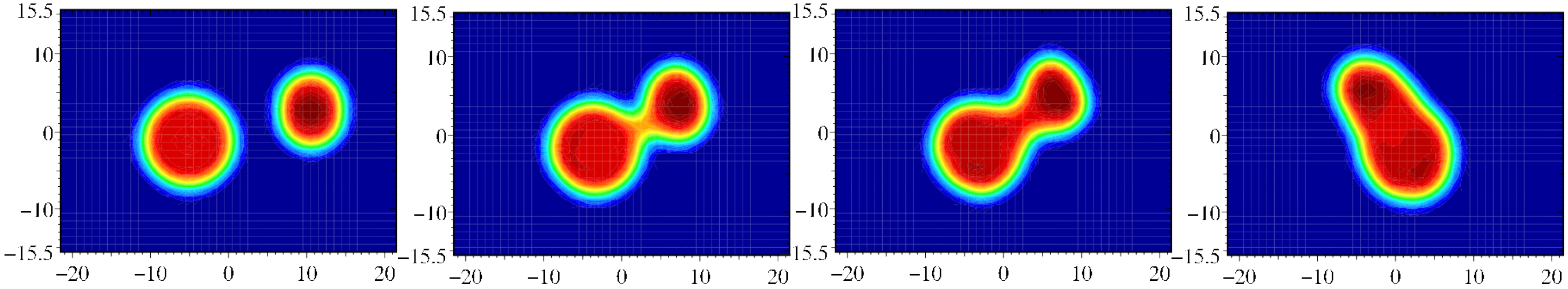
- Only input is the EDF (structure information only)
- TDDFT gives the *most probable outcome*
- Describe reactions and structure on an equal footing microscopically

# Modern TDDFT Codes

VU-TDDFT Code

- Basis-Spline discretization for high accuracy
- 3-D Cartesian lattice – no geometrical simplification
- Complete EDF including all terms (time-even, full time-odd)
- Coded in Fortran-95 and OpenMP


1. Umar, Oberacker, VU-TDDFT, Phys. Rev. C 73, 054607 (2006)
2. Maruhn, Reinhard, Stevenson, Umar, Sky3D, Comp. Phys. Comm. 85, 2195 (2014)

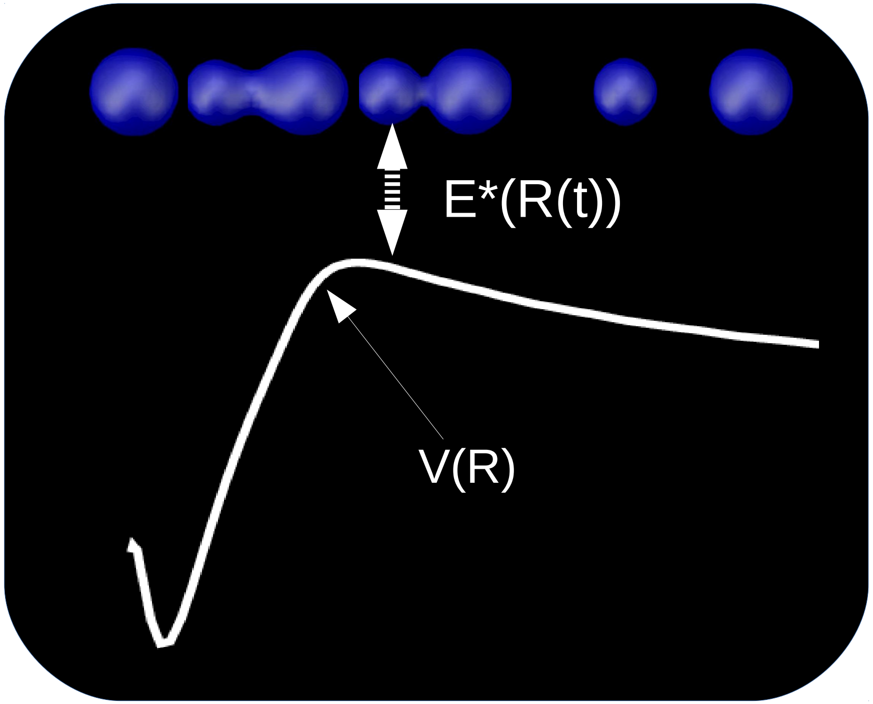
# TDDFT + Density Constraint = Internuclear Potentials

- Minimize energy with density constraint during unhindered TDDFT

$$E_{DC}(t) = min_{\rho} \left\{ E[\rho_n, \rho_p] + \int d^3r \lambda_n(\mathbf{r})[\rho_n(\mathbf{r}) - \rho_n^{tdhf}(\mathbf{r}, t)] + \int d^3r \lambda_p(\mathbf{r})[\rho_p(\mathbf{r}) - \rho_p^{tdhf}(\mathbf{r}, t)] \right\}$$

- Microscopic dynamical internuclear potential – can calculate subbarrier fusion, capture

$$V(R) = E_{\mathrm{DC}}(R) - E_{A_1} - E_{A_2}$$




- Parameter-free, only depends on chosen EDF
- Dynamical, energy-dependent
- Calculate E*(t) and M(R)
- Extensively applied to fusion barrier calculations

# TDHF + density constraint (DCTDHF)

Energy written in terms of the Energy Density Functional (EDF)

$$\mathrm{E} = \int d^3\mathbf{r}\, \mathcal{H}(\mathbf{r})$$

Skyrme EDF

$$\mathcal{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau_0 + \mathcal{H}_{I=0}(\mathbf{r}) + \mathcal{H}_{I=1}(\mathbf{r}) + \mathcal{H}_C(\mathbf{r})$$

$$\mathrm{H_I}(\mathbf{r}) = C_\mathrm{I}^{\rho}\rho_\mathrm{I}^2 + C_\mathrm{I}^{s}\mathbf{s}_\mathrm{I}^2 + C_\mathrm{I}^{\Delta\rho}\rho_\mathrm{I}\Delta\rho_\mathrm{I} + C_\mathrm{I}^{\Delta s}\mathbf{s}_\mathrm{I}\cdot\Delta\mathbf{s}_\mathrm{I} +$$

$$\mathrm{C}_\mathrm{I}^{\tau}\left(\rho_\mathrm{I}\tau_\mathrm{I} - \mathbf{j}_\mathrm{I}^2\right) + C_\mathrm{I}^{T}\left(\mathbf{s}_\mathrm{I}\cdot\mathbf{T}_\mathrm{I} - \overleftrightarrow{J}_\mathrm{I}^2\right) +$$

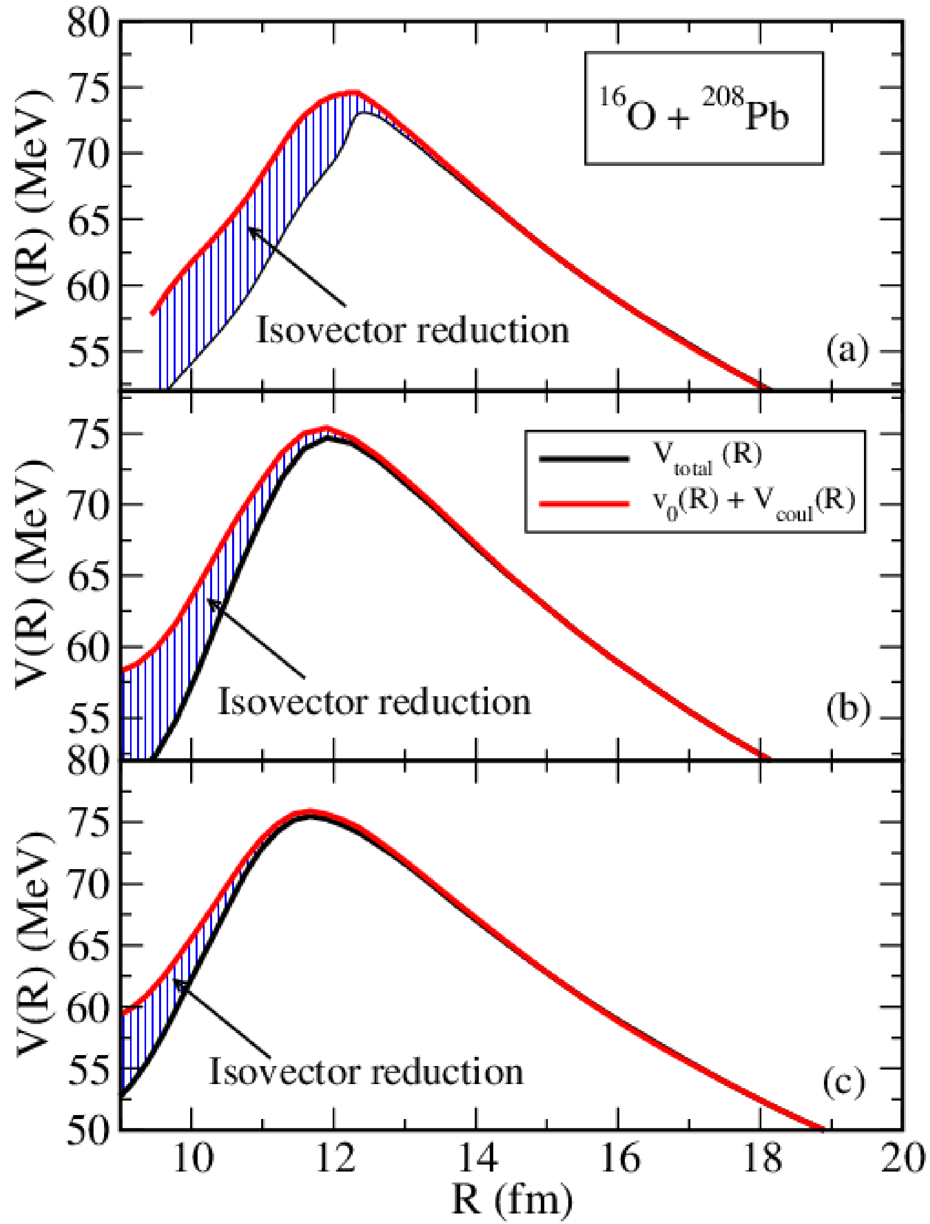
$$\mathrm{C}_\mathrm{I}^{\nabla J}\left(\rho_\mathrm{I}\nabla\cdot\mathbf{J}_\mathrm{I} + \mathbf{s}_\mathrm{I}\cdot(\nabla\times\mathbf{j}_\mathrm{I})\right)$$

Allows for isospin decomposed ion-ion interaction barrier

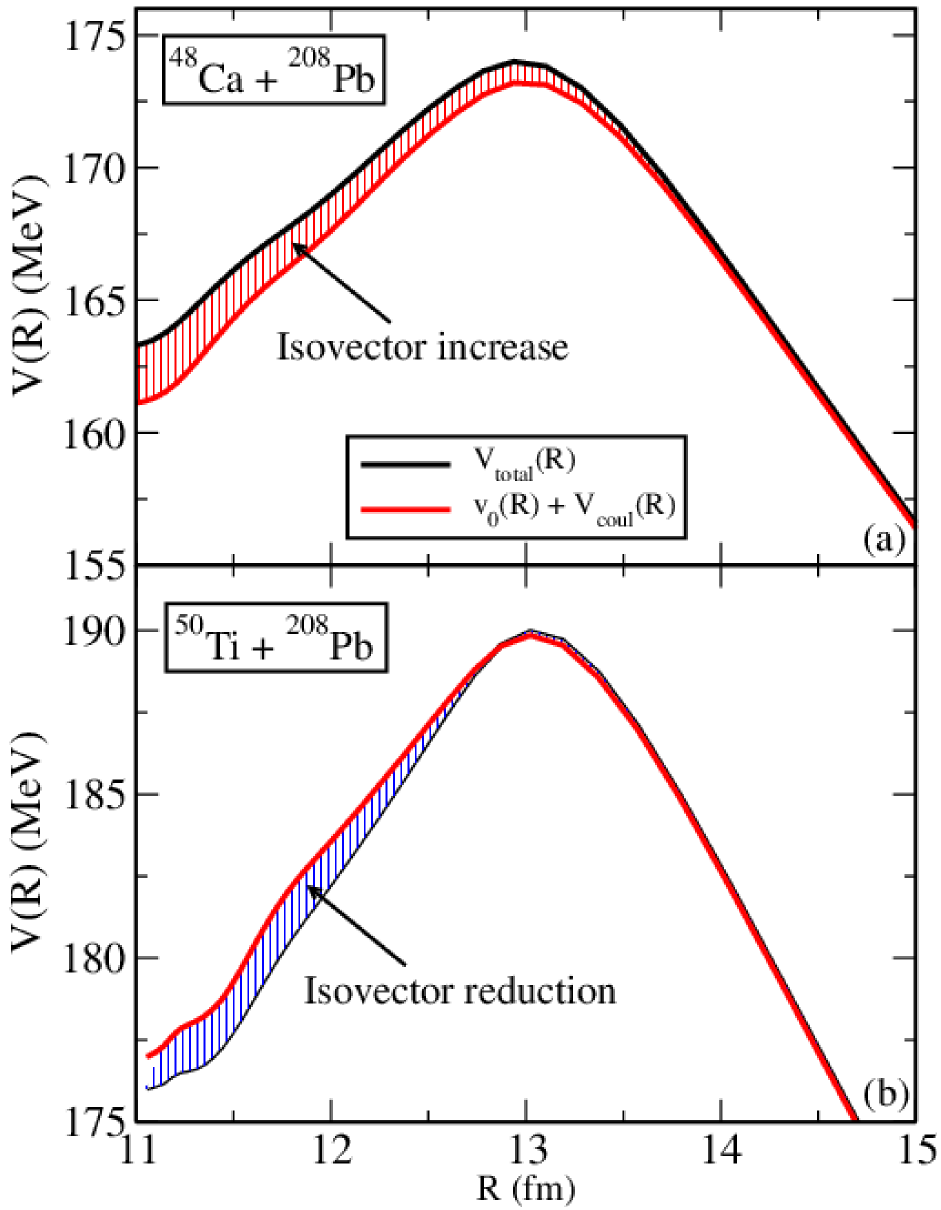
$$\mathrm{V(R)} = \mathrm{E_{DC}}(R) - E_{\mathrm{A}_1} - E_{\mathrm{A}_2}$$

$$\mathrm{V(R)} = \mathrm{V_{I=0}}(R) + V_{\mathrm{I=1}}(R) + V_C(R)$$

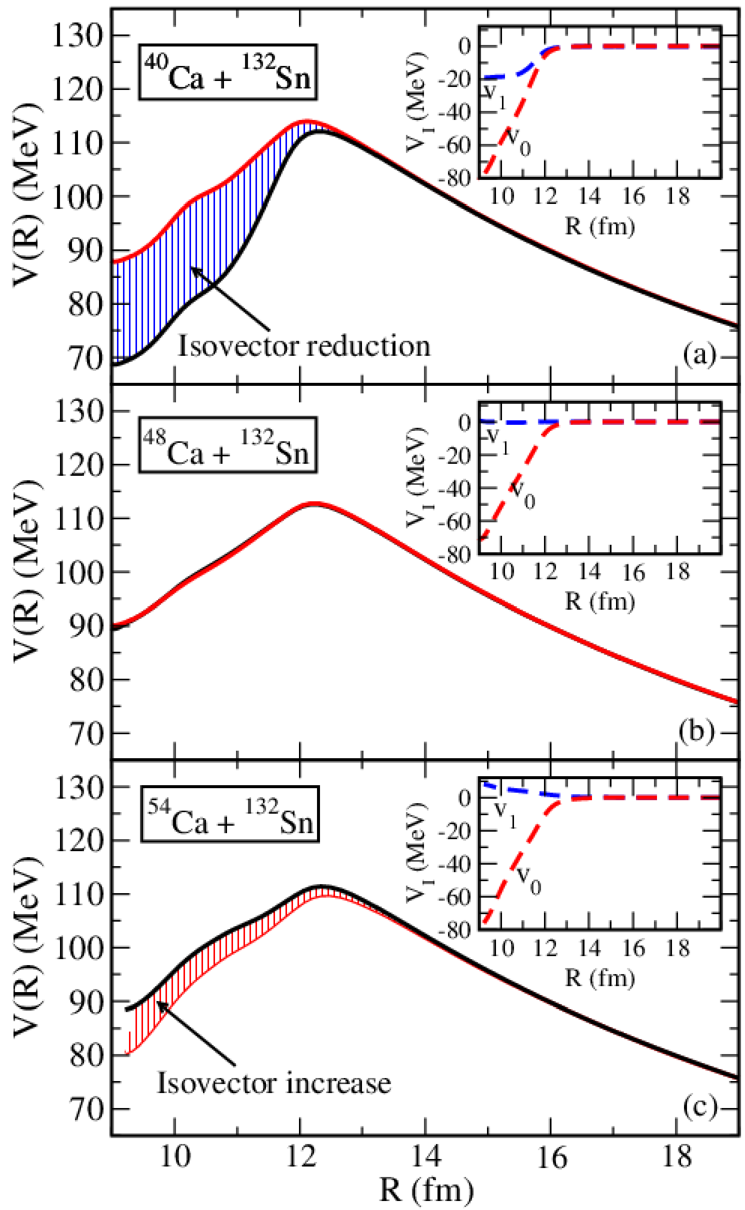
# Isospin Decomposition – $^{16}O + ^{208}Pb$



# Isospin Decomposition – $^{48}$Ca, $^{50}$Ti + $^{208}$Pb



# Isospin Decomposition – $^{40,48,54}Ca+^{132}Sn$



# $^{54}Ca+^{132}Sn$