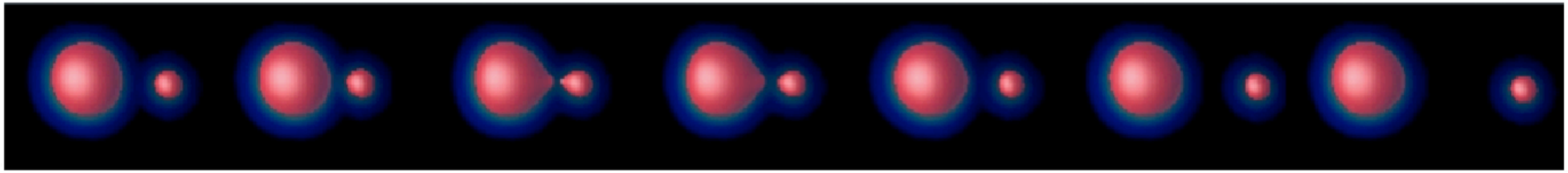


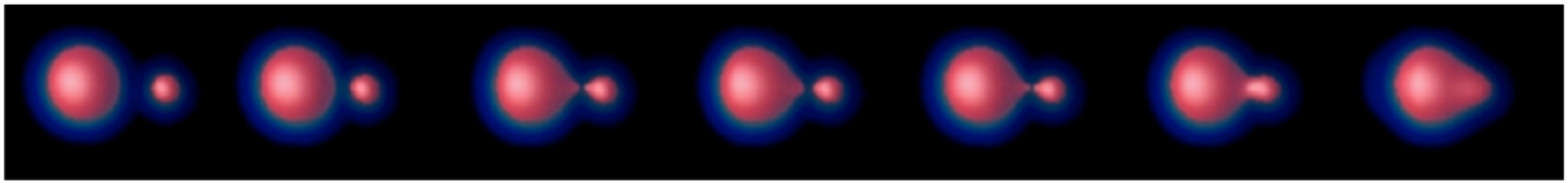
Microscopic approach to heavy-ion fusion:

Effects of the Pauli exclusion principle

Cédric Simenel, Mahananda Dasgupta, David Hinde,
Edward Simpson, Kirsten Vo-Phuoc

Department of Nuclear Physics, ANU

Kyle Godbey, Sait Umar
Vanderbilt University (USA)



« Pauli » Exclusion Principle

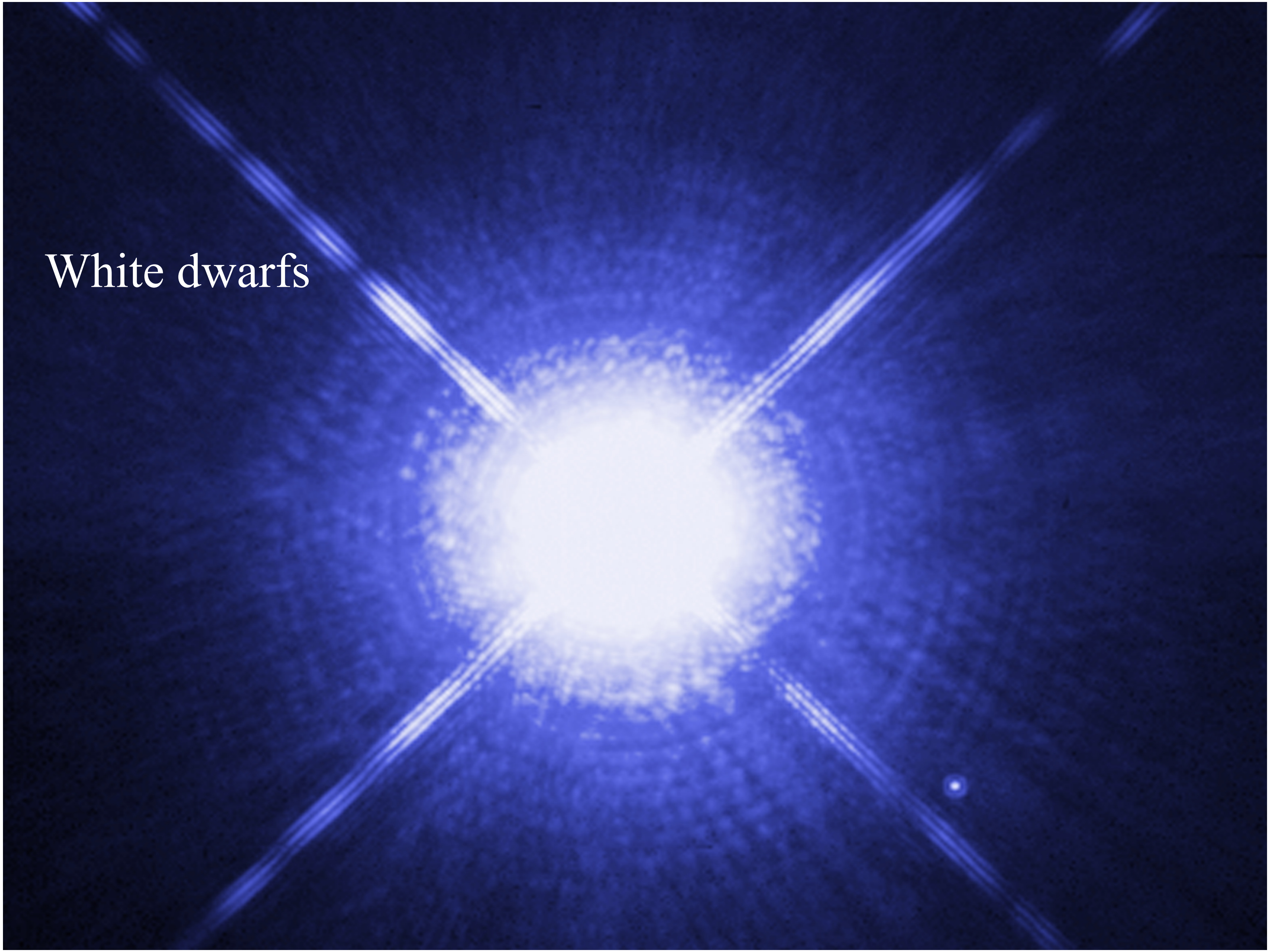
Edmund Clifton Stoner

"The distribution of electrons among atomic energy levels," The London, Edinburgh and Dublin Philosophical Magazine **47**, 1168 (1924)

Wolfgang Pauli

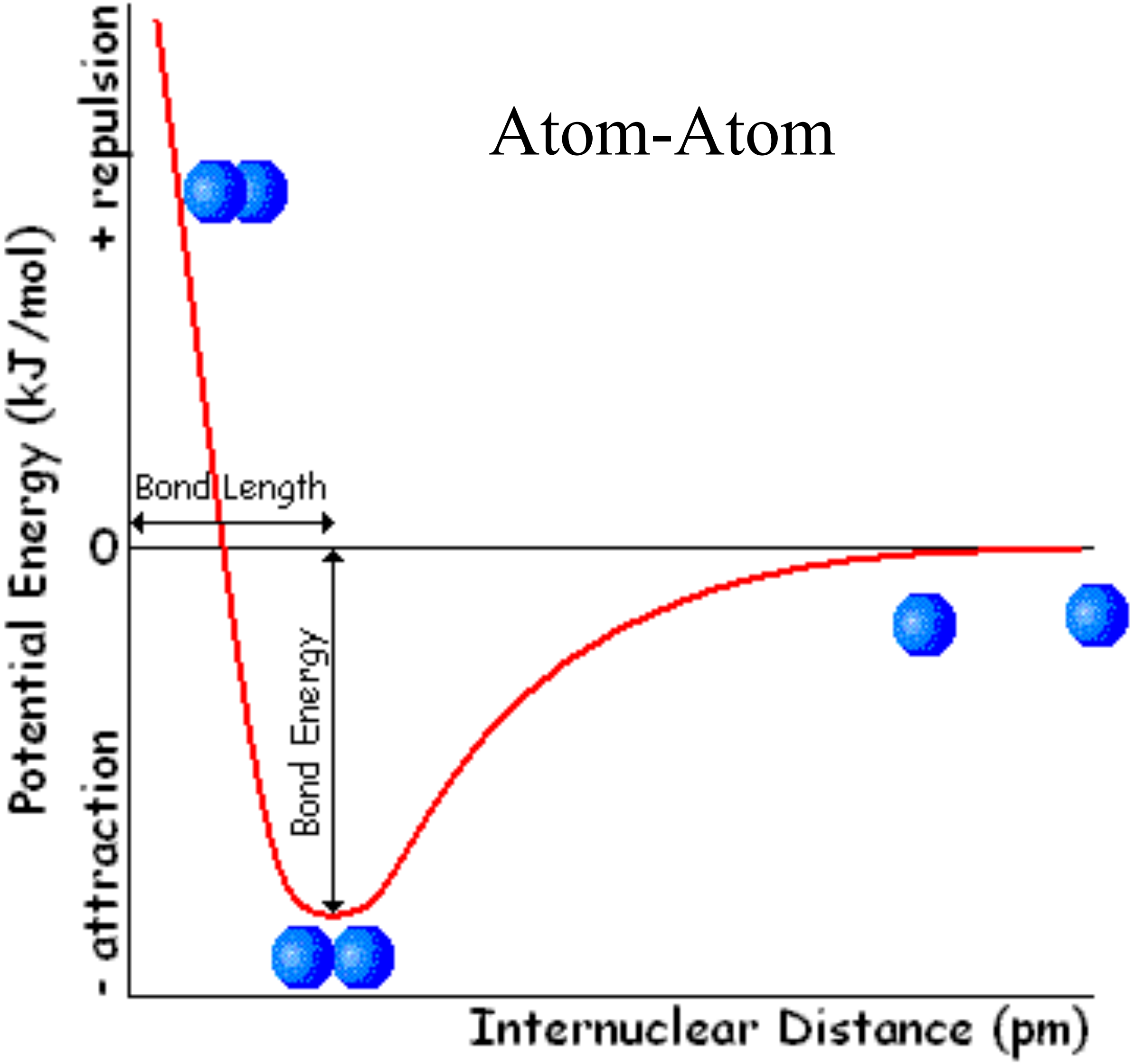
Z. Phys **31**, 765 (1925)

« It shall be forbiden for more than one electron to have the same value of quantum numbers »


White dwarfs

Pauli repulsion

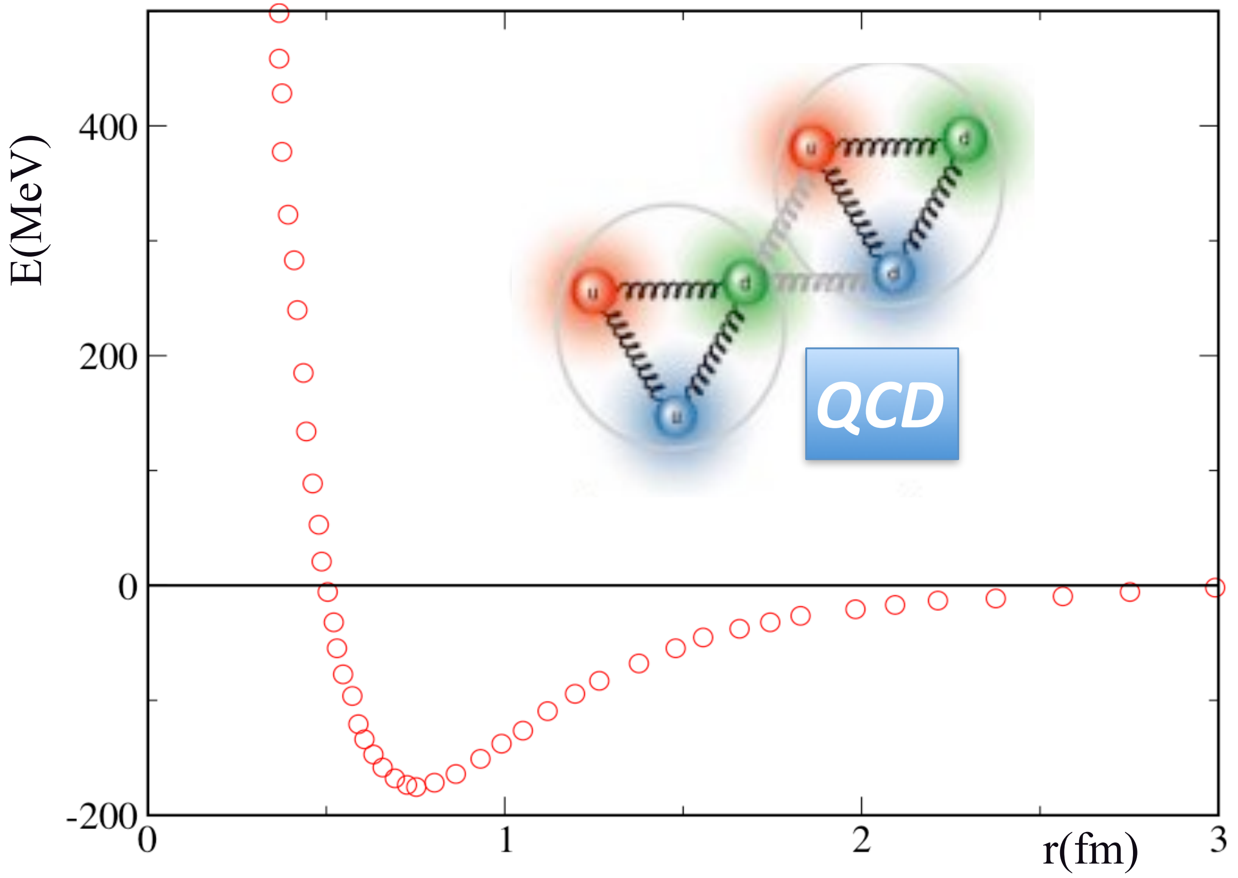
Repulsion between composite systems of identical fermions at short distance



Pauli repulsion

Repulsion between composite systems of identical fermions at short distance

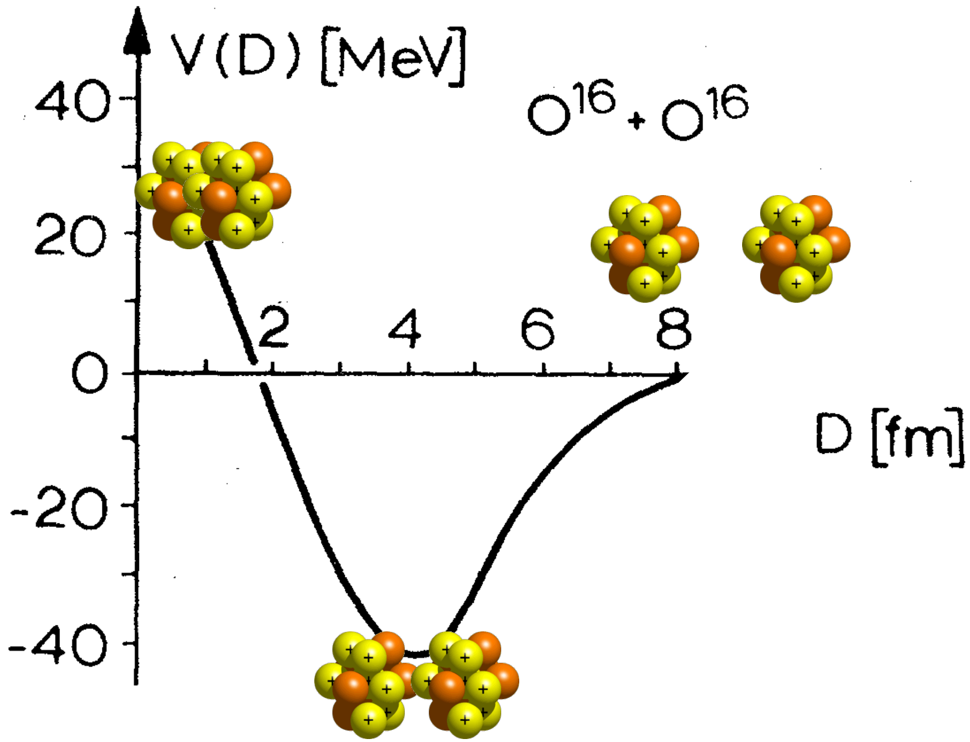
Nucleon-Nucleon



Pauli repulsion

Repulsion between composite systems of identical fermions at short distance

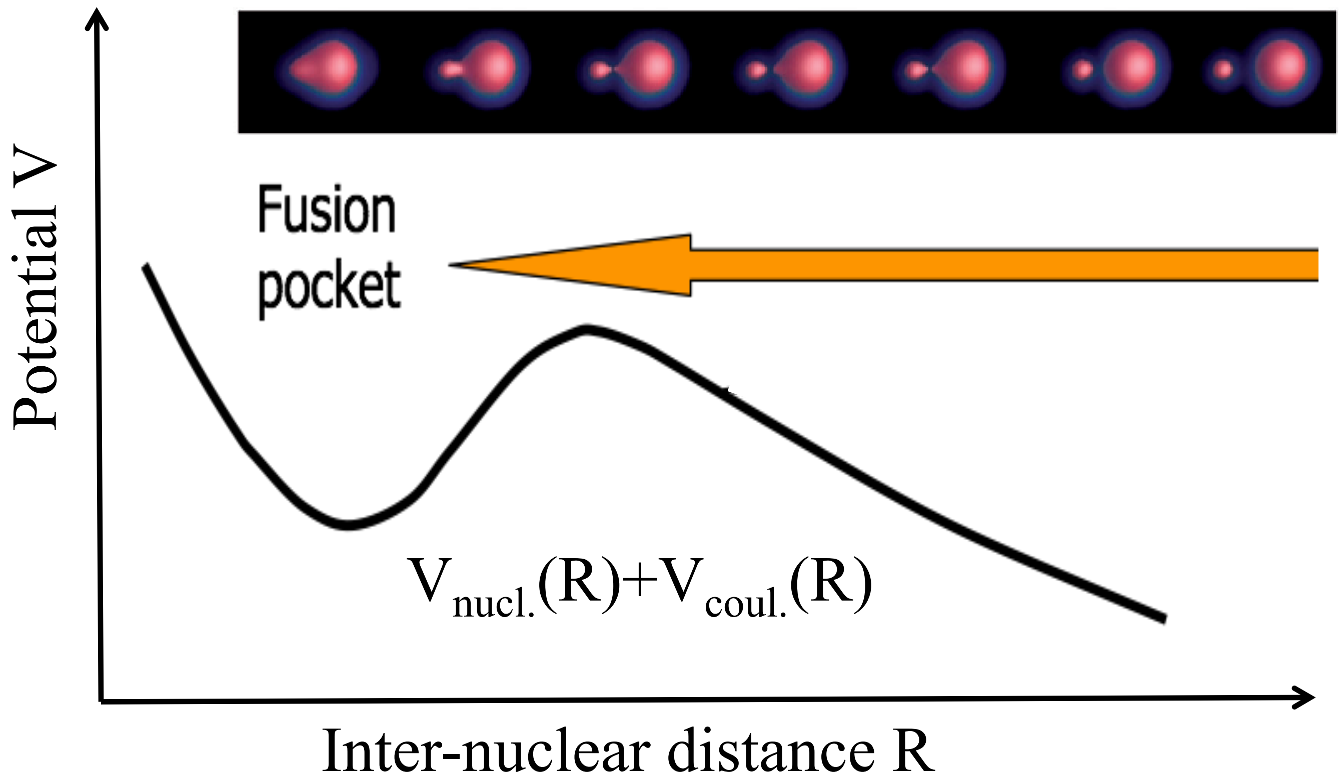
Nucleus-Nucleus



T. Fliessbach, Z. Phys. **247**, 117 (1971).

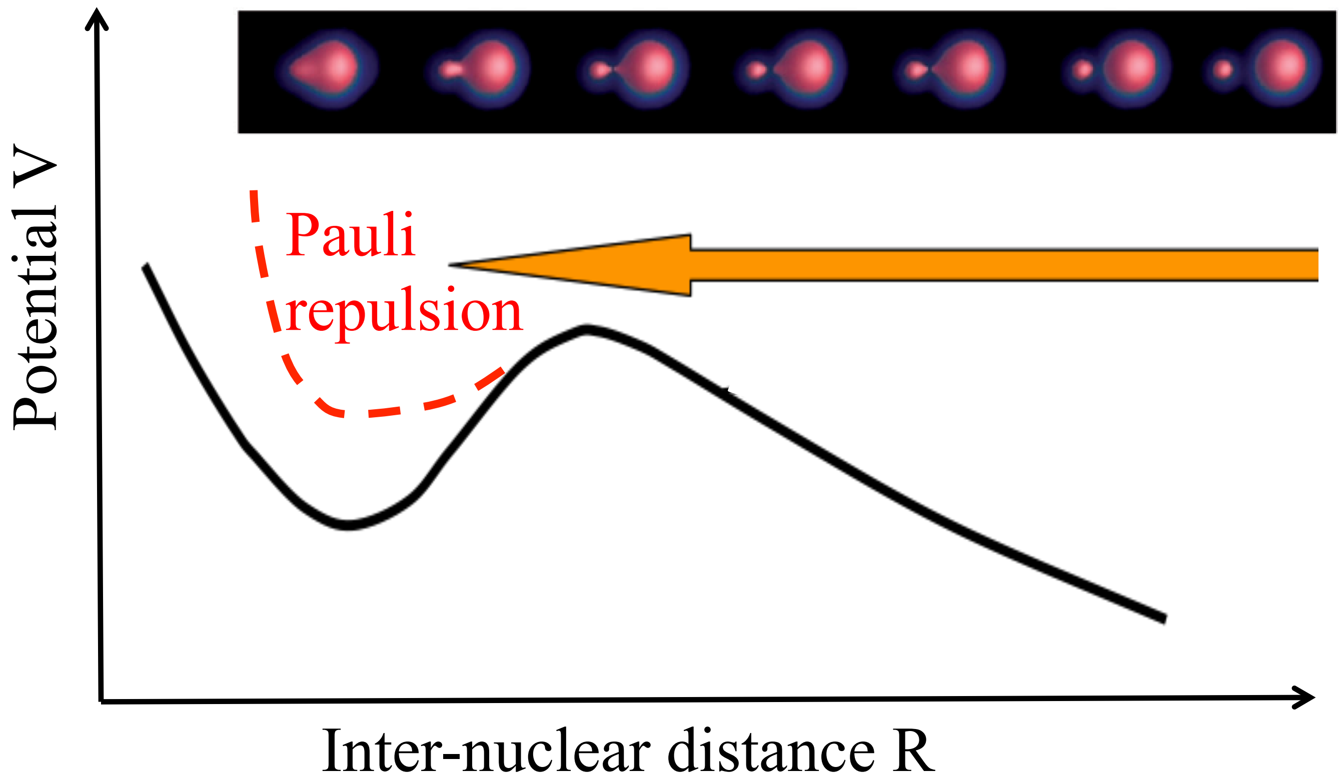
Pauli repulsion

Impact on fusion?



Pauli repulsion

Impact on fusion?

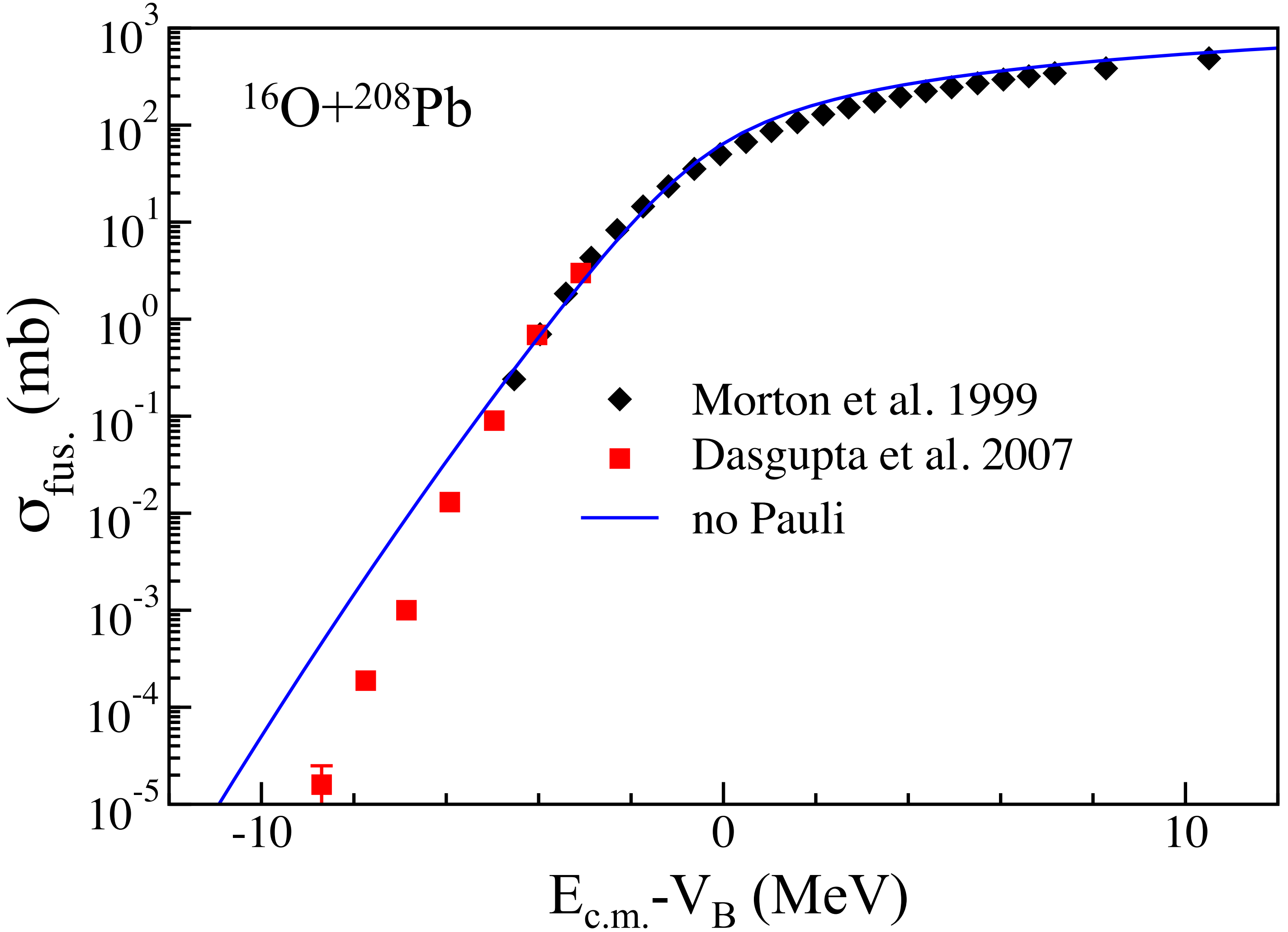


=> Pauli repulsion negligible at the barrier

Deep Sub-Barrier Fusion Hindrance

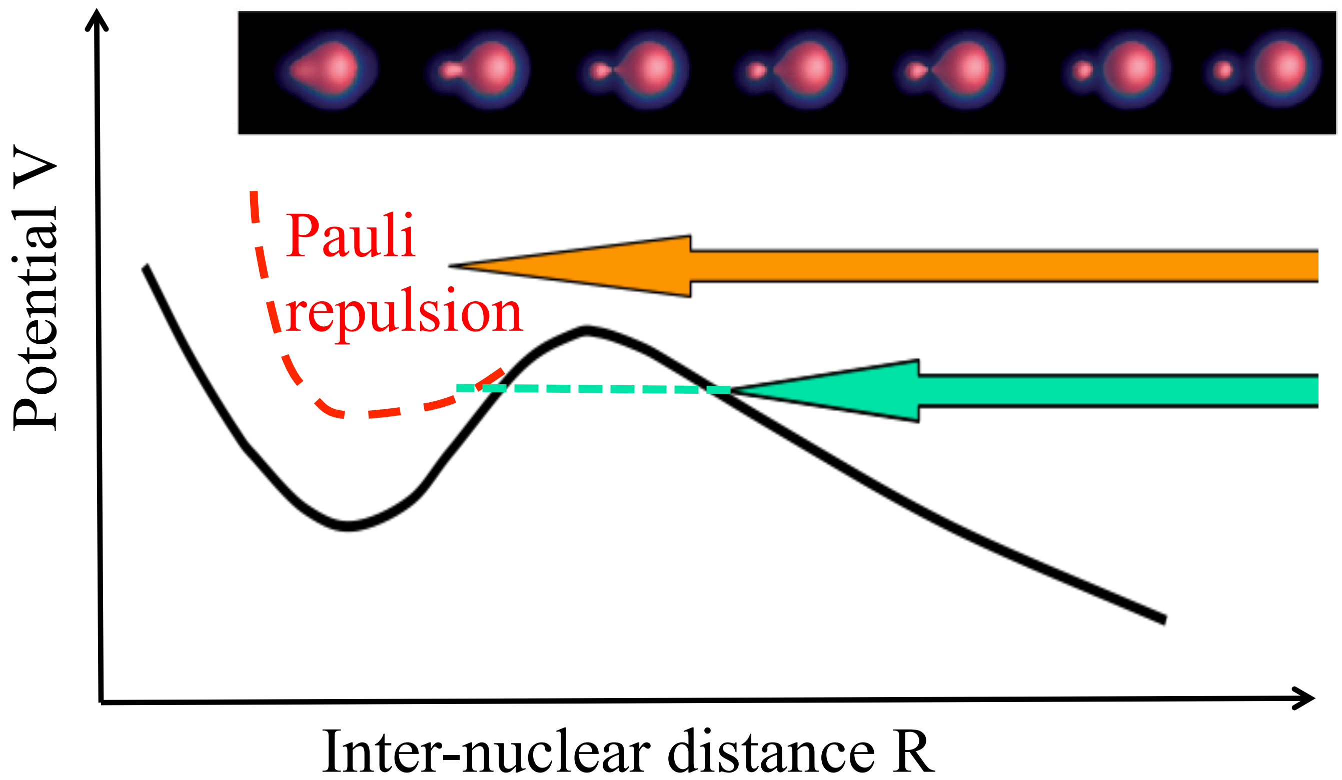
Jiang *et al.*, PRL (2002)

Deep Sub-Barrier Fusion Hindrance



Pauli repulsion

Impact on fusion?



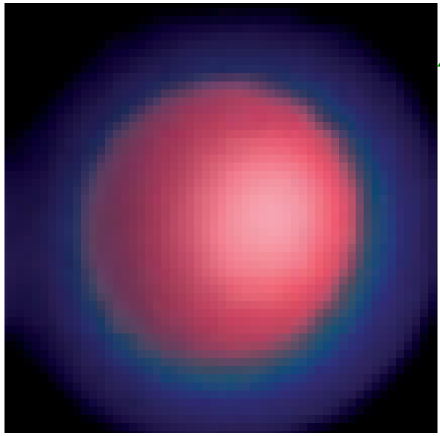
=> Pauli repulsion expected to reduce sub-barrier fusion

Microscopic approach

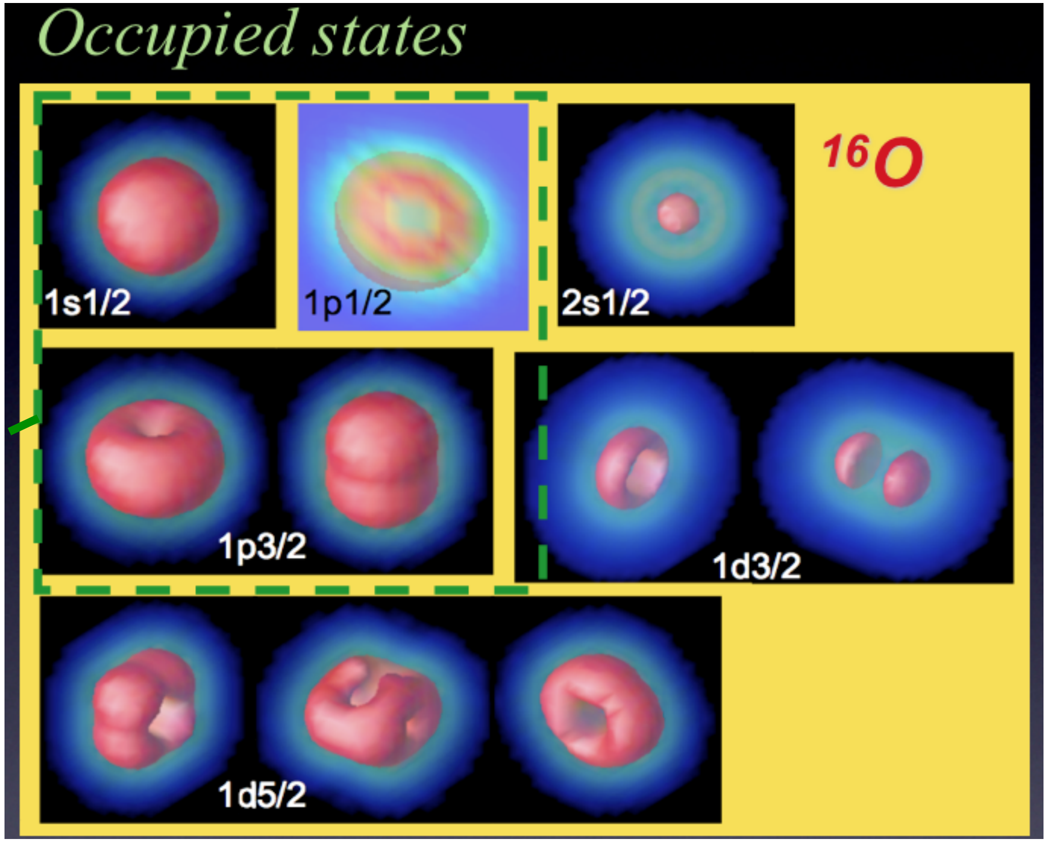
Hartree-Fock (HF)

$$\delta \langle \Phi | \hat{H} | \Phi \rangle = 0$$

Independent nucleons
= Slater determinant (=> Pauli)



$$\rho(\mathbf{r})$$



$$E[\rho] \equiv E[\rho, \tau, \mathbf{J} \cdots] = \int d^3r\, \mathcal{H}(\mathbf{r})$$

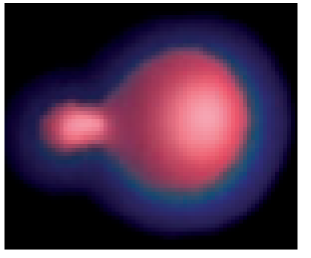
Microscopic approach

Frozen Hartree-Fock (FHF)

Brueckner *et al.*, PR **173**, 944 (1968)

$$V_{FHF}(R) = E[\rho_1 + \rho_2] - E[\rho_1] - E[\rho_2]$$

(No Pauli)



$\rho_1(\mathbf{r}) + \rho_2(\mathbf{r} - \mathbf{R})$

Microscopic approach

Frozen Hartree-Fock (FHF)

Brueckner *et al.*, PR **173**, 944 (1968)

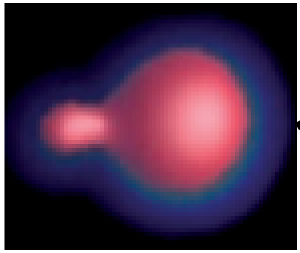
$$V_{FHF}(R) = E[\rho_1 + \rho_2] - E[\rho_1] - E[\rho_2]$$

(No Pauli)

Density-Constrained Frozen Hartree-Fock (DCFHF)

Simenel *et al.*, arXiv:1610.02663

$$\delta \langle \Phi | \left[\hat{H} - \int d\mathbf{r}\, \lambda(\mathbf{r}) \rho(\mathbf{r}) \right] | \Phi \rangle = 0$$

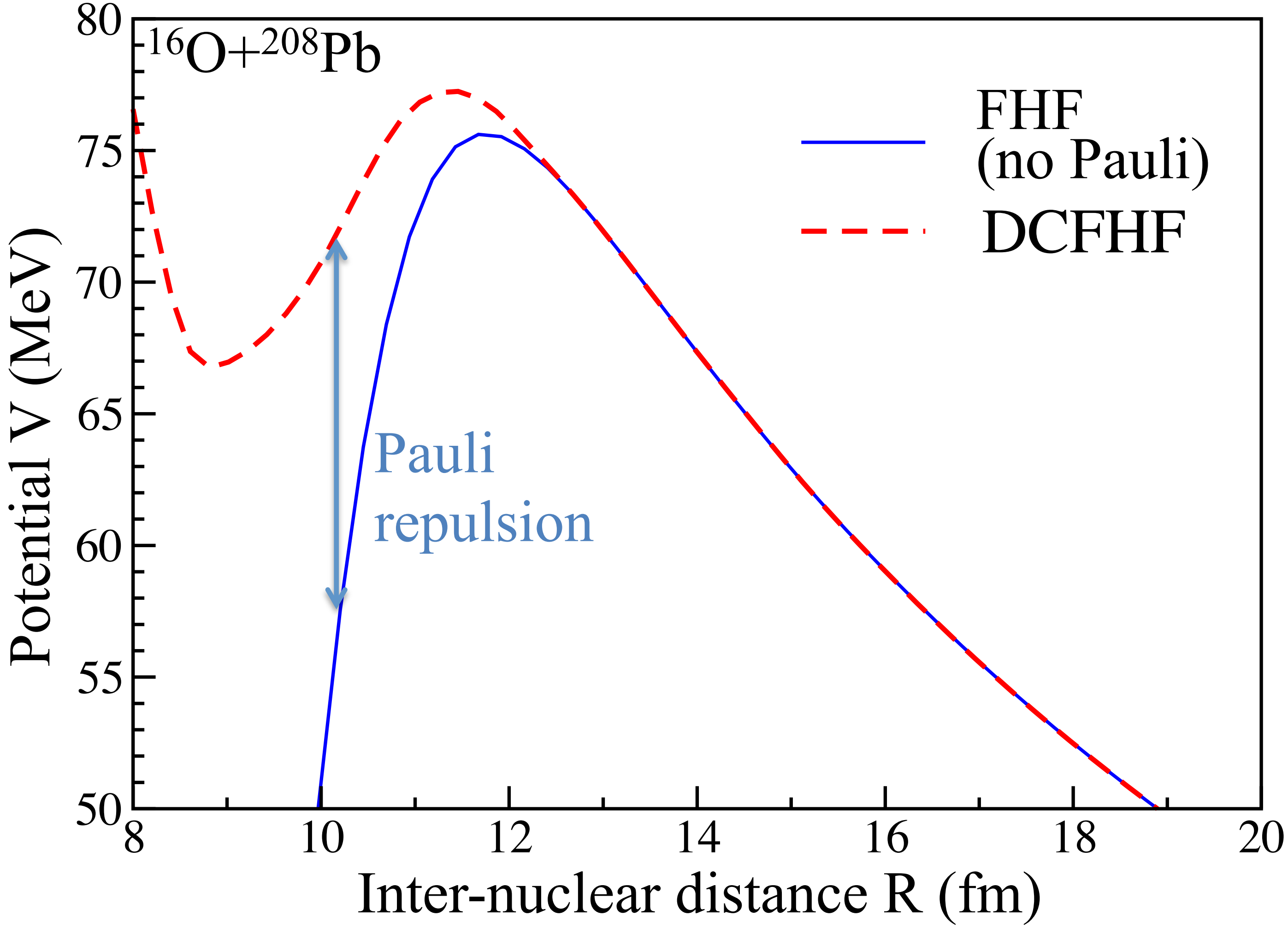


$\rho_1(\mathbf{r}) + \rho_2(\mathbf{r} - \mathbf{R})$

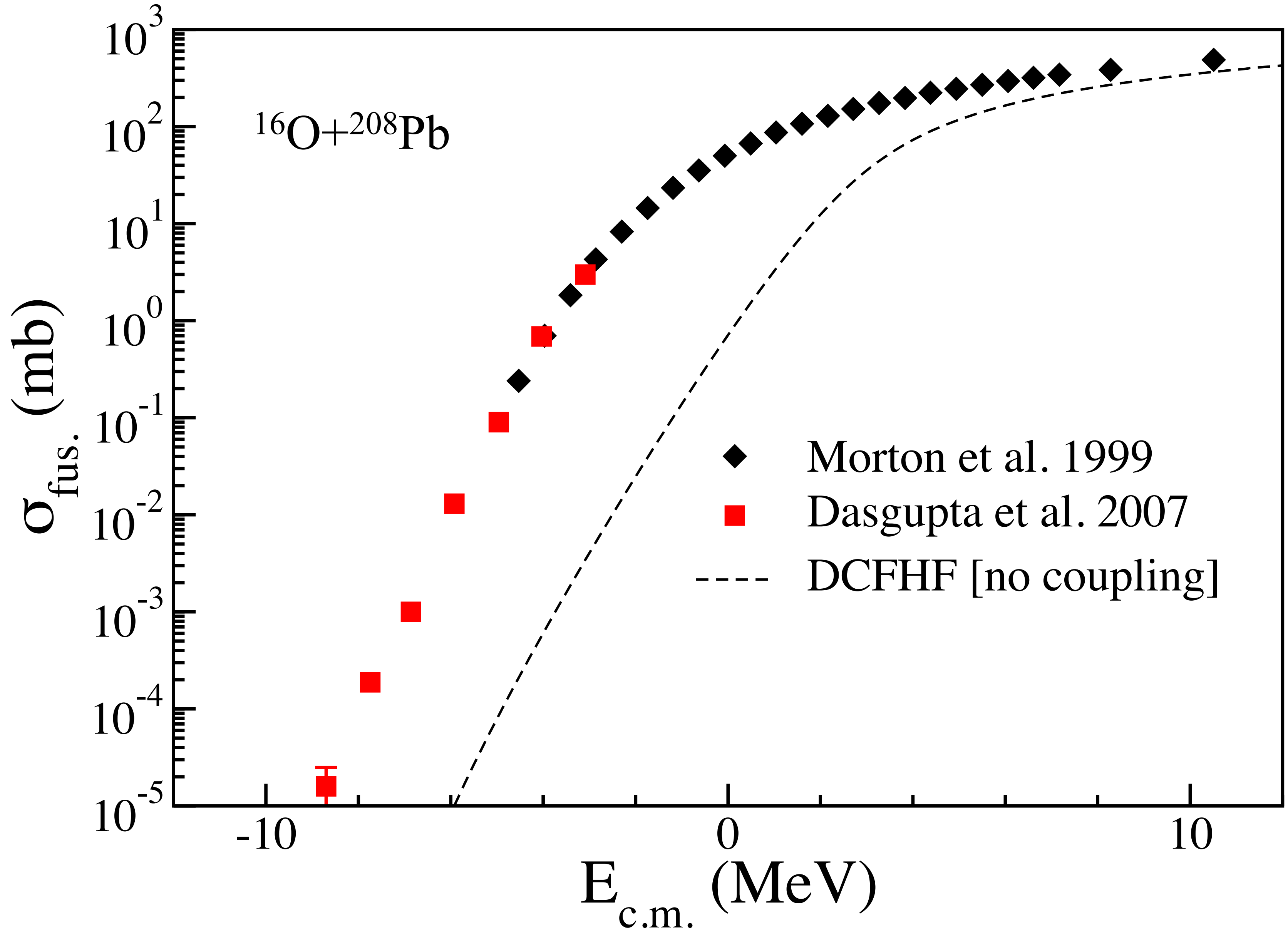
$$V_{DCFHF}(R) = \langle \Phi | \hat{H} | \Phi \rangle - E[\rho_1] - E[\rho_2]$$

Nucleus-nucleus potential

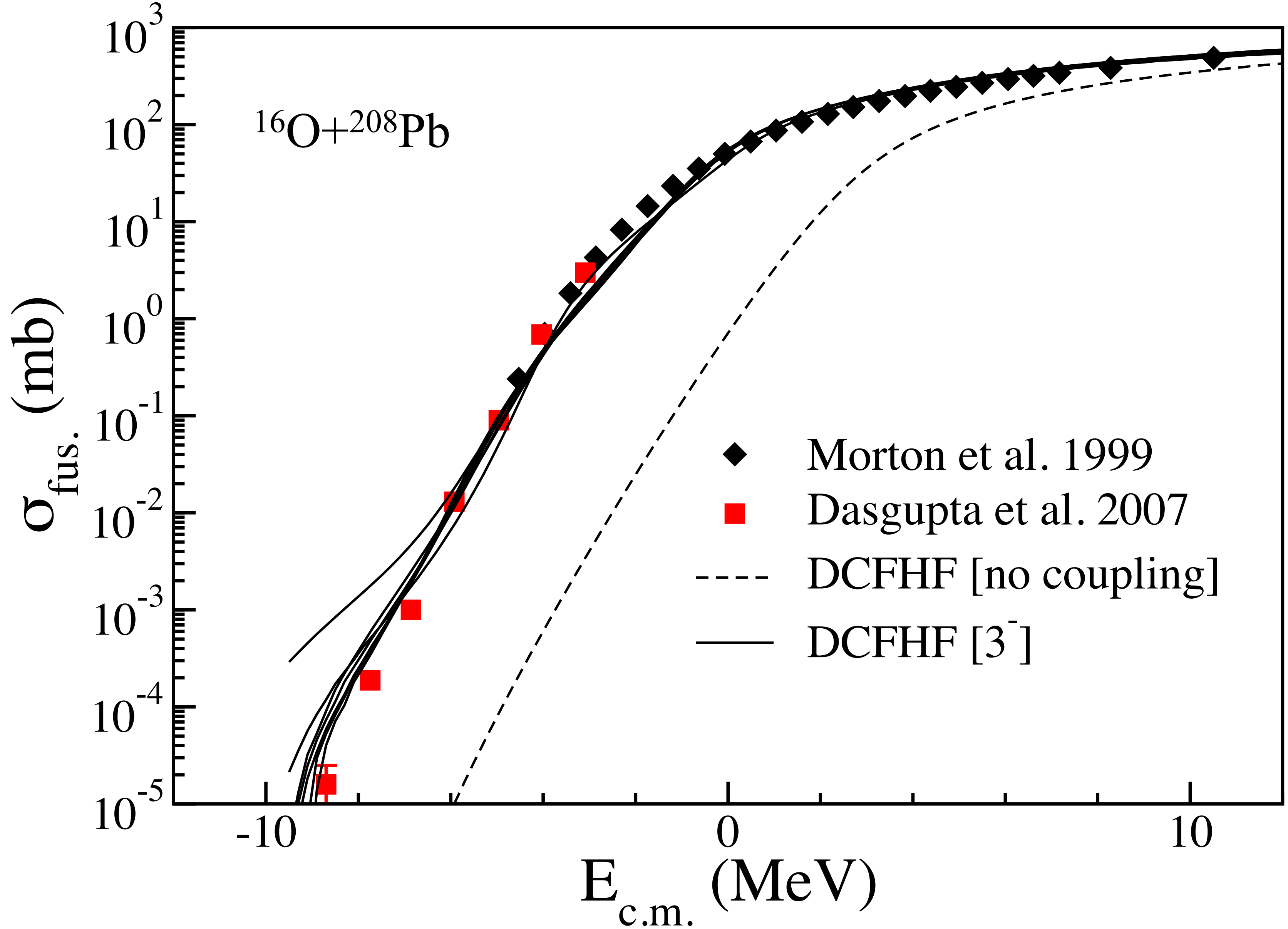
Pauli repulsion from DCFHF



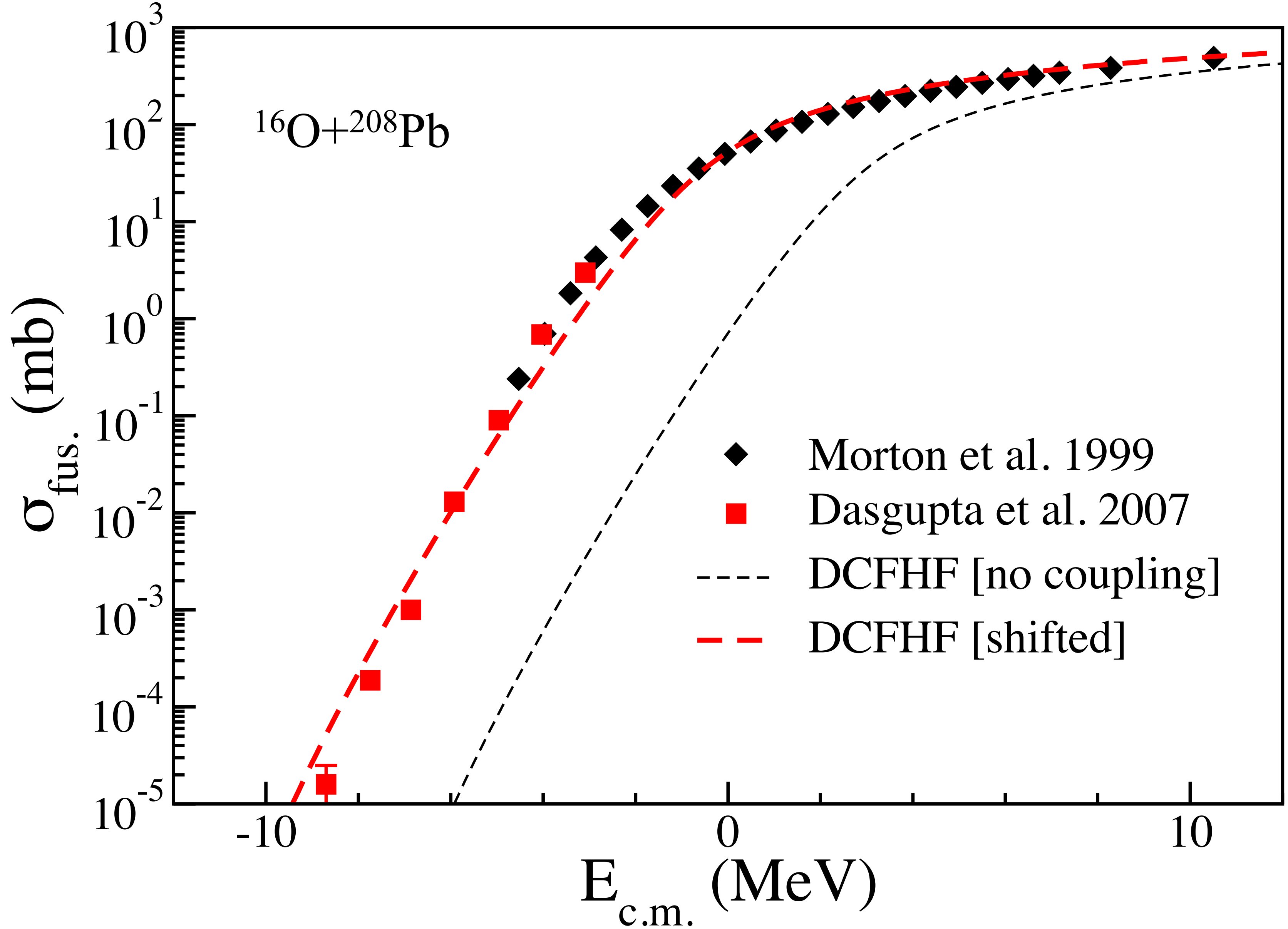
Deep Sub-Barrier Fusion Hindrance



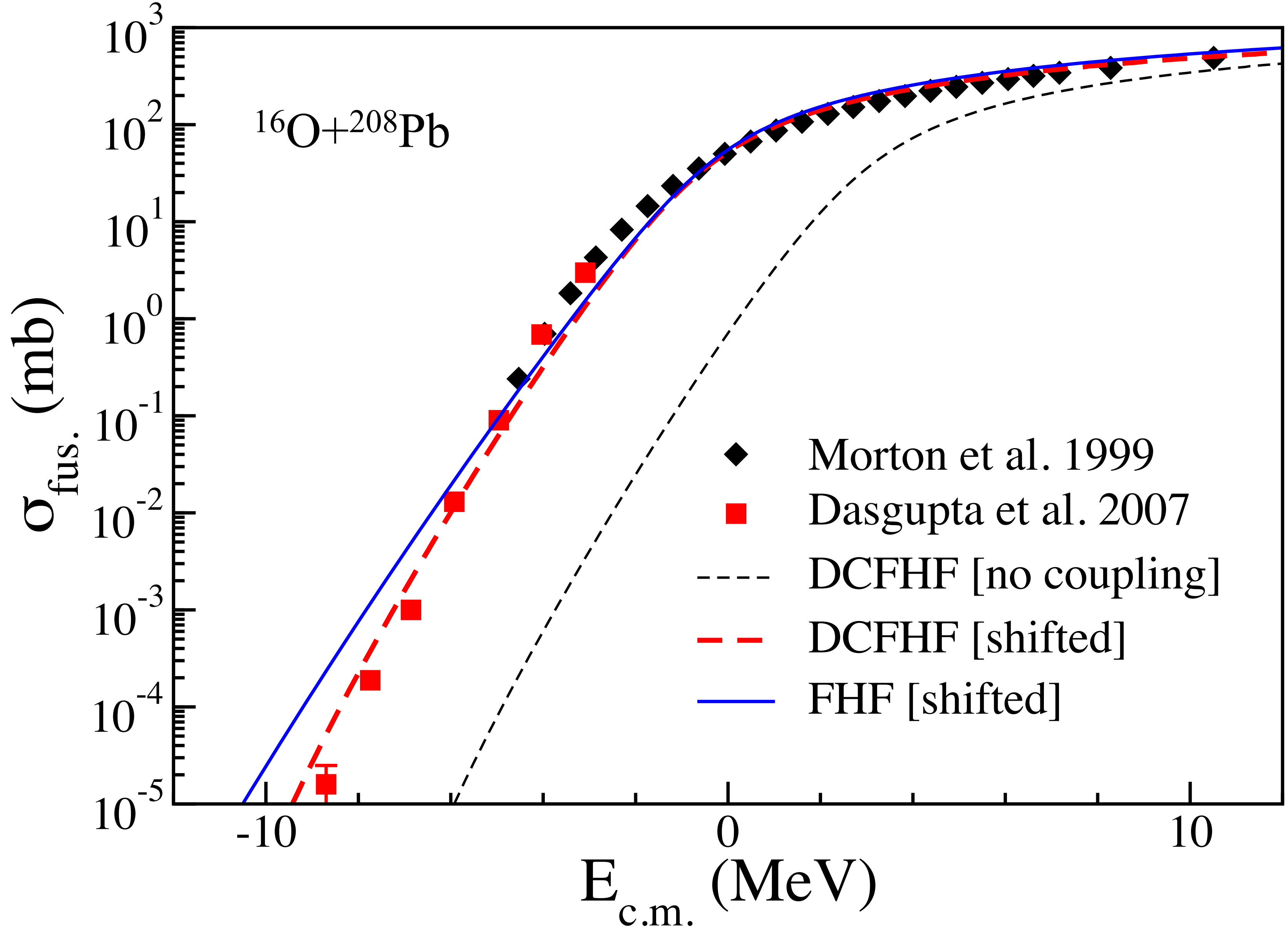
Deep Sub-Barrier Fusion Hindrance



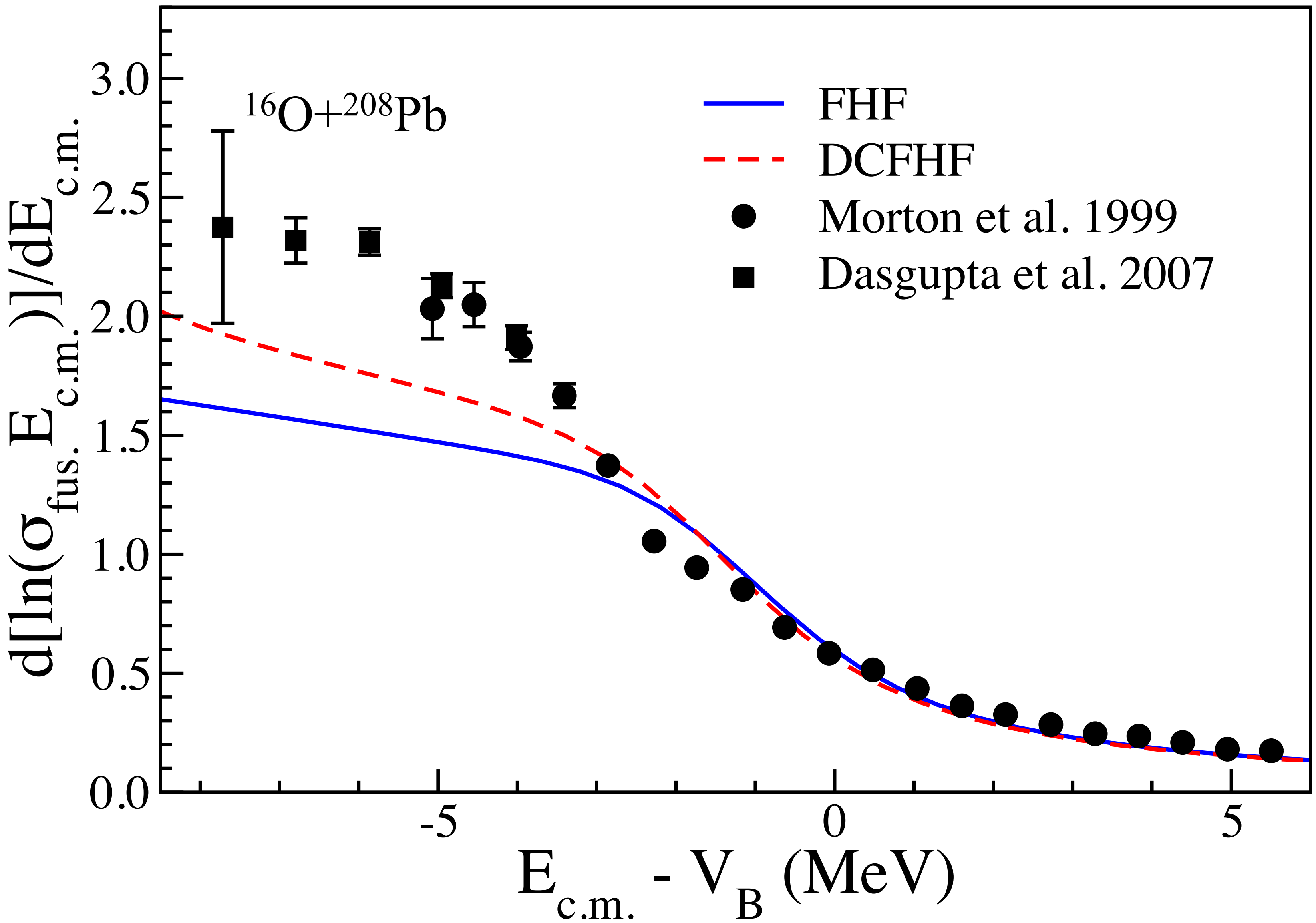
Deep Sub-Barrier Fusion Hindrance



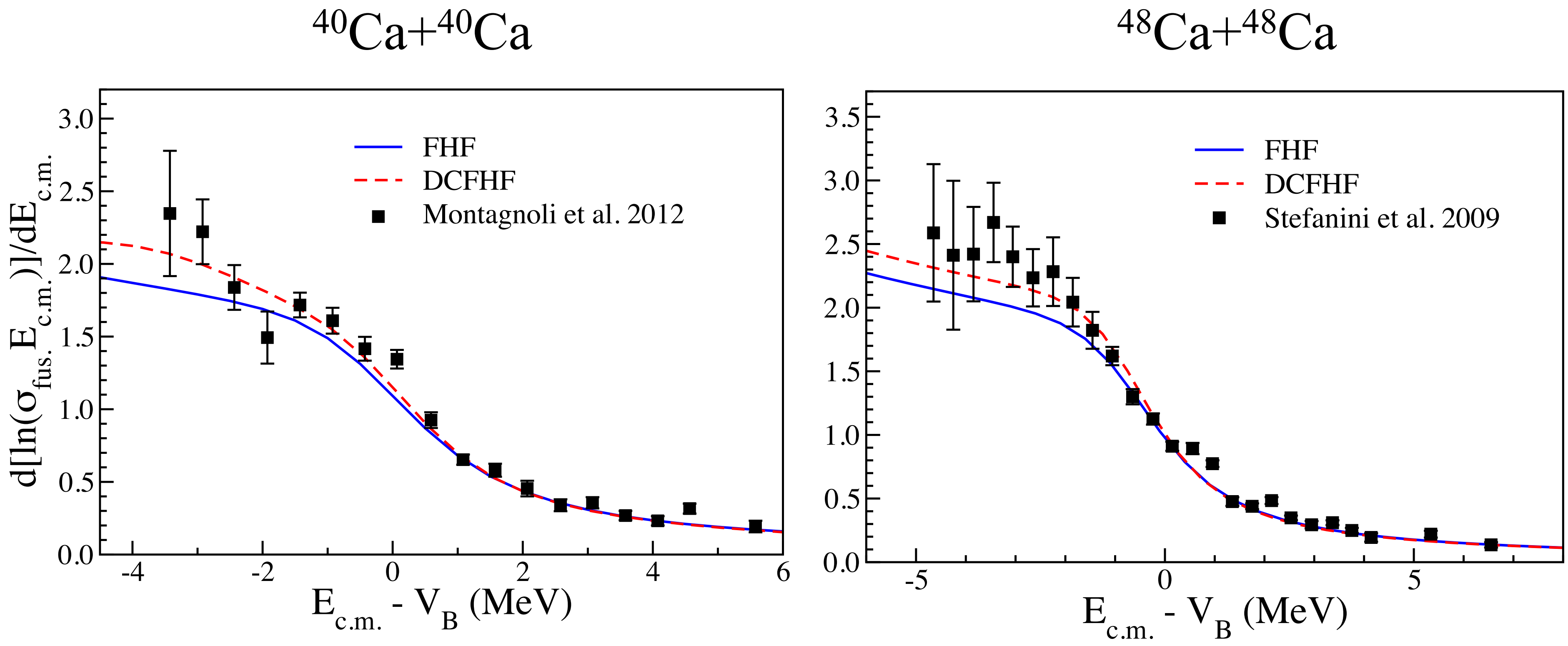
Deep Sub-Barrier Fusion Hindrance



Deep Sub-Barrier Fusion Hindrance



Deep Sub-Barrier Fusion Hindrance



Deep Sub-Barrier Fusion Hindrance

Other hindrance mechanisms

- Incompressibility (Misicu & Esbensen, PRL2006)
- Adiabaticity (Ichikawa et al., PRL 2009)
- Decoherence (Dasgupta et al., PRL 2007)
- Dissipation (Evers et al., PRC 2011)
- Vibration damping (Ichikawa et al., PRC 2015)
- …

=> Need for dynamical description

Microscopic approach

Time-Dependent Hartree-Fock (TDHF)

Dirac (1930)

$$\delta \langle \Phi | \left[\hat{H} - i\partial_t \right] | \Phi \rangle = 0$$

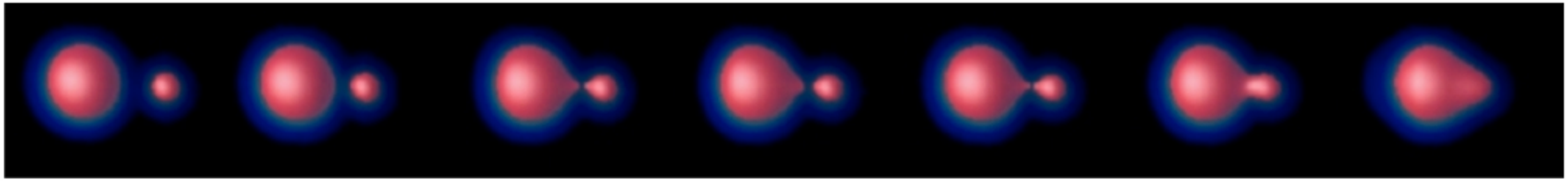
Microscopic approach

Time-Dependent Hartree-Fock (TDHF)

Dirac (1930)

$$\delta \langle \Phi | \left[\hat{H} - i\partial_t \right] | \Phi \rangle = 0$$

$^{16}O+^{208}Pb$



Microscopic approach

Time-Dependent Hartree-Fock (TDHF)

Dirac (1930)

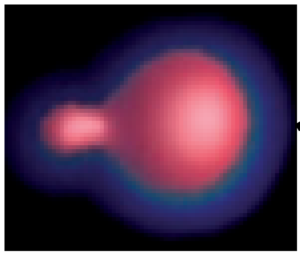
$$\delta \langle \Phi | \left[\hat{H} - i\partial_t \right] | \Phi \rangle = 0$$

=> Dynamical potential (Washiyama, Lacroix, PRC 2008)

Density-Constrained Time-Dependent Hartree-Fock (DCTDHF)

Umar and Oberacker, PRC **74**, 021601 (2006)

$$\delta \langle \Phi | \left[\hat{H} - \int d\mathbf{r}\, \lambda(\mathbf{r})\rho(\mathbf{r}) \right] | \Phi \rangle = 0$$



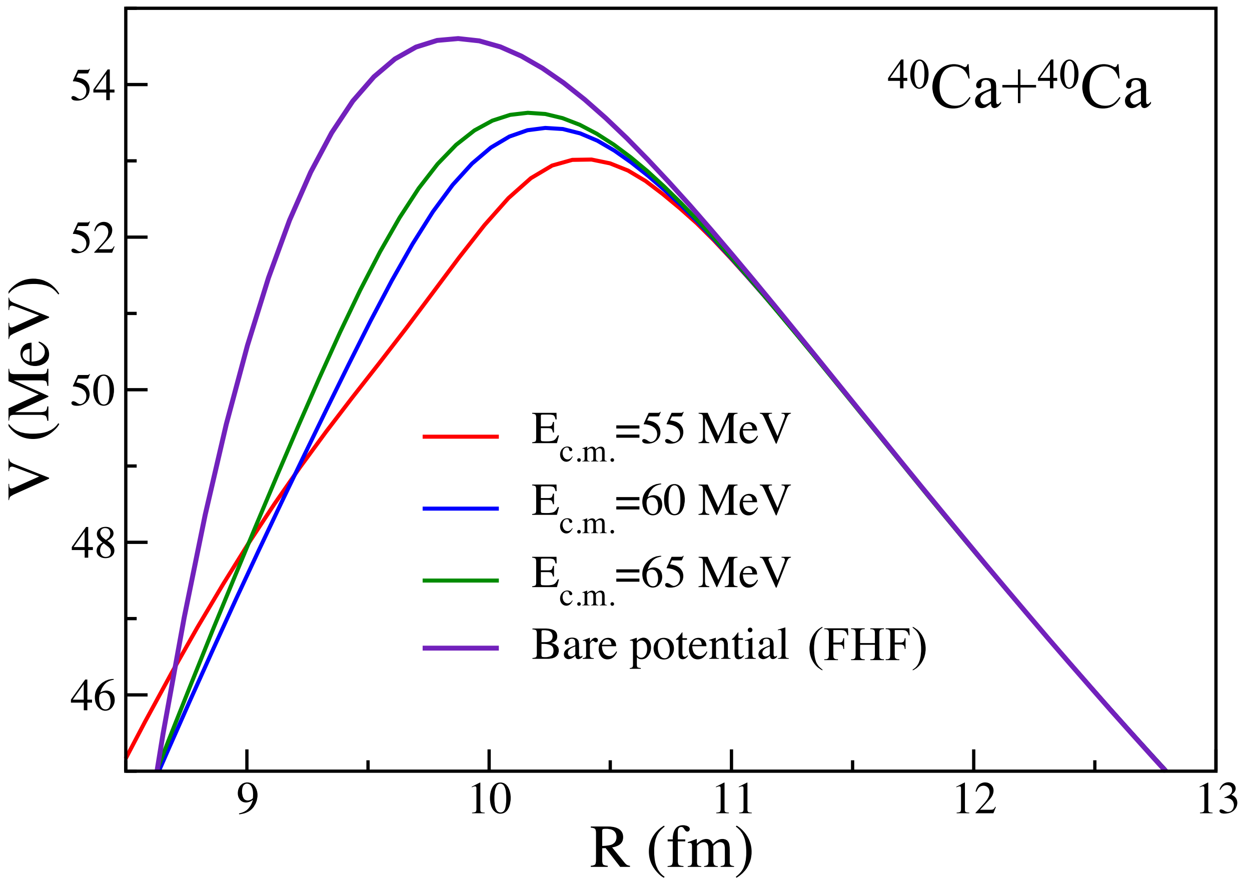
$$\rho_{TDHF}(\mathbf{r}, t)$$

$$V_{DCTDHF}[R(t)] = \langle \Phi | \hat{H} | \Phi \rangle - E[\rho_1] - E[\rho_2]$$

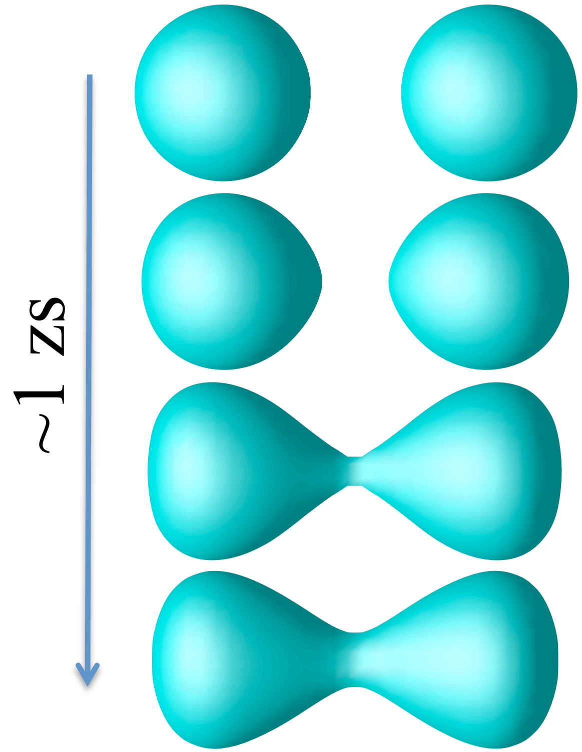
Dynamics

Density-Constrained Time-Dependent Hartree-Fock (DCTDHF)

Umar, CS, Oberacker, PRC 2014



CS *et al.*, PRC 2013

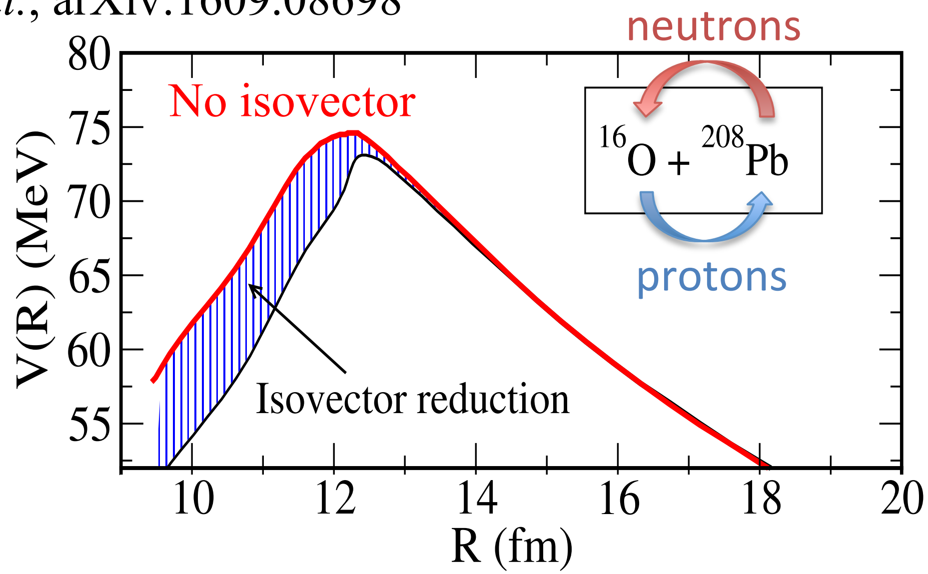


=> Energy-dependent potential (Washiyama, Lacroix, PRC 2008)

Dynamics

Transfer contribution to the potential

Godbey *et al.*, arXiv:1609.08698

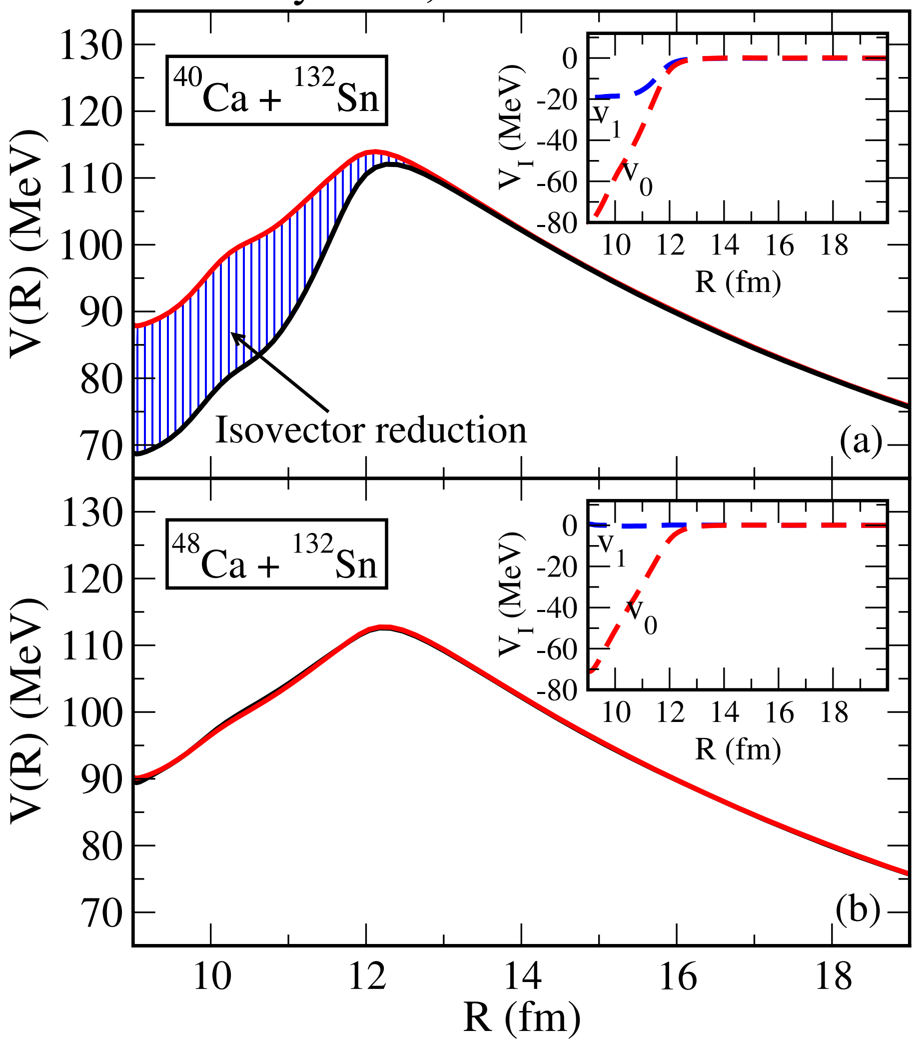


$$\mathscr{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau_0 + \mathscr{H}_0(\mathbf{r}) + \mathscr{H}_1(\mathbf{r}) + \mathscr{H}_C(\mathbf{r})$$

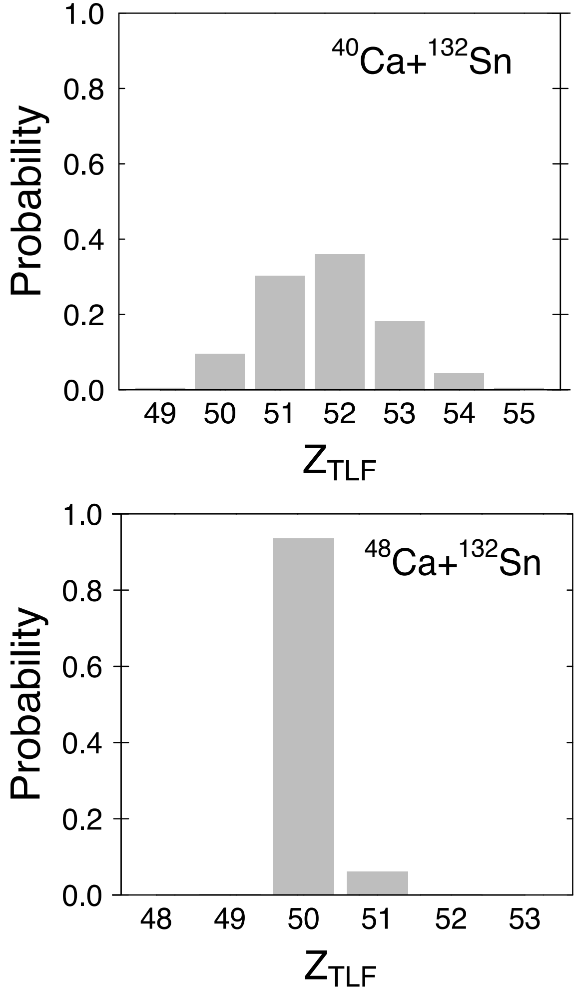
Dynamics

Transfer contribution to the potential

Godbey *et al.*, arXiv:1609.08698



Vo Phuoc *et al.*, PRC 2016



Conclusions

- Effect of Pauli exclusion principle on fusion
- New microscopic approach:
  Density-Constrained Frozen Hartree-Fock
  => bare potential
  Density-Constrained Time-Dependent Hartree-Fock
  => dynamical potential
- Pauli repulsion inside the fusion barrier
- Deep sub-barrier fusion hindrance

Perspectives

- Nucleosynthesis in stars, e.g., $^{12}C+^{12}C$
- Energy-dependence
- Many-body tunnelling