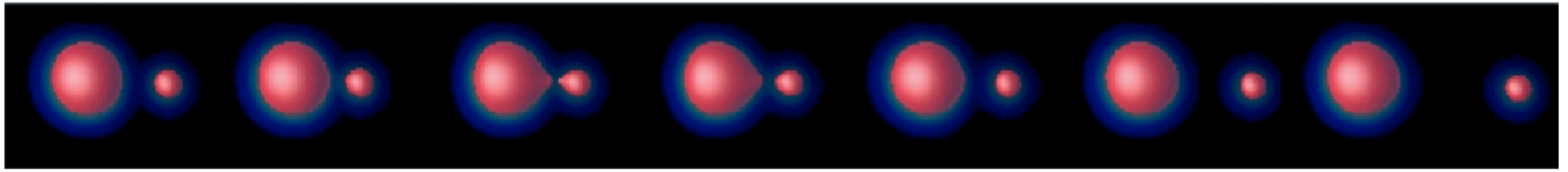
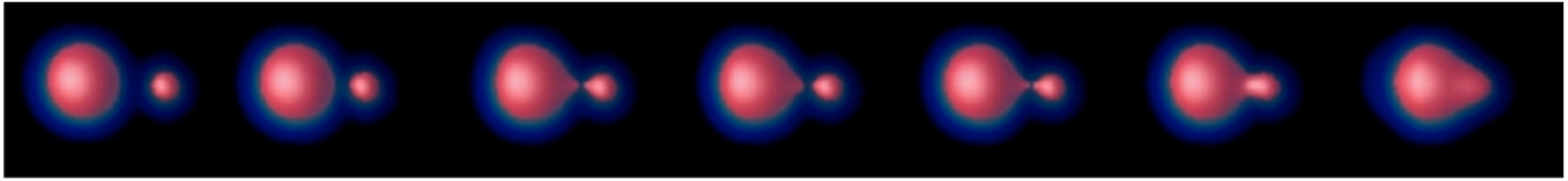


Microscopic Approach to Heavy-Ion Fusion

Cédric Simenel

Department of Nuclear Physics, ANU (Canberra)



Open questions in fusion studies

- Deep sub-barrier fusion hindrance
- Tunnelling of a many-body system
- Coupling to transfer and break up channels
- Fusion with exotic nuclei (neutron skin, isospin dynamics…)

Outline

- **Nucleus-nucleus potential with Pauli repulsion**
  Impact on deep-sub barrier fusion
- **Dynamical effects:**

  Vibrational couplings

  Fusion with exotic nuclei

Nucleus-nucleus potential with Pauli repulsion

Frozen Hartree-Fock (FHF)

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

➔ No Pauli

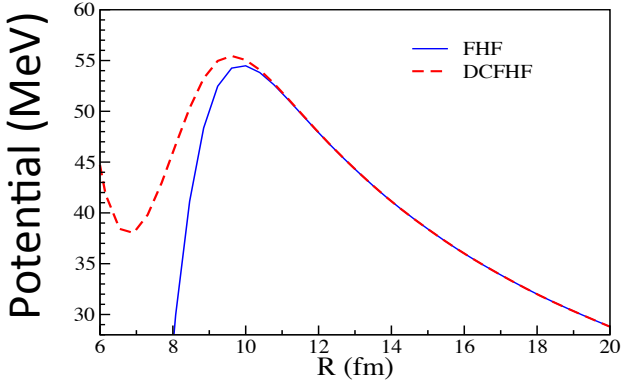
Density-Constrained Frozen Hartree-Fock (DCFHF)

Simenel, Umar *et al.*, in preparation

➔ Includes Pauli

Nucleus-nucleus potential with Pauli repulsion

sion potential extracted from the



developed to reconstruct the states following a G
orthogonalization. However, these methods coul
using i-analytic methods. The DCFHF
ut any approximation.

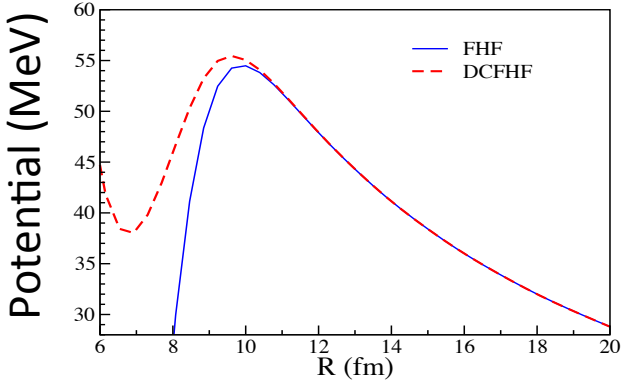
us now discuss another t tho
nt for Pauli repulsion simply by increasin

FIG. 2. (Color online) Pauli repu
difference between the DCFHF
dashed line is obtained from Eq. (

The evaluation of observable

Nucleus-nucleus potential with Pauli repulsion

sion potential extracted from the



developed to reconstruct the states following a G
orthogonalization. However, these methods coul
using i-analytic methods. The DCFHF
ut any approximation.

us now discuss another t tho
nt for Pauli repulsion simply by increasin

FIG. 2. (Color online) Pauli repu
difference between the DCFHF
dashed line is obtained from Eq. (

The evaluation of observable

Pauli repulsion

Nucleus-nucleus potential with Pauli repulsion

sion potential extracted from the

developed to reconstruct the states following a G

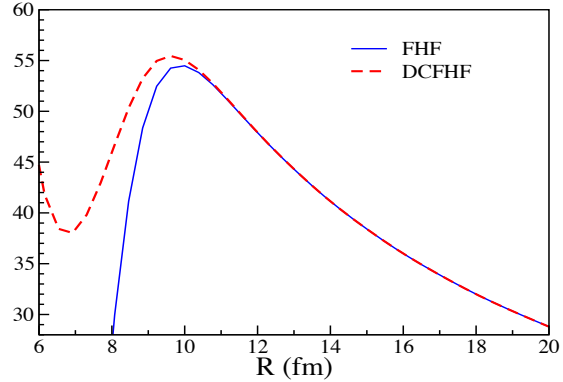


FIG. 2. (Color online) Pauli repu
difference between the DCFHF
dashed line is obtained from Eq. (

Pauli repulsion

Log slope

and FHF potentials. The dotted-
5) (see text).

s, however, requires antisym-

gonalization. However, these methods coul
using i-analytic methods. The DCFHF
ut any approximation.

us now discuss another t tho
nt for Pauli repulsion simply by increasin

orthc gonalization. However, these methods co
plied using semi-analytic methods. The DCFH
withc ut any approximation.

Le us now discuss another traditional meth
accu nt for Pauli repulsion simply by increas

The evaluation of observable

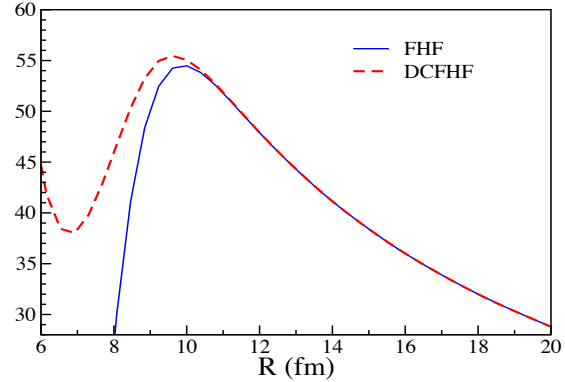
difference between the DCFHF
dashed line is obtained from Eq.

The evaluation of observable

Nucleus-nucleus potential with Pauli repulsion

sion potential extracted from the

developed to reconstruct the states following a G



and FHF potentials. The dotted-
5) (see text).

s, however, requires antisym-

orthc gonalization. However, these methods co
plied using semi-analytic methods. The DCFH
withc ut any approximation.

Le us now discuss another traditional meth
accu nt for Pauli repulsion simply by increas

FIG. 2. (Color online) Pauli repu
difference between the DCFHF
dashed line is obtained from Eq. (

Pauli repulsion

-> Deep sub-barrier fusion hindrance

The evaluation of observable

difference between the DCFHF
dashed line is obtained from Eq.

The evaluation of observable

Log slope

Vibrational couplings

were shown (25) to give rise to a Gaussian distributic

Sub-barrier fusion enhancement due to dynamical couplings:

- Low-lying vibrations
- Rotational states
- Transfer

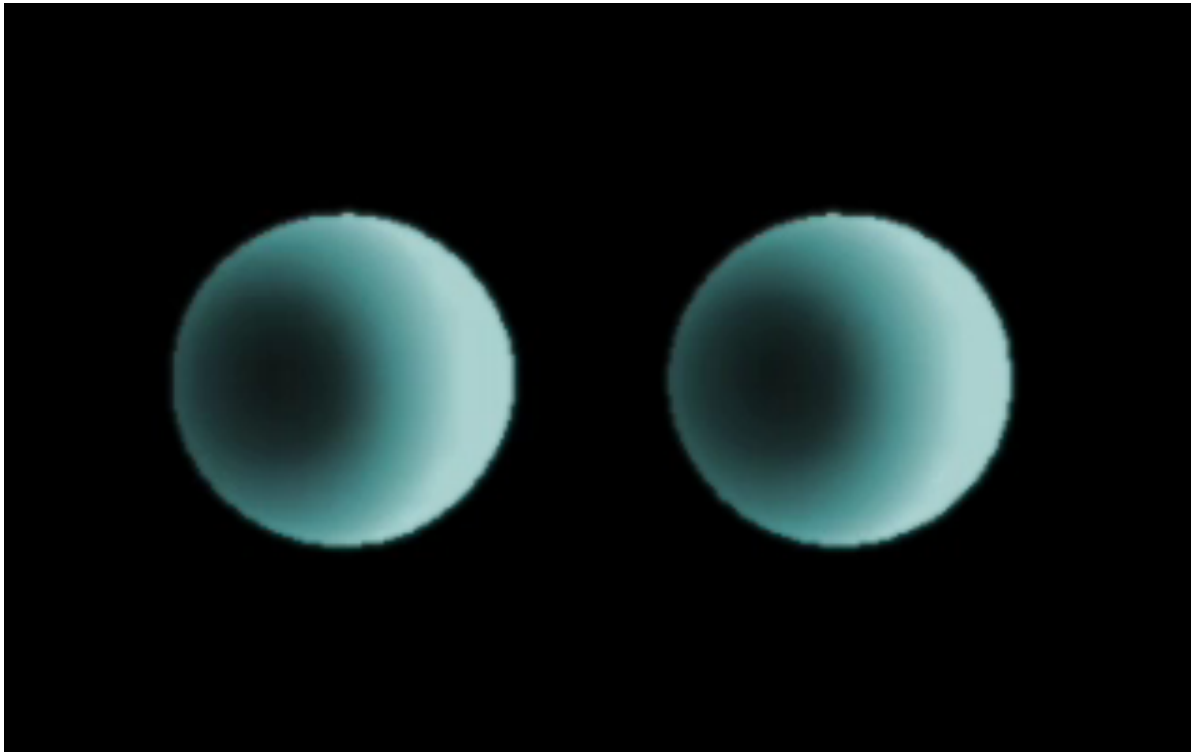
Can we confirm this interpretation of sub-barrier fusion enhancement with microscopic calculations?

See Dasgupta *et al.*, Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998) - *Review*

Vibrational couplings

Time-dependent Hartree-Fock

$^{40}Ca+^{40}Ca$
E_{cm}=53.3 MeV



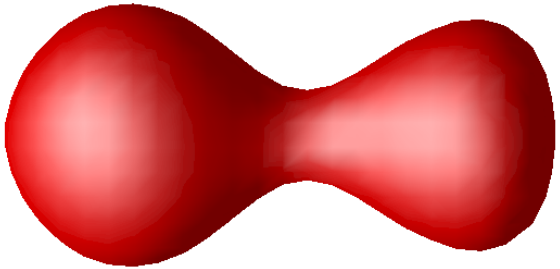
Simenel *et al.*, PRC **88**, 043604 (2013)

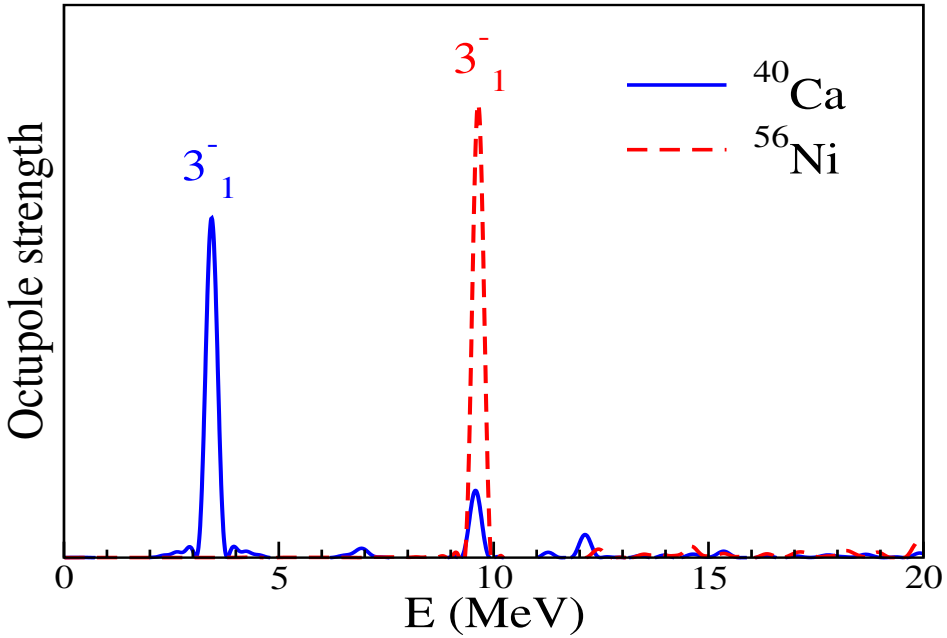
Vibrational couplings

Time-dependent Hartree-Fock

$^{40}Ca+^{56}Ni$

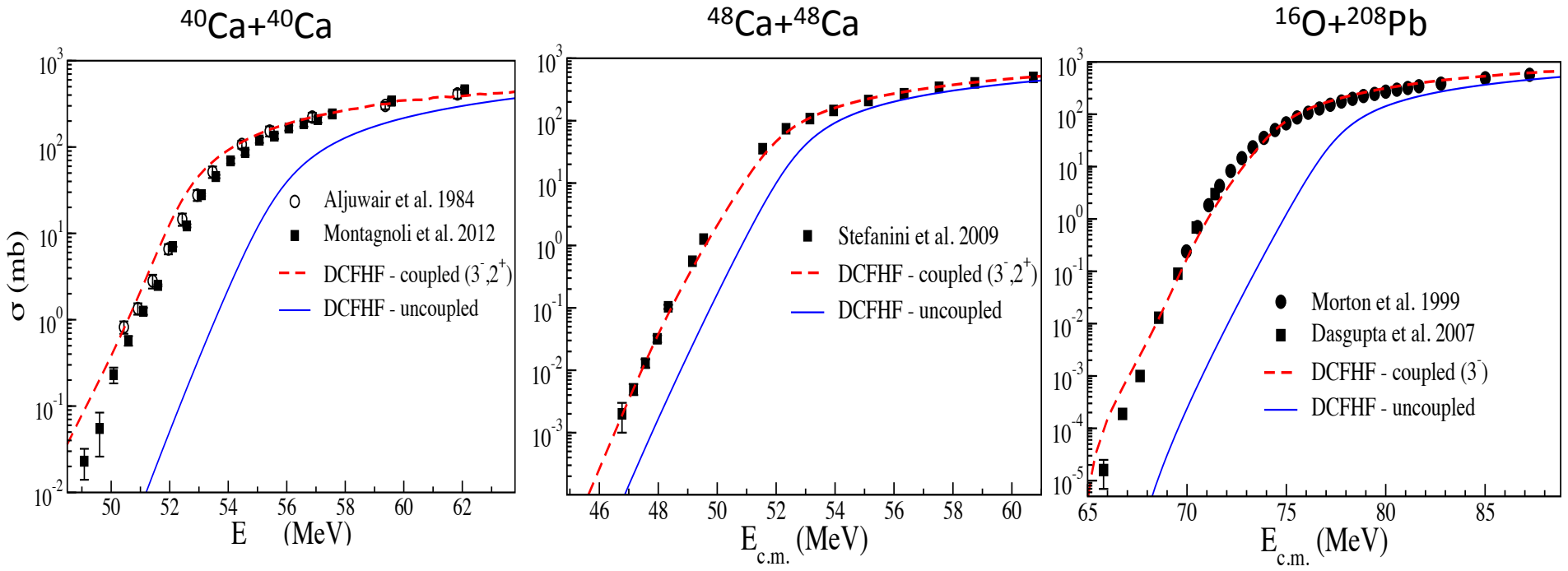
E_{cm}=74.2 MeV





TDHF (=RPA) vibrational spectra (octupole)

Vibrational couplings



CS, Umar *et al.*, in preparation

Fusion with exotic nuclei

- Neutron skin reduces the bare barrier
- Washed out by dynamics
- Dynamics increases V_B for A>50

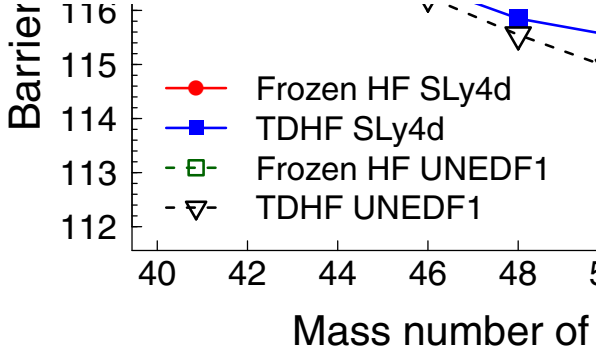


FIG. 5. Bare potential barrier energies from
and TDHF fusion thresholds for ^{A}Ca + ^{116}Sn ar
to the calcium mass number for the SLy4d (soli
(dashed lines) parametrizations.

Vo-Phuoc, CS, Simpson, PRC **93**, 034604 (2016)

Fusion with exotic nuclei

- Neutron skin reduces the bare barrier
- Washed out by dynamics
- Dynamics increases V_B for A>50
- Charge transfer affects Coulomb

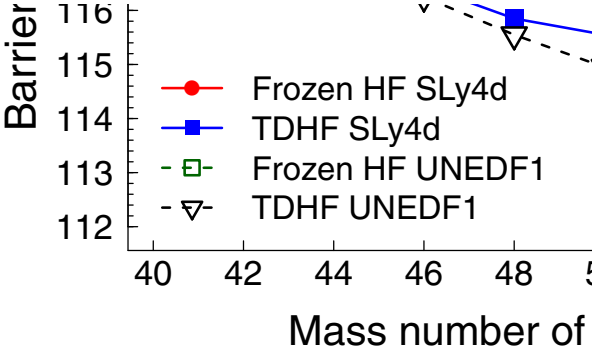


FIG. 5. Bare potential barrier energies from
and TDHF fusion thresholds for ^{A}Ca + ^{116}Sn ar
to the calcium mass number for the SLy4d (soli
(dashed lines) parametrizations.

40 42

FIG. 9. The avera
axis) of the TLF. T
anticipated $\overline{Z}_{TLF}$ valu
with the TLF having
(horizontal dotted lin

Vo-Phuoc, CS, Simpson, PRC **93**, 034604 (2016)

Fusion with exotic nuclei

- Neutron skin reduces the bare barrier
- Washed out by dynamics
- Dynamics increases V_B for A>50
- Charge transfer affects Coulomb
- Isospin equilibration

Density-Constrained TDHF
Godbey, Umar, CS, in preparation

FIG. 2. (Color online) For the O+ Pb system; isoscalar DC-TDHF potentials. The shaded region c the reduction originating from the isovector contribut ergy density. (b) Plotted are the isoscalar and isovector to the interaction barrier without the Coulomb potentia

As an example of a more asymmetric system w calculations for the ^{16}O+^{208}Pb system. In Fig. the same quantities as in Fig. 1. The TDHF was $E_{\rm c.m.} = 75$ MeV. Here we see a substantial e of sub-barrier fusion due to the isovector dynan Fig. 2(b) shows the individual isoscalar and isov butions to the barrier without the Coulomb inte

R (fm)

FIG. 4. (Color online) For the ^{48}Ca+^{132}Sn system; isoscalar DC-TDHF potentials. For this reaction we see originating from the isovector contribution to the energ Plotted are the isoscalar and isovector contributions to t barrier without the Coulomb potential.

In summary, we have developed a microscopic study the effect of isospin dynamics on fusion b have shown that for most systems isovector dyna in the thinning of the barrier thus enhancing the

Conclusions

- Do not forget Pauli
- Do not forget microscopic
- Do not forget dynamics

Perspectives

- Many-body tunnelling
- Dissipation and transfer in Coupled-Channels
- Sensitivity of the force

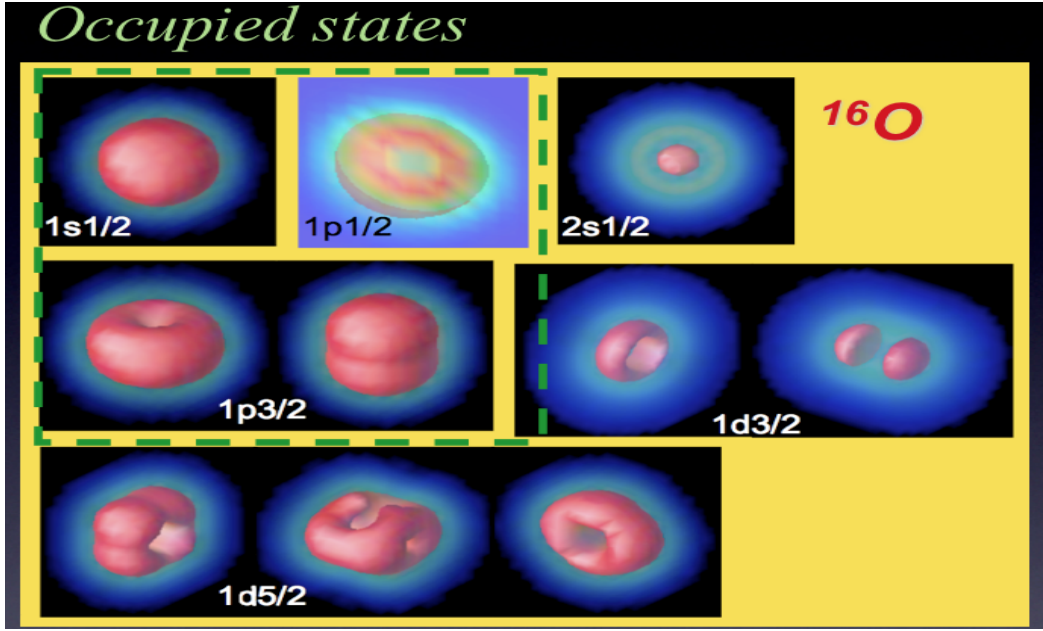
Collaboration

- ANU: Dasgupta, Hinde, McRae, Simenel, Simpson, Vo-Phuoc, Williams
- Vanderbilt: Godbey, Oberacker, Umar
- Strasbourg: Bourgin, Courtin, Haas

TDHF for heavy-ion collisions

HF calculations of the collision partners

Energy density functional (Skyrme SLy4*d*) from *structure* only

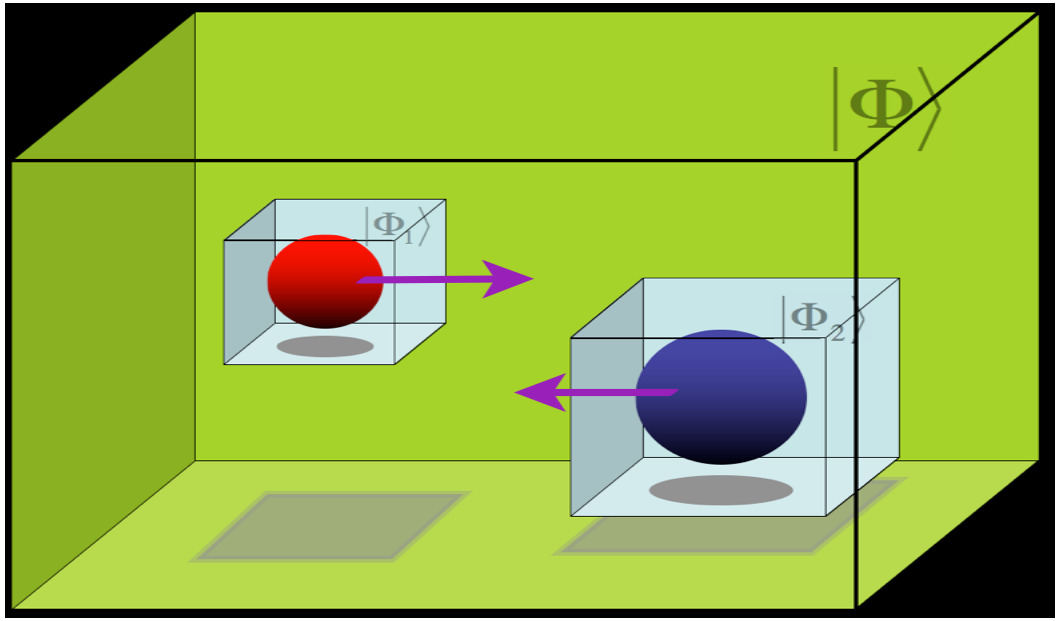


C.S., Lacroix, Avez, «Quantum Many-Body Dynamics: applications to nuclear reactions» (VDM Verlag) 2010

TDHF for heavy-ion collisions

Initial state

Galilean boost



C.S., Lacroix, Avez, «Quantum Many-Body Dynamics: applications to nuclear reactions» (VDM Verlag) 2010

Fusion

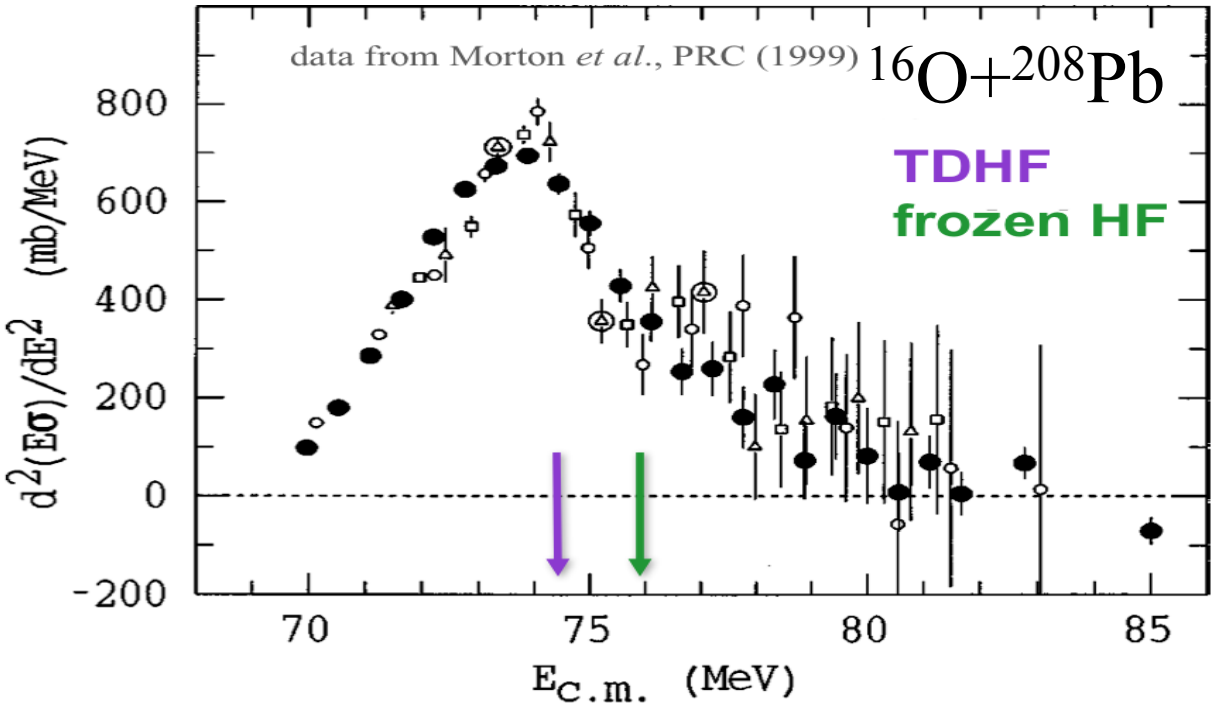
Fusion barrier

Experimental barrier distributions

Dasgupta *et al*,
Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998)

Dynamical effects on the barrier

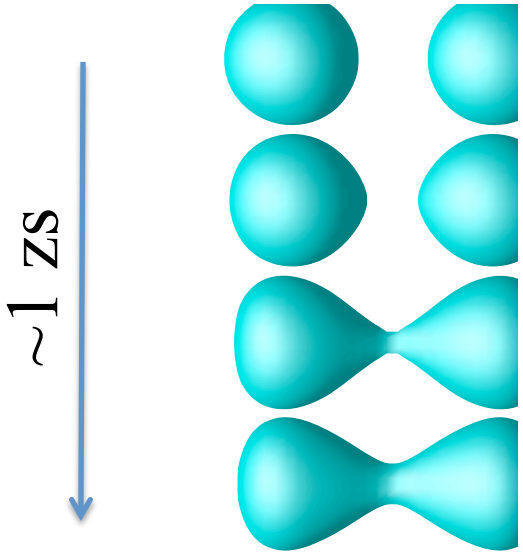
C.S. and Avez, IJMPE **17**, 31 (2008)

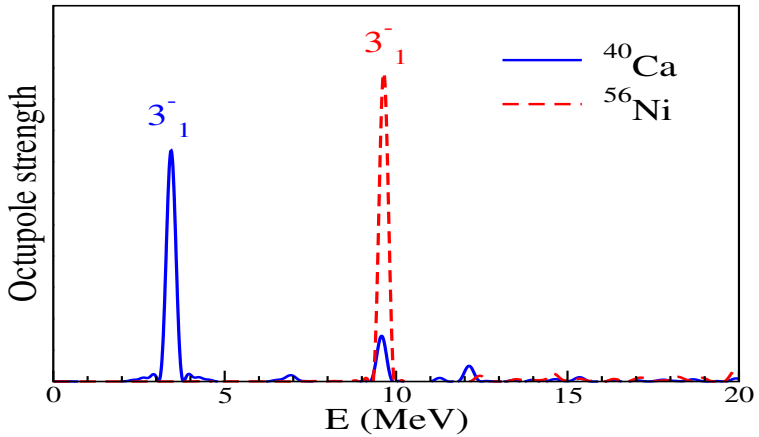


Fusion

Comparison between $^{40}Ca+^{40}Ca$ and $^{56}Ni+^{56}Ni$

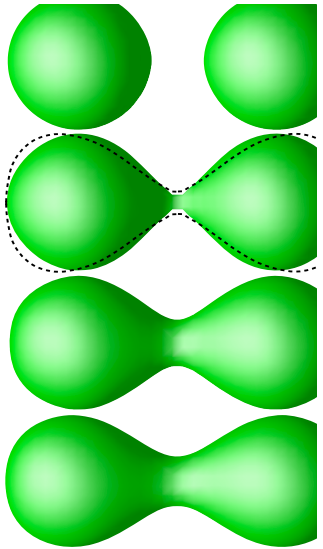
$^{40}Ca+^{40}Ca$





TDHF vibrational spectra (octupole)

$^{56}Ni+^{56}Ni$



Simenel *et al.*, PRC **88**, 043604 (2013)