Effect of spin-orbit and tensor force on dissipation dynamics in TDHF theory

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Outlines

I. Introduction

- brief introduction of TDHF theory

II. Effect of spin-oribt and tensor force

- dissipation dynamics
- fusion cross section

III. Summary and outlook

TDHF theory: historical remarks

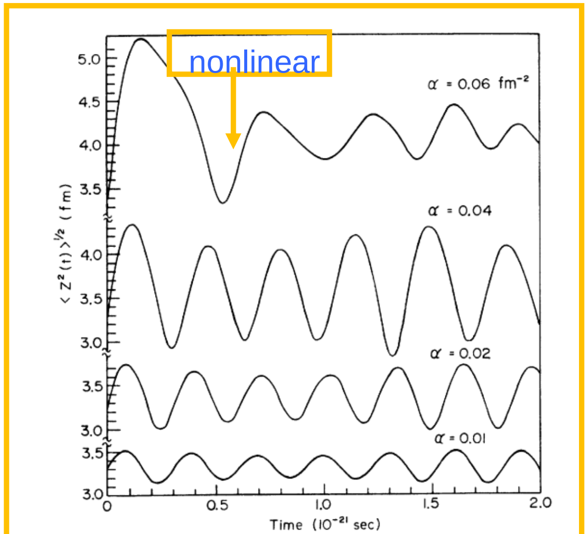
- Method was first applied by Bonche, Koonin, and Negele,

fusion excitation function, fission, deep-inelastic collisions, nuclear molecules, collective excitation and resonance dynamics

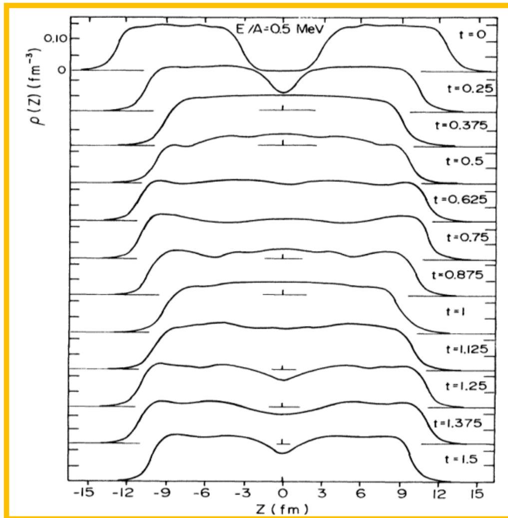
PHYSICAL REVIEW C VOLUME 13, NUMBER 3 MARCH 1976

One-dimensional nuclear dynamics in the time-dependent Hartree-Fock approximation*

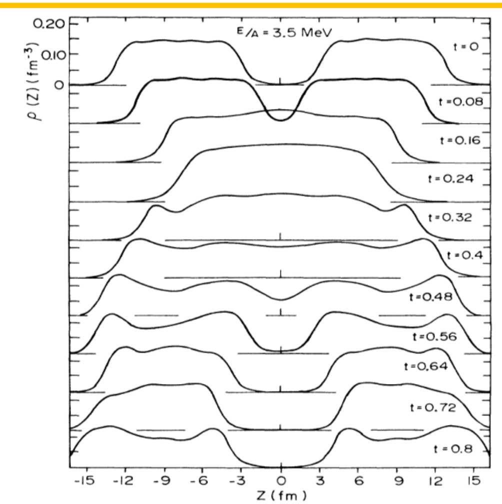
P. Bonche,† S. Koonin,‡ and J. W. Negele§



giant resonance = RPA



fusion



deep inelastic collision

TDHF theory: historical remarks

- many groups in the late '70s and '80s performed more extensive calculations in 2 and 3 dimensions, limited by the computers of the time, e.g.,

  K. T. R. Davies, V. Maruhn-Rezvani, K. R. Sandhya-Devi, S. J. Krieger, J. A. Maruhn

  R. Y. Cusson, H. Stöcker, J. A. Maruhn

  H. Flocard, M. S. Weiss

most calculation in 2D axial geometry,
no l*s-force (essential for correct shell structure)

hindrance

The conflict between TDHF prediction and experimental data promotes the theoretical development

puzzle of small fusion window

PHYSICAL REVIEW C VOLUME 24, NUMBER 1 JULY 1981

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract and a keyword abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Search for a fusion L window in the $^{16}O+^{16}O$ system at $E_{c.m.}=34$ MeV

A. Lazzarini, H. Doubre,* K. T. Lesko, V. Metag,† A. Seamster, R. Vandenbosch, and W. Merryfield
Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195

(Received 17 February 1981)

We have measured the inelastic scattering c
The inelastic yield is dominated by single and
$6.1 \leq E_x \leq 7.1$ MeV in ^{16}O. The yield for ene
significantly less than time-dependent Hartree
nonfusion for low partial waves is predicted.

NUCLEAR REACTIONS $^{16}O(^{16}O,^{16}O')$
$E_x = 0$–20 MeV, inelastic

Time-dependent Hartree-Fock (TDHF) calculations[1–5] indicate that the collision between two heavy ions does not lead to compound nucleus formation for the smallest impact parameters if the center of mass energy is sufficiently high. The reaction proceeds instead to a two-body final state with a total kinetic energy determined by the Coulomb barrier for the two ions. Unlike symmetric fission, the angular distribution does not increase towards smaller scattering angles. TDHF calculations by Koonin and Flanders[6] predict that for the $^{16}O+^{16}O$ reaction at $E_{c.m.}=34$ MeV the partial waves $L \leq 6$ do not lead to fusion. The corresponding deep inelastic cross section is expected to be 132 mb. Recent publications by Dhar and Nilsson[7] and also by Wolschin[8] point out that the the occurrence of nonfusion at lower bombarding ener-

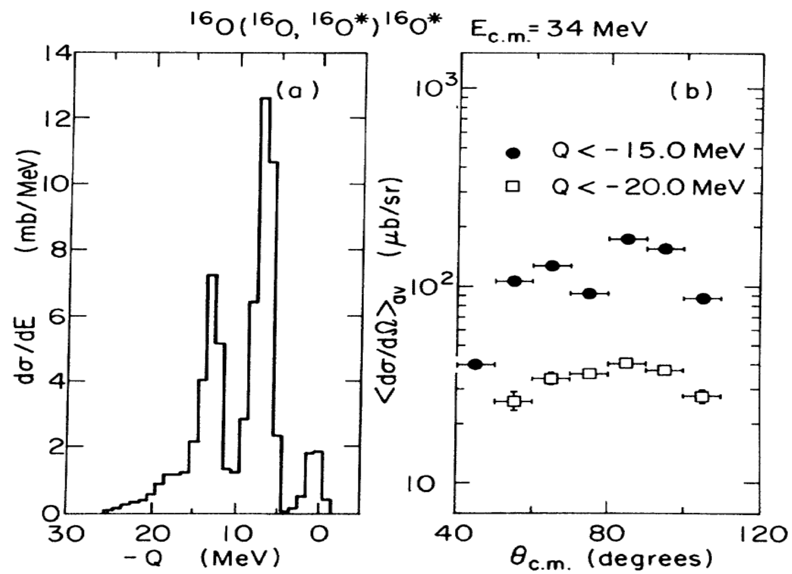


FIG. 2. (a) A projection of the Wilczynski plot onto the TKE axis. (b) Angular distributions for selected Q-value ranges. The points represent averages over 10° intervals in the center of mass.

Spin-orbit coupling solved puzzle of small fusion window

A. S. Umar, M. R. Strayer, and P.-G. Reinhard, Phys. Rev. Lett 56, 2793 (1986).

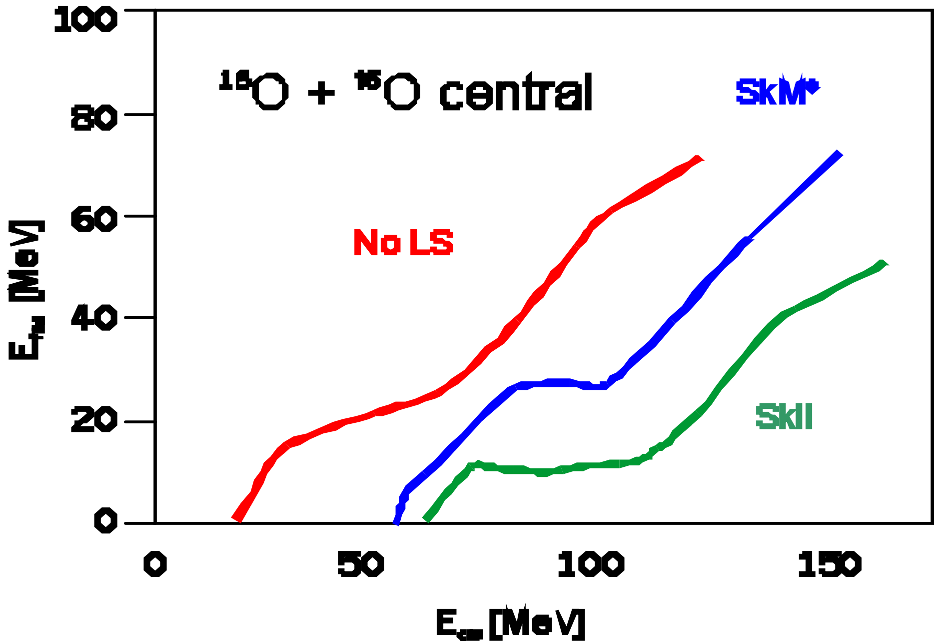
TABLE I. Thresholds for the inelastic scattering of $^{16}O + ^{16}O$ system.

Force	Skyrme II (MeV)	Skyrme M* (MeV)
Spin orbit	68	70
No spin orbit	31	27

TABLE II. Total fusion cross sections for the $^{16}O + ^{16}O$ system for different parametrizations of the Skyrme force with and without spin-orbit part. The last row shows the corresponding experimental cross section from Ref. 20.

Force	$E_{c.m.} = 20$ MeV (mb)	$E_{c.m.} = 34$ MeV (mb)
II	1315	~0
II + *LS*	1466	1694
M*	1389	~0
M* + *LS*	1460	1822
Bonche-Koonin-Negele	912	794
Expt.	850	1075

Include time-even spin-oribt force



Omission of l*s-coupling underestimated the energy dissipation so that the energy window of fusion reactions was too small in comparison with experiments.

Fusion window problem revisited

M. Tohyama and A. S. Umar, Phys. Rev. C65, 037601 (2002).

TABLE I. Threshold energy E_{th} in the center-of-mass frame for the head-on collisions of $^{16}O + ^{16}O$. Fusion occurs below E_{th}.

Method	E_{th} (MeV)
TDHF without $\vec{l}\cdot\vec{s}$	30
TDDM without $\vec{l}\cdot\vec{s}$	66
TDHF with $\vec{l}\cdot\vec{s}$	69
TDDM with $\vec{l}\cdot\vec{s}$	80

TDDM: time-dependent density matrix theory includes both one- and two-body collisions

- The l*s force has significant effect on the collision dynamics;
- The role of l*s force can be compensated by two-body collisions when l*s is absent;
- The increase in E_{th} remains small due to two-body collisions when spin-orbit force was already included;

TDHF theory: advantages vs. limitations

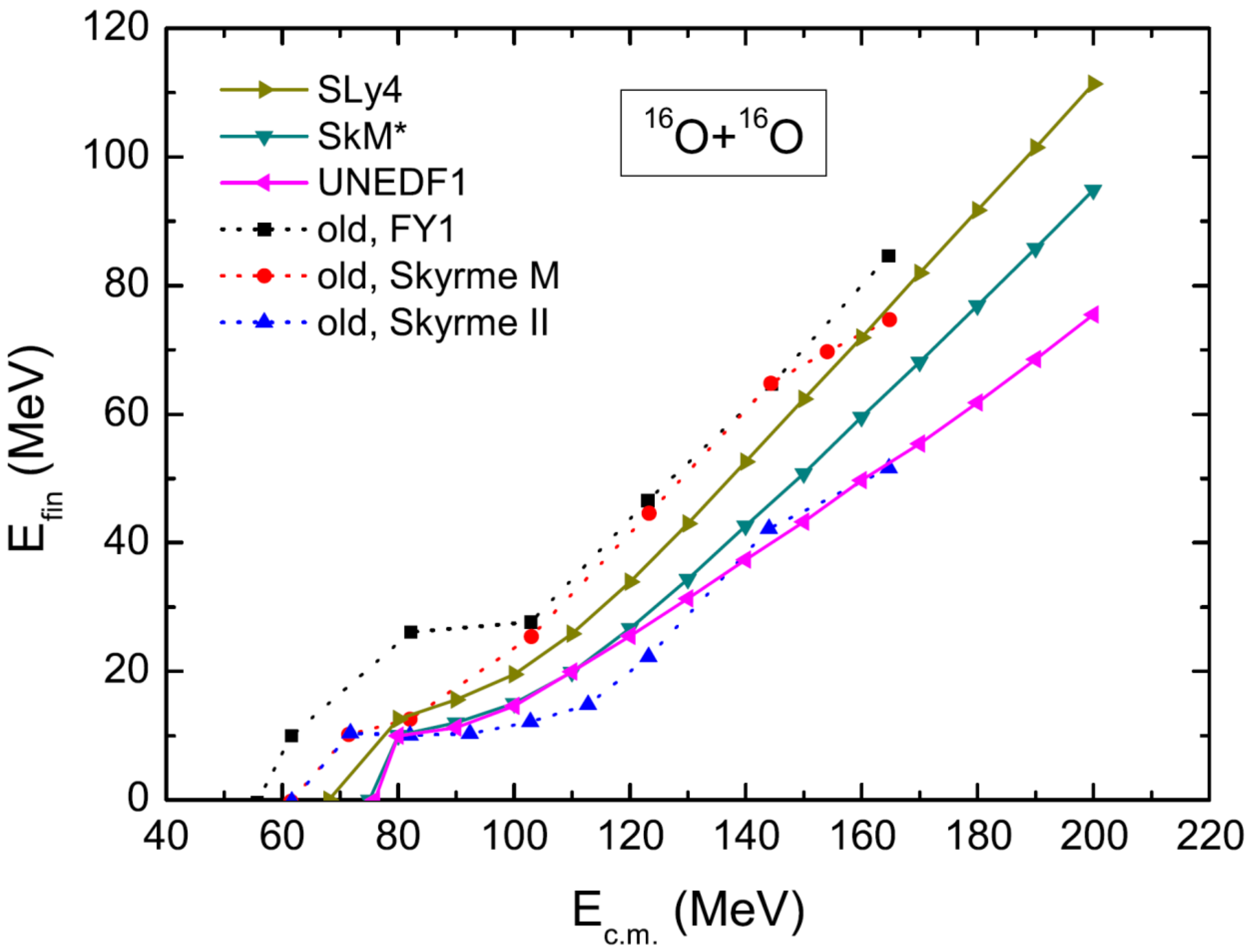
Advantages

- Fully microscopic, parameter-free theory in heavy-ion collisions;
- Treat nuclear structure and reactions in a unified framework (same EDF);
- Dynamical effects in heavy-ion collisions (neck formation, deformation, surface vibrations, nucleon exchange) are automatically incorporated;
- Quantum effects (pauli principle, antisymmetrization of wavefunction, spin-orbit force) are treated in a quantum mechanical way;

Limitations

- Only one-body dissipation (collision with walls of mean-field);
- Tunneling effect is missing;

Effect of spin-orbit force on dissipation dynamics



P.-G. Reinhard et. al., Phys. Rev. C 37, 1026 (1988).

the difference

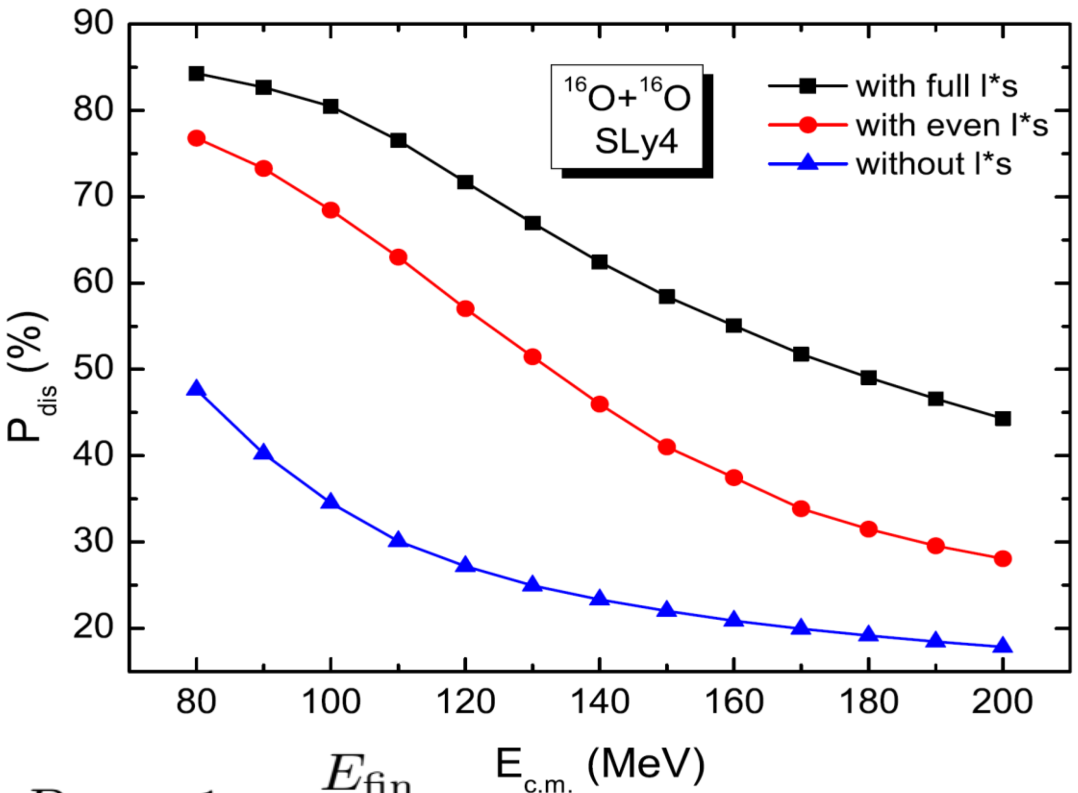
✧ l*s force

✧ symmetry restrictions

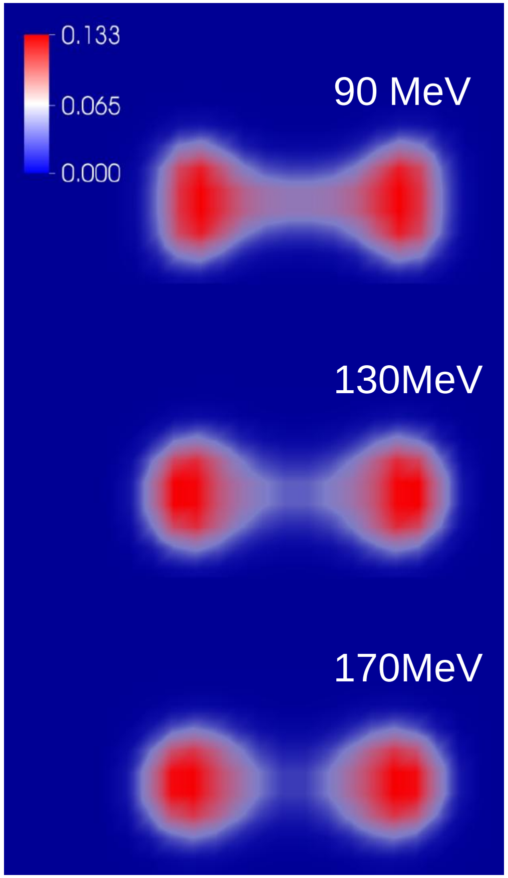
✧ gradient of density

Gao-Feng Dai, Lu Guo, En-Guang Zhao, and Shan-Gui Zhou, Phys. Rev. C (submitted)

Effect of spin-orbit force on dissipation dynamics

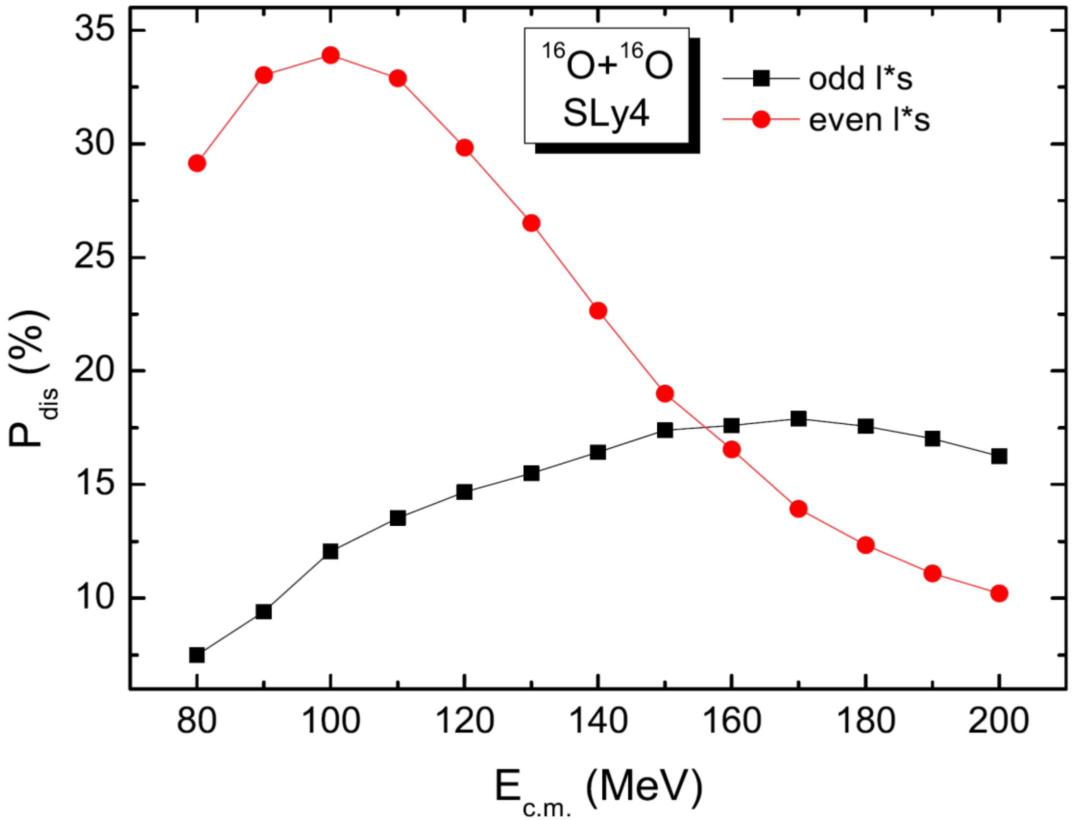


$$P_{\rm dis} = 1 - \frac{E_{\rm fin}}{E_{\rm c.m.}}$$



- The l*s force causes a significant enhancement of the dissipation;
- The energy dissipation decrease as c.m. energy increases owing to the competition of collective motion and single-particle degrees of freedom;

Effect of spin-orbit force on dissipation dynamics

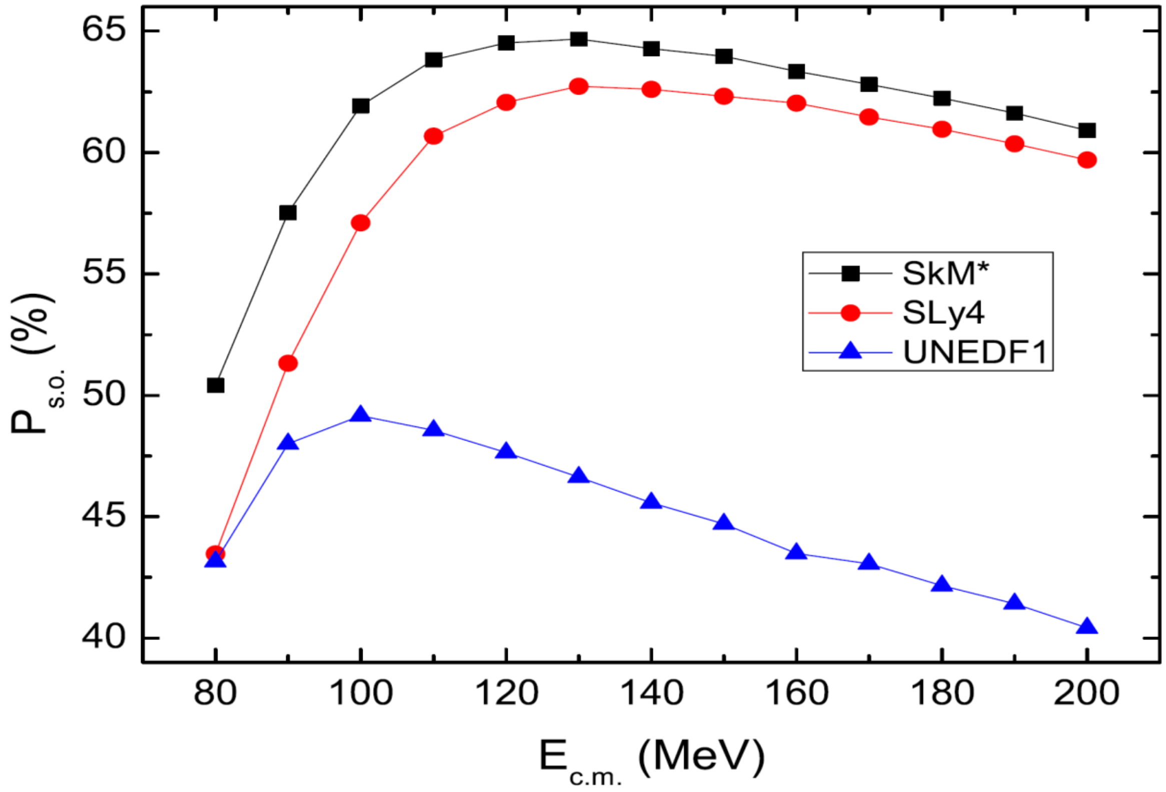


$$\mathcal{H}_{\rm ls}^{\rm even} = -\frac{1}{2}t_4(\rho\nabla\cdot\vec{J} + \sum_q \rho_q\nabla\cdot\vec{J}_q),$$

$$\mathcal{H}_{\rm ls}^{\rm odd} = -\frac{1}{2}t_4(\vec{s}\cdot\nabla\times\vec{j} + \sum_q \vec{s}_q\cdot\nabla\times\vec{j}_q),$$

The time-even coupling of spin-orbit force plays a dominant role at low energies, while the influence of time-odd terms is notable at high energies.

Effect of spin-orbit force on dissipation dynamics



$$P_{\mathrm{s.o.}} = \frac{\left(P_{\mathrm{dis}}^{\mathrm{full}} - P_{\mathrm{dis}}^{\mathrm{no}}\right)}{P_{\mathrm{dis}}^{\mathrm{full}}}$$

Around 40%~65% of the energy dissipation depending on the different Skyrme parameters is found to arise from the spin-orbit force in deep-inelastic collisions.

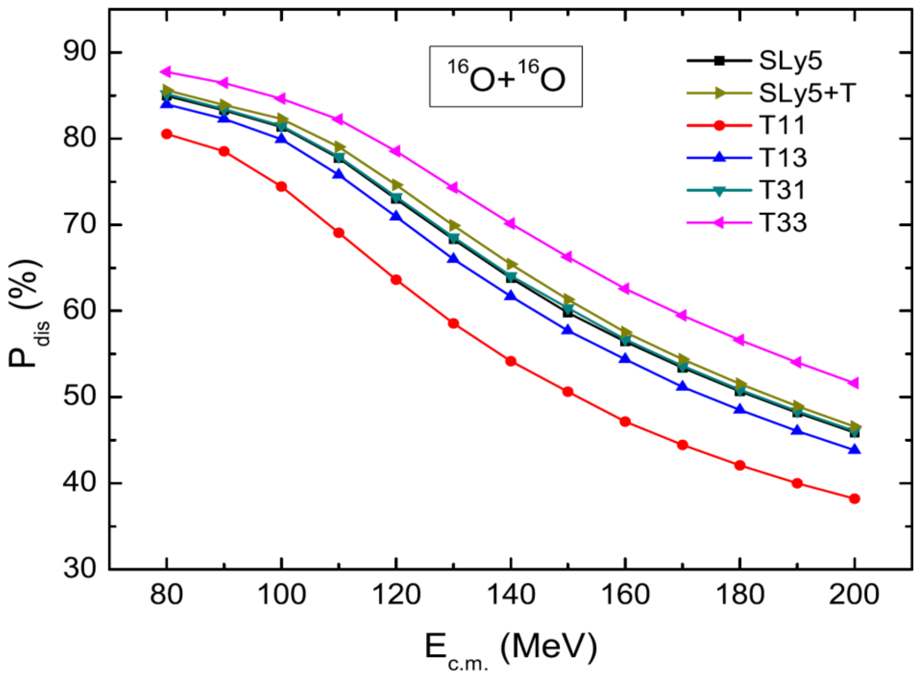
Effect of spin-orbit force on dissipation dynamics

TABLE I. Calculations of fusion cross section for ^{16}O+^{16}O at $E_{\mathrm{c.m.}} = 70.5$ MeV with three Skyrme parametrizations and experimental data with errors [70].

Force	σ_{fus} (mb)
SLy4	1282
SkM*	1287
UNEDF1	1327
Exp.	1056 ± 125

TDHF calculations overestimated the experimental data by about 20%; reasonably reproduced the experimental data, considering that no free-parameters are fitted to the reaction dynamics.

Effect of tensor force on dissipation dynamics



$$\mathcal{H}^{t} = \frac{1}{2}\alpha\left(\mathbf{J}_{n}^{2} + \mathbf{J}_{p}^{2}\right) + \beta \mathbf{J}_{n} \cdot \mathbf{J}_{p},$$

$$\alpha = \alpha_{c} + \alpha_{t}, \qquad \beta = \beta_{c} + \beta_{t},$$

Force	α_T	β_T	α_C	β_C	α	β
SLy5	0.0	0.0	80.2	−48.9	80.2	−48.9
SLy5+T	−170.0	100.0	80.2	−48.9	−89.8	51.1
T11	−142.8	−17.5	82.8	−42.5	−60.0	−60.0
T13	−21.6	−15.1	81.6	−44.9	60.0	−60.0
T31	−159.4	74.2	99.4	−14.2	−60.0	60.0
T33	−40.8	71.1	100.8	−11.1	60.0	60.0

For the reaction systems with N=Z,

- The tensor dependence of energy dissipation is attributed to the parameters $|\alpha+\beta|$;
- With the small $|\alpha+\beta|$, the small effect of tensor force on the dissipation, as SLy5+T, T13, T31;
- The large value of $|\alpha+\beta|$ gives rise to the strong effect on the dissipation as T11 and T33;

Effect of tensor force on dissipation dynamics

Force	σ_{fus} (mb)
SLy5	1307
SLy5+T	1327
T11	1161
T13	1265
T31	1326
T33	1327
Exp.	1056 ± 125

The theoretical fusion cross section with T11 tensor force well reproduce experimental data

Force	α_T	β_T	α_C	β_C	α	β
SLy5	0.0	0.0	80.2	−48.9	80.2	−48.9
SLy5+T	−170.0	100.0	80.2	−48.9	−89.8	51.1
T11	−142.8	−17.5	82.8	−42.5	−60.0	−60.0
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T33	−40.8	71.1	100.8	−11.1	60.0	60.0

Summary and outlook

Summary

- Three-dimensional TDHF with full Skyrme functional and without any symmetry restrictions;
- The dissipation decreases as the c.m. energy increases owing to the competation of collective motion and single –particle degrees of freedom;
- The spin-orbit force causes a significant enhancement of the dissipation;
- The time-even coupling of l*s force plays a dominant role at low energies, while the influence of time-odd termsis notable at high energies;
- The tensor force may either enhance or reduce the dissipation depending on different parameter
- The theoretical fusion cross section reasonable reproduced the experimental data;

Outlook

- The dissipation dynamics in heavier systems;
- The fusion excitation function with tensor force in heavier, asymmetric and exotic systems;

Thank you for your attention