Role of tensor force in nuclear dynamics

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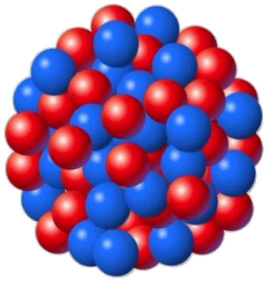
Contents

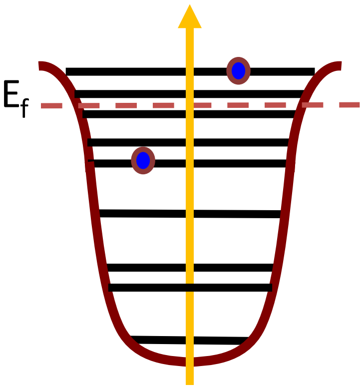
Time-dependent Hartree-Fock theory

□ time-dependent Hartree-Fock (TDHF) theory

$$S = \int_{t_1}^{t_2} \langle \Psi(t) | H - i\hbar\partial_t | \Psi(t) \rangle \, dt, \qquad H = \sum_{i=1}^{A} t_i + \sum_{i<j}^{A} v_{ij}$$

$$\Psi(\mathrm{r}_1, r_2, \cdots, r_A, t) = \frac{1}{\sqrt{A!}} \det\left|\varphi_\lambda(r_i, \mathrm{t})\right|, \qquad i\hbar\frac{\partial\varphi_\lambda}{\partial t} = h\varphi_\lambda$$





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 theory: historical remarks

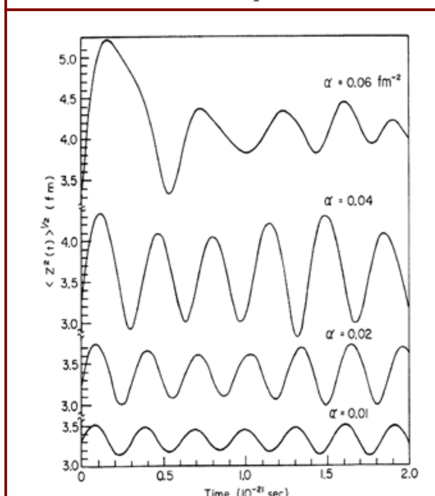
- ☐ TDHF was proposed by Dirac in 1930s and first applied to nuclear physics in 1976

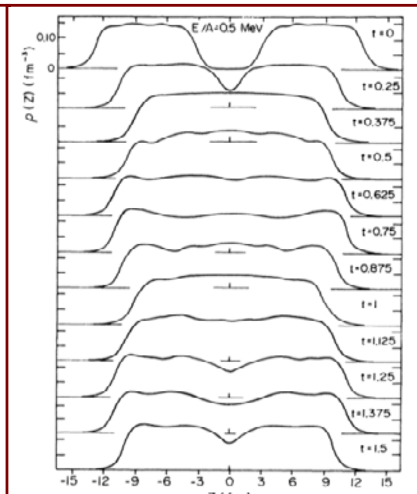
PHYSICAL REVIEW C VOLUME 13, NUMBER 3 MARCH 1976

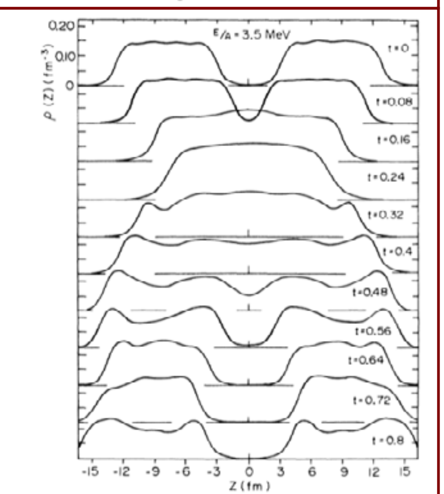
One-dimensional nuclear dynamics in the time-dependent Hartree-Fock approximation*

P. Bonche,† S. Koonin,‡ and J. W. Negele§
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 14 October 1975)

The time-dependent Hartree-Fock theory is applied to the large amplitude dynamics of slabs of spin and isospin symmetric nuclear matter. The slabs are translationally invariant in two transverse dimensions, and with the simplified effective interaction used in this work, the problem is reduced to a set of coupled nonlinear







giant resonance = RPA   fusion   deep inelastic collisions

- ☐ fusion dynamics
- ☐ Deep inelastic collisions
- ☐ fission dynamics
- ☐ Resonances dynamics
- ☐ nuclear molecular
- ☐ collective excitation
- ☐ ……

TDHF theory: historical remarks

- **After the first application, many extensive studies in 70s and 80s**

many approximations and restrictions of symmetries

- **Omission of spin-orbit force**

  Boneche et al., PRC17, 1700 (1978); Davies and Koonin, PRC 23, 20142 (1981);

- **Axial-symmetry 2D geometry**

  Maruhn et al., PRC 31, 1289 (1985); Reinhard et al. PRC 37, 1026 (1988);

- **……**

A hindrance for the theoretical development

TDHF theory: historical remarks

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 submitt... section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than ... pages and must be accompanied by an abstract and a keyword abstract. Page proofs are sent to authors, but, because of the r... tion 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. Merryf...
Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195
(Received 17 February 1981)

We have measured the inelastic scattering cross section for the reaction $^{16}O(^{16}O,^{16}O')^{16}O$. The inelastic yield is dominated by single and double excitation of the group of states with $6.1\leq E_x\leq 7.1$ MeV in ^{16}O. The yield for energy losses greater than 15 MeV is 5.9 mb. This is significantly less than time-dependent Hartree-Fock calculations indicate for this system where nonfusion for low partial waves is predicted.

NUCLEAR REACTIONS $^{16}O(^{16}O,^{16}O')$, $E_{c.m.}=34$ MeV, $\sigma(E_x,\theta_{c.m.})$; $\theta_{c.m.}=30°–90°$, $E_x=0–20$ MeV, inelastic yields compared to TDHF.

Time-dependent Hartree-Fock (TDHF) calcula- tions[1–5] indicate that the collision between two he... ions does not lead to compound nucleus formatio... 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 t... kinetic energy determined by the Coulomb barrie... the two ions. Unlike symmetric fission, the angul... distribution does not increase towards smaller sca... ing 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 fusio... The corresponding deep inelastic cross section is e... pected to be 132 mb. Recent publications by Dha... and Nilsson[7] and also by Wolschin[8] point out that occurrence of nonfusion at lower bombarding ene... gies depends sensitively on the assumptions used

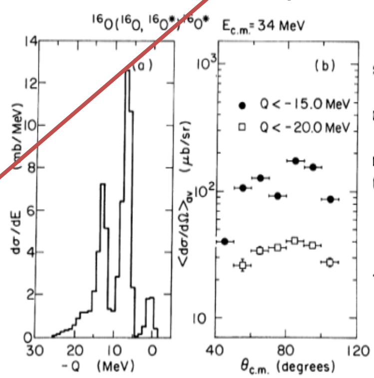


FIG. 2. (a) A projection of the Wilczynski plot onto the TKE axis. (b) Angular distributions for selected Q-value ranges. The points represent averages over 10° intervals in the center of mass.

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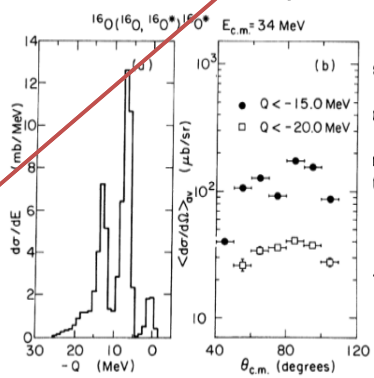

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□ Puzzle of small fusion window

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

TDHF theory: historical remarks

- **Inclusion of time-even spin-orbit force**

A. S. Umar *et al.*, Phys. Rev. Lett 56, 2793 (1986)

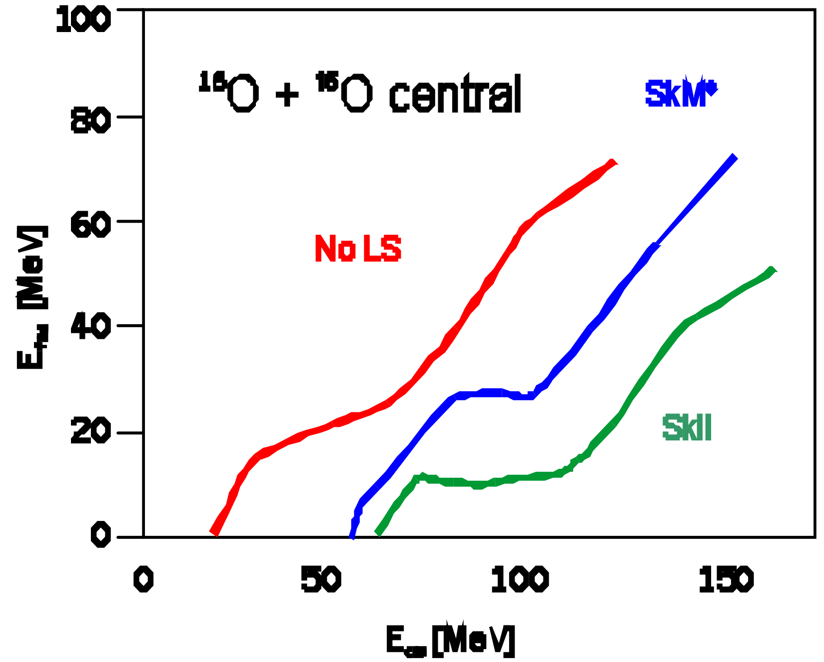
TDHF theory: historical remarks

□ Inclusion of time-even spin-orbit force

A. S. Umar *et al.*, PRL56, 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



- □ Upper fusion threshhold was increased more than 2 times with l*s;
- □ Energy dissipation was increased significantly with l*s;

TDHF theory: historical remarks

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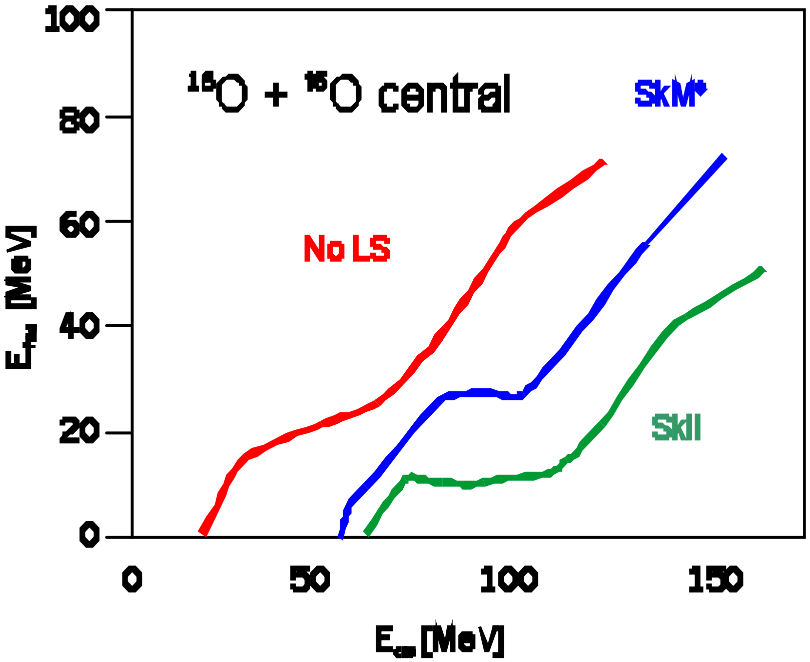


- ☐ Upper fusion threshhold was increased more than 2 times with l*s;
- ☐ Energy dissipation was increased significantly with l*s;

solved the puzzle of small fusion window

Importance of spin-orbit force

□ Galilean invariance in TDHF

Inclusion of both time-even and time-odd l*s force

Importance of spin-orbit force

Galilean invariance in TDHF

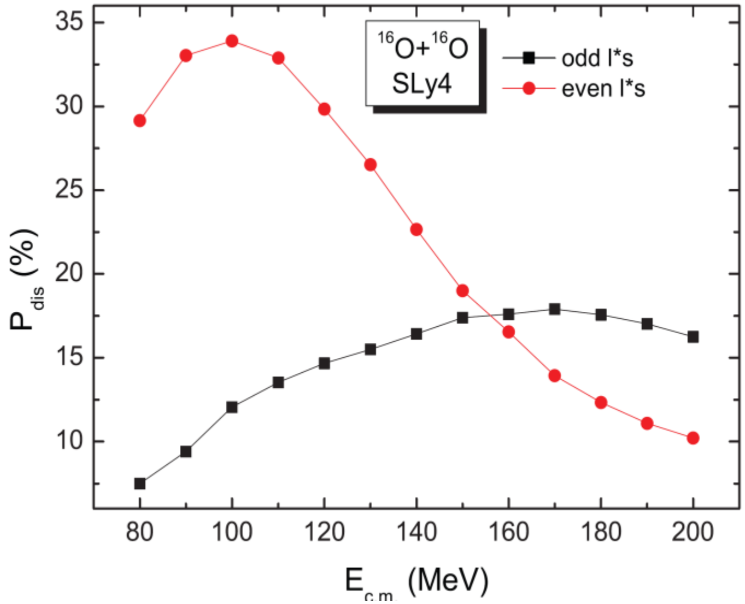
Inclusion of both time-even and time-odd l*s force

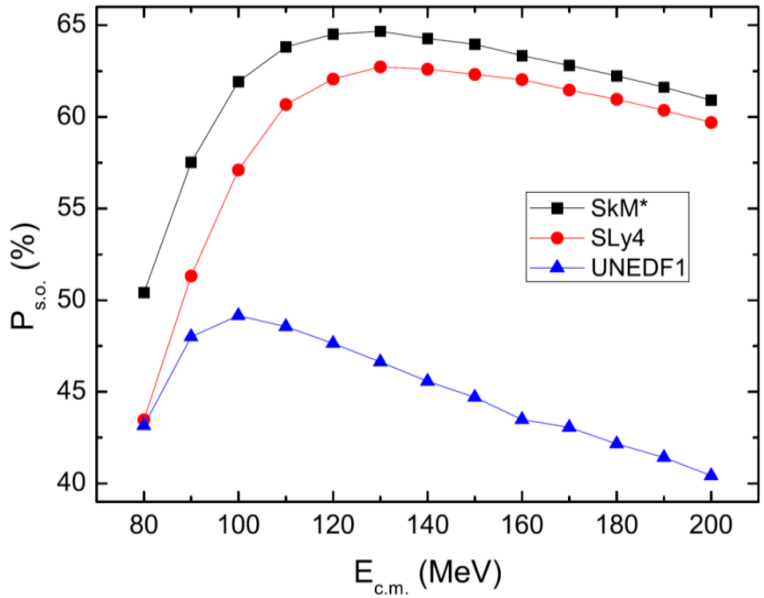
- Without any symmetry restrictions
- Full skyrme functional
- 3D coordinate space

Importance of spin-orbit force

Galilean invariance of TDHF

Inclusion of both time-even and time-odd l*s force





- $P_{dis} = E_{dis}/E_{c.m.}$, $P_{so} = 1 - P^{(no\ l*s)}/P^{(full\ l*s)}$
- **Time-even l*s is important in low energy, while time-odd l*s is at high energy;**
- **Around 40%~65% of the energy dissipation arise from spin-orbit force;**

G. F. Dai, Lu Guo, E.G. Zhao, and S.G. Zhou, Phys. Rev. C90, 044609 (2014).

Effect of tensor force in fusion dynamics

☐ Nucleon-nucleon interaction:

Tensor force: the most obviously missing component in HIC

Tensor force in original Skyrme force has been neglected in most calculations

$$V_{\mathrm{sk}}(r) = t_0(1+x_0\hat{P}^{\hat{\sigma}})\delta(r_1-r_2) + \frac{t_1}{2}(1+x_1P^{\sigma})\left[k'2\delta(r_1-r)+\delta(r_1-r_2)k^2\right]$$

$$+t_2(1+x_2\hat{P}^{\hat{\sigma}})k'\cdot\delta(r_1-r)k + \frac{t_3}{6}(1+x_3P^{\sigma})\rho^{\alpha}\left(\frac{r_1+r_2}{2}\right)\delta(r_1-r_2)$$

$$+iW_0(\sigma_1+\sigma_2)k'\times\delta(r_1-r_2)k$$

$$\boxed{\begin{aligned}&+\frac{t_e}{2}\left\{\begin{aligned}&\left[3(\sigma_1\cdot k')(\sigma_2\cdot k')-(\sigma_1\cdot\sigma_2)k'^2\right]\delta(r)\\&+\delta(r)\left[3(\sigma_1\cdot k)(\sigma_2\cdot k)-(\sigma_1\cdot\sigma_2)k^2\right]\end{aligned}\right\}\\&+t_o\left[3(\sigma_1\cdot k')\delta(r)(\sigma_2\cdot k)-(\sigma_1\cdot\sigma_2)k'\delta(r)k\right]\end{aligned}}$$

Effect of tensor force in fusion dynamics

- **Energy density functional (EDF) including tensor force**

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

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

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

Implementation of tensor force

PHYSICAL REVIEW C **93**, 054617 (2016)

Skyrme tensor force in heavy ion collisions

P. D. Stevenson,[1] E. B. Suckling,[1,2] S. Fracasso,[1] M. C. Barton,[1] and A. S. Umar[3]
[1]*Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom*
[2]*Dept. of Meteorology, University of Reading, Reading, RG6 6BB, United Kingdom*
[3]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*

$^{16}O+^{16}O$ deep-inelastic collisions

ACKNOWLEDGMENTS

This work was funded by the UK Science and Technology the preparation of this manuscript. During the refereeing process, Lu Guo and collaborators noticed a discrepancy between one of our calculations, as presented in a preprint of this paper on the arXiv server, and their implementation of the tensor terms. We are grateful to them, as it prompted us to check our calculation, in which it turned out that we had mistyped the result from our output file into the table for one force parametrization.

Contents

Effect of tensor force in fusion dynamics

- **Spin-saturated closed shells**:

20 and 40

5 representative collisions:

all are doubly magic closed shells---no pairing necessary

N_s	Reaction
4	$^{40}Ca+^{40}Ca$
3	$^{40}Ca+^{48}Ca$
2	$^{48}Ca+^{48}Ca$
1	$^{48}Ca+^{132}Sn$
0	$^{56}Ni+^{56}Ni$

N_s is the total number of spin-saturated magic number in target and projectile.

Effect of tensor force in fusion dynamics

☐ Skyrme tensor force:

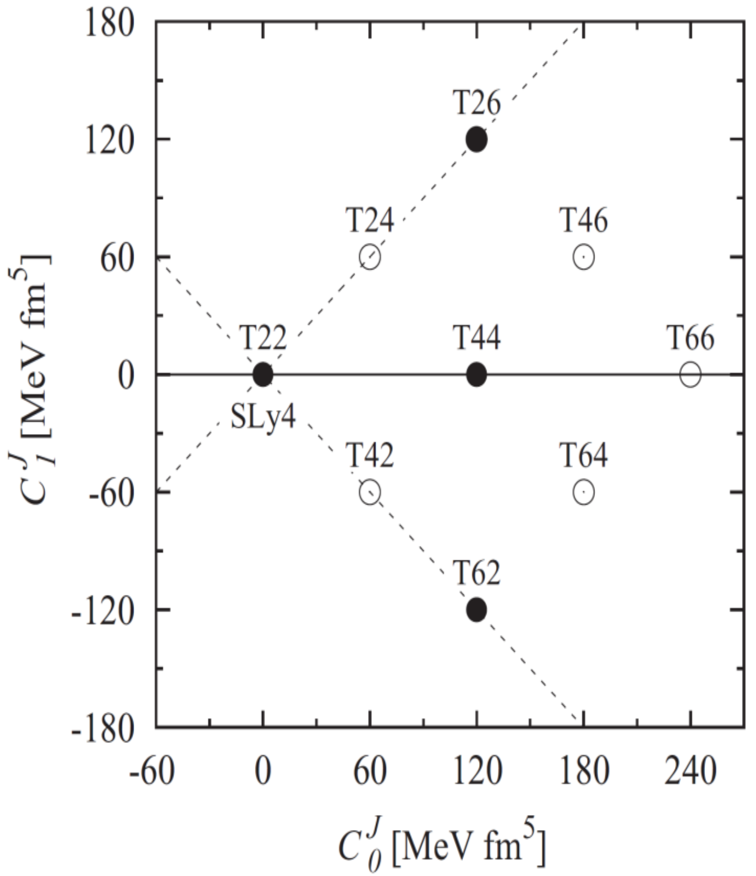
- **perturbative addition to the existing standard interactions, e.g. SLy5t**
- **complete readjustment of the full set of parameters on the same footing, e.g., T*IJ***

  SLy5, SLy5t;

  T22, T26, T44, T62;

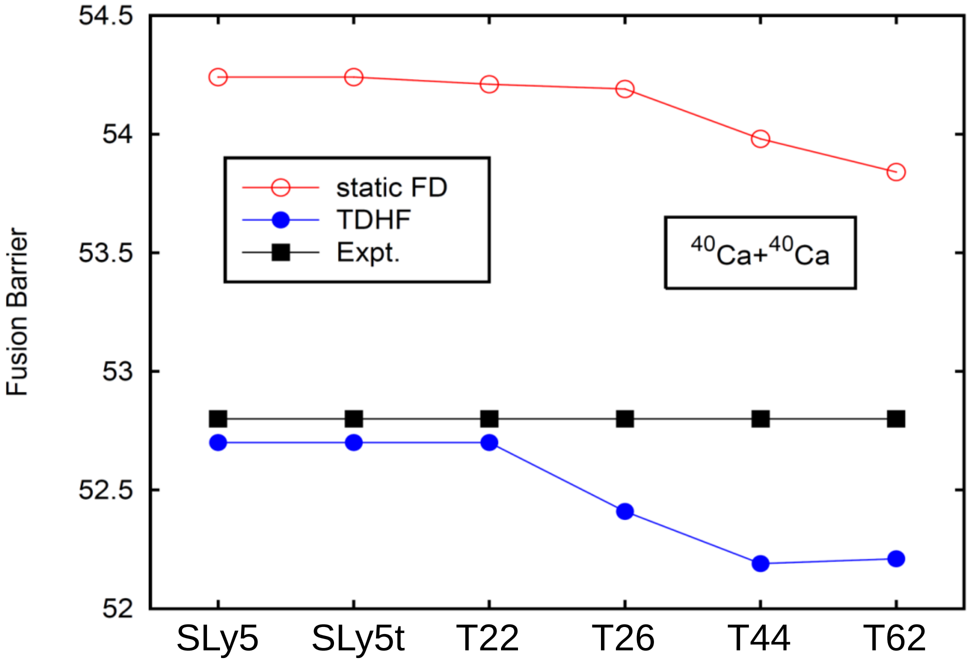
☐ Questions to be addressed:

- How much of the changes is caused by tensor force itself?
- By the rearrangement of all other terms during the fit of the parametrizations?
- By the time-even part of the EDF, that is, the modification of s.p. orbitals,
- By the time-odd part of the EDF?



Effect of tensor force in fusion dynamics

□ Coulomb barrier: static and dynamic



□ Static barrier:

from EDF-FD

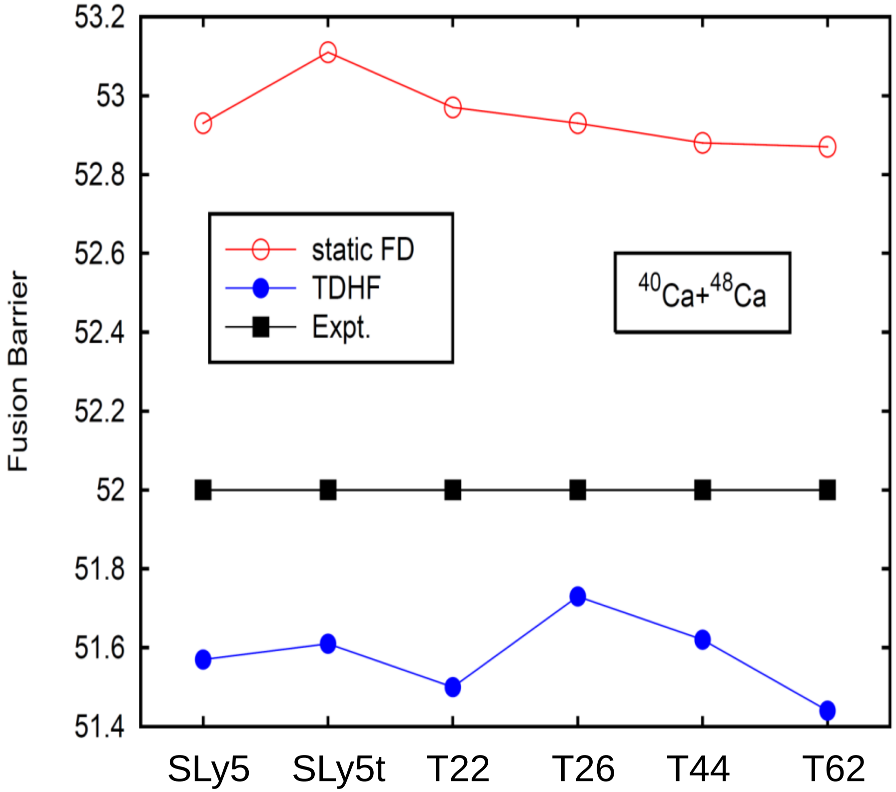
$$V^{FD}(R) = \varepsilon[\hat{\rho}_{P+T}](R) - \varepsilon[\rho_P] - \varepsilon[\rho_T]$$

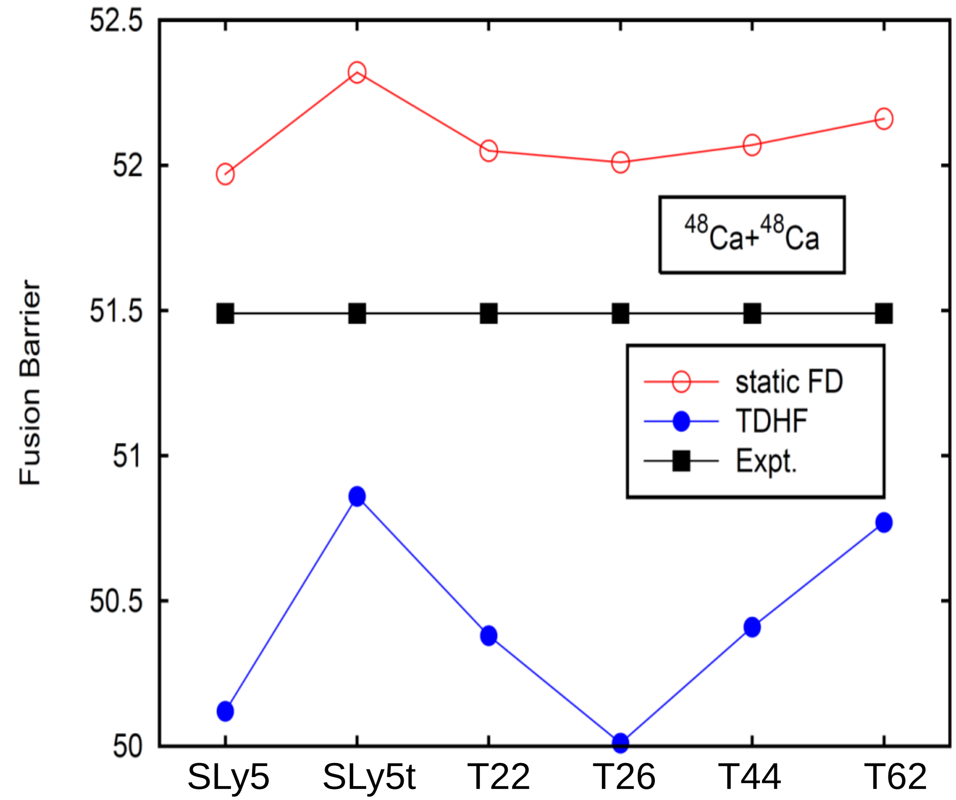
- **Neglect pauli effect;**
- **Neglect couplings;**

□ Dynamic TDHF barrier:

- □ Static barrier is systematically higher than experiments and dynamic TDHF barrier;
- □ Dynamic TDHF barrier has better agreement with experiments;
- □ For static barrier, tensor force contributes only to time-even terms, that is…
- □ For dynamic barrier, both time-even and time-odd terms are naturally presented;

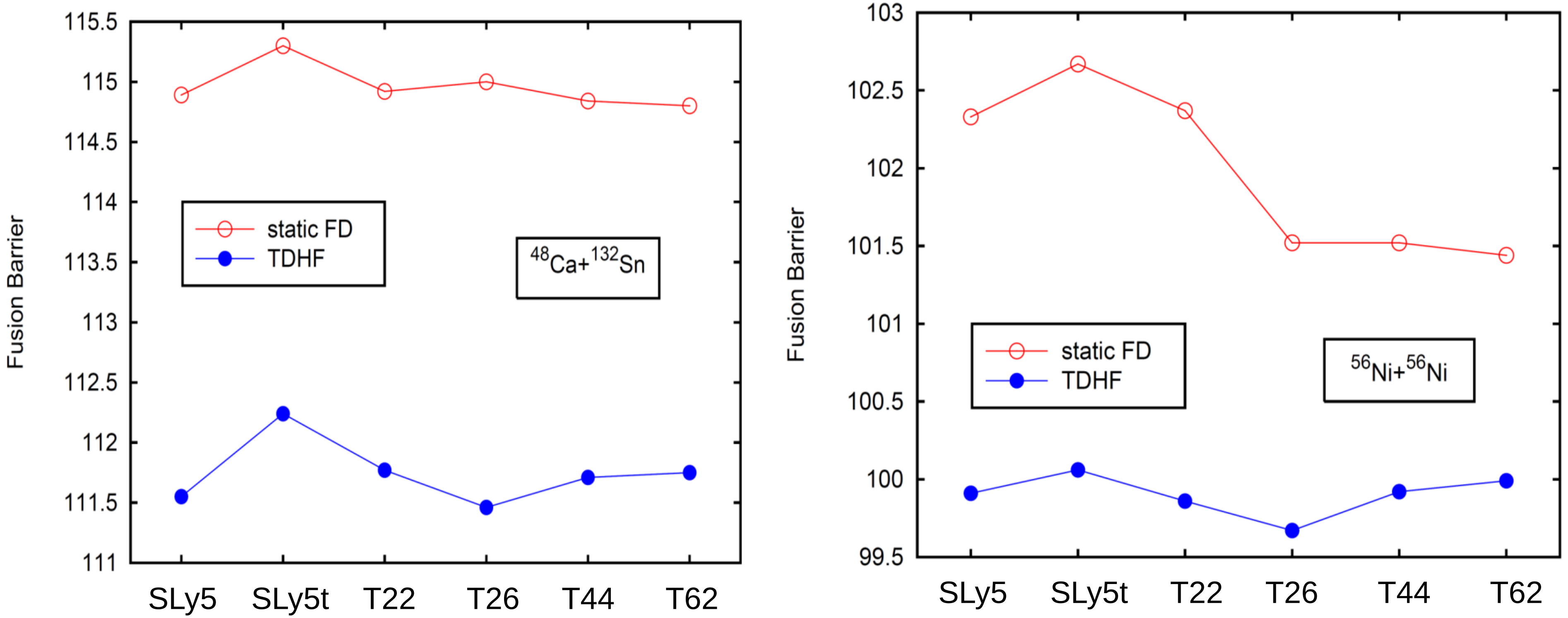
Effect of tensor force on fusion barrier





- Tensor force SLy5t increases the barrier height and improves the agreement with experiments;
- Effect of tensor force TIJ has been quite different for different systems, depends on the isoscalar and isovector couplings, the subtle interplay between structure and reactions

Effect of tensor force on fusion barrier

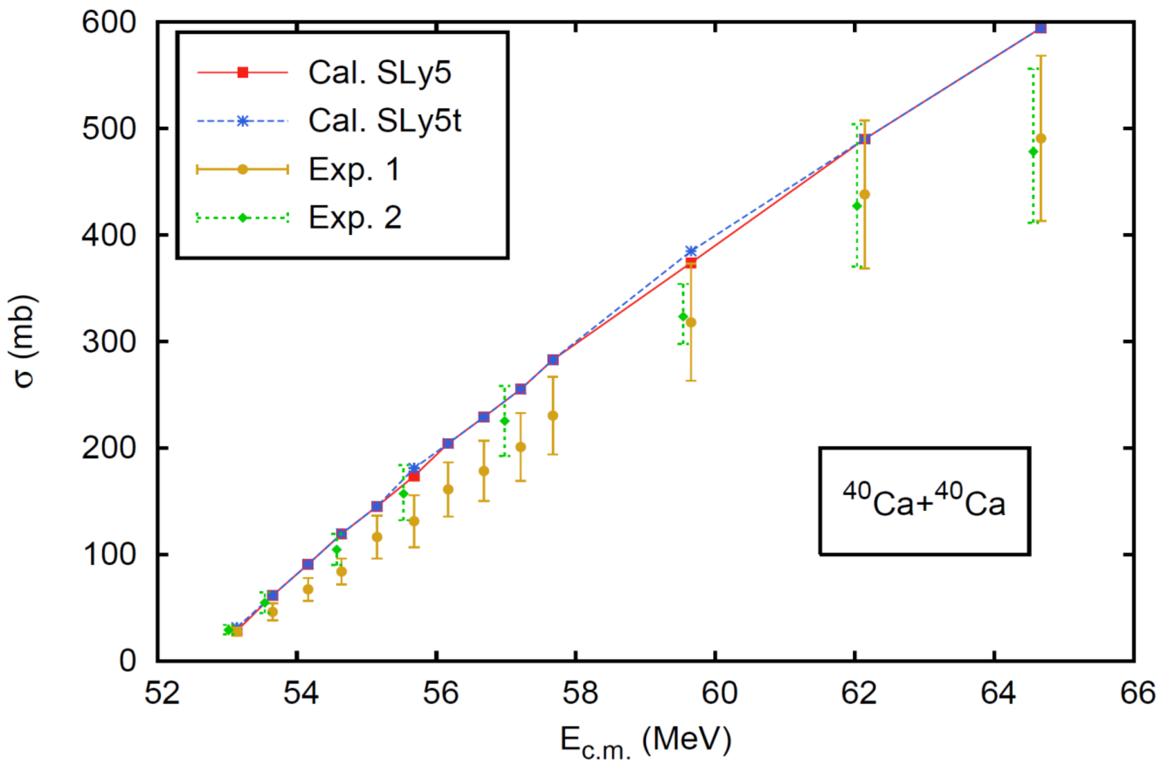


- Similar trends are observed as the spin-unsaturated systems.;

Effect of tensor force on fusion cross section

- **Another important experimental observable**

Parameter free calculation

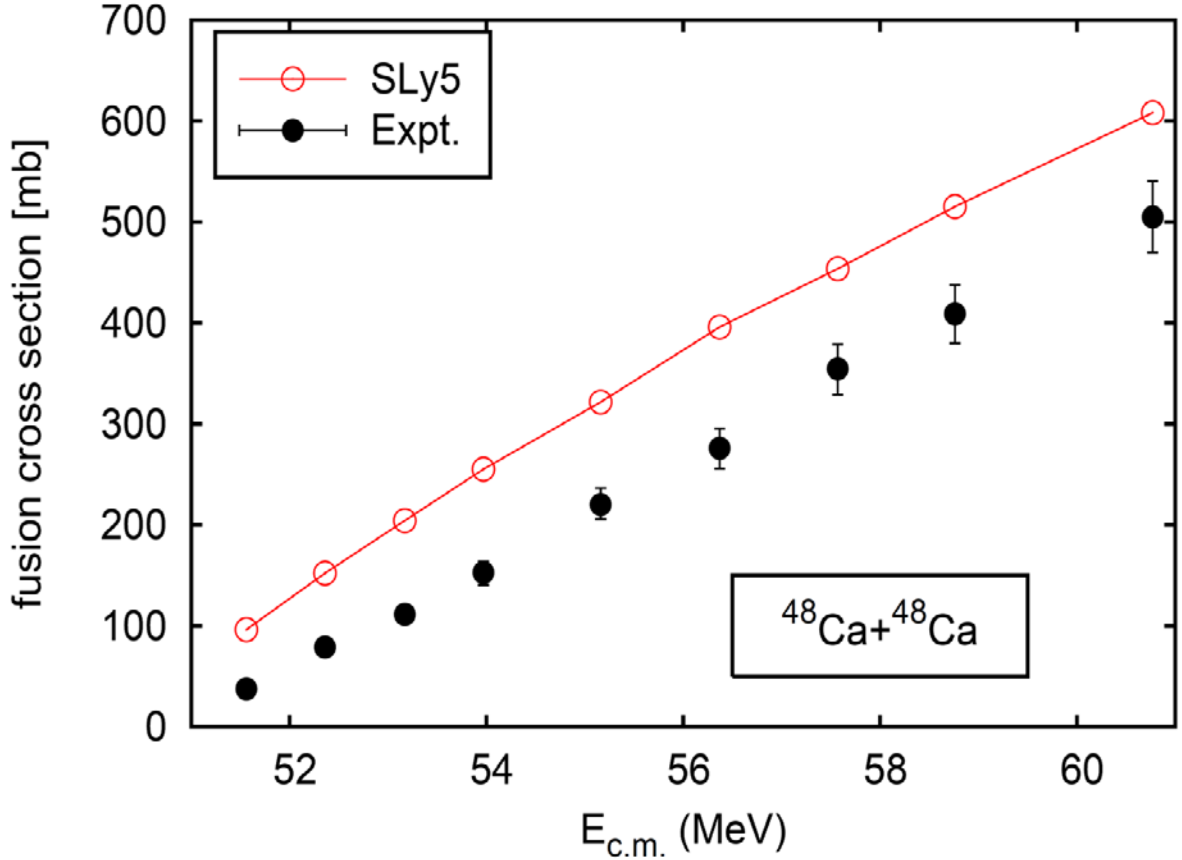


- Tensor force has negligible effect on the fusion cross section of spin-saturated reaction $^{40}Ca+^{40}Ca$
- This is consistent with the observation of Coulomb barrier;

Effect of tensor force on fusion cross section

Another important experimental observable

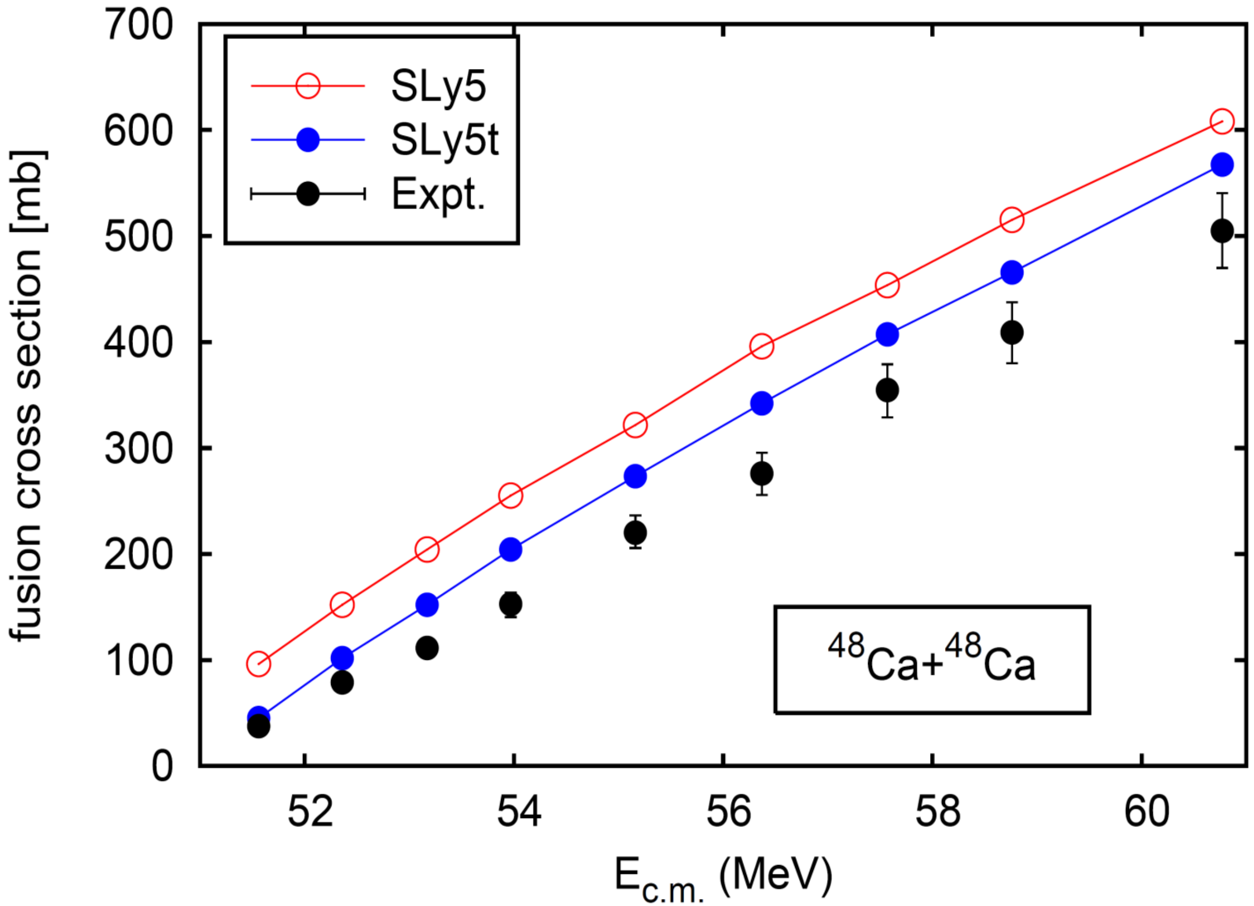
Parameter free calculation



- the theoretical cross section overall overestimates the experiments.

Effect of tensor force on fusion cross section

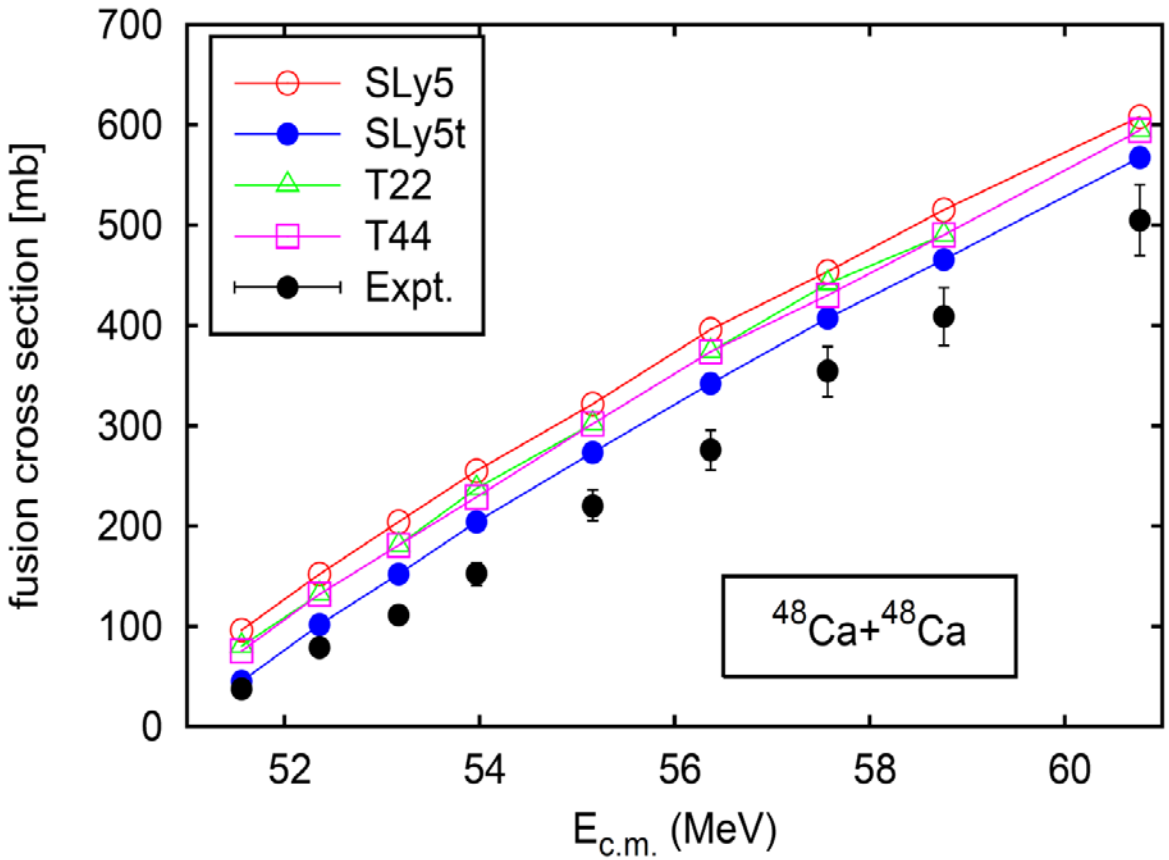
Parameter free calculation



- with the tensor force included, the TDHF cross section has much better agreement with the experiments.

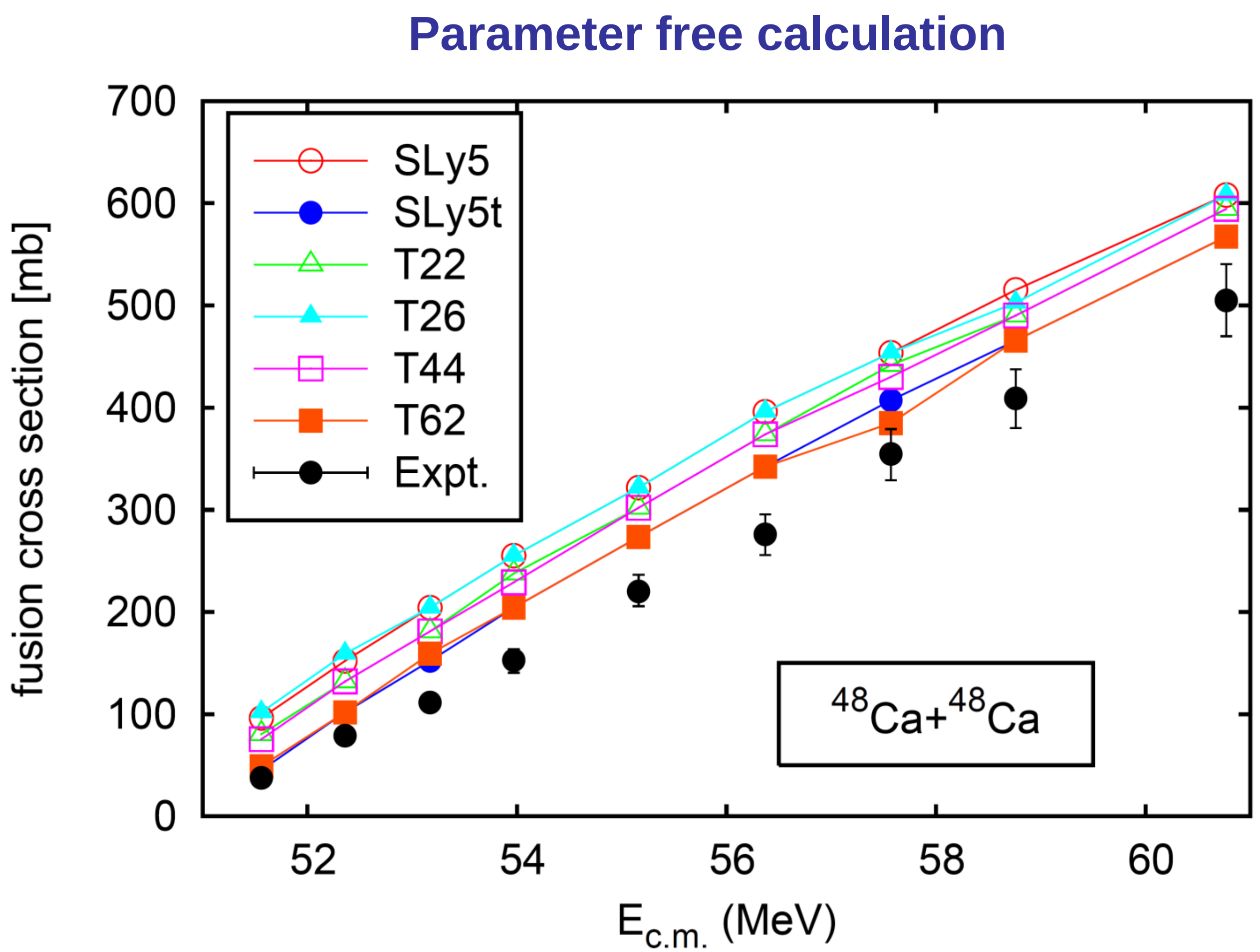
Effect of tensor force on fusion cross section

Parameter free calculation



- Cross section with T22 and T44 are similar, lies in between SLy5 and SLy5t;

Effect of tensor force on fusion cross section

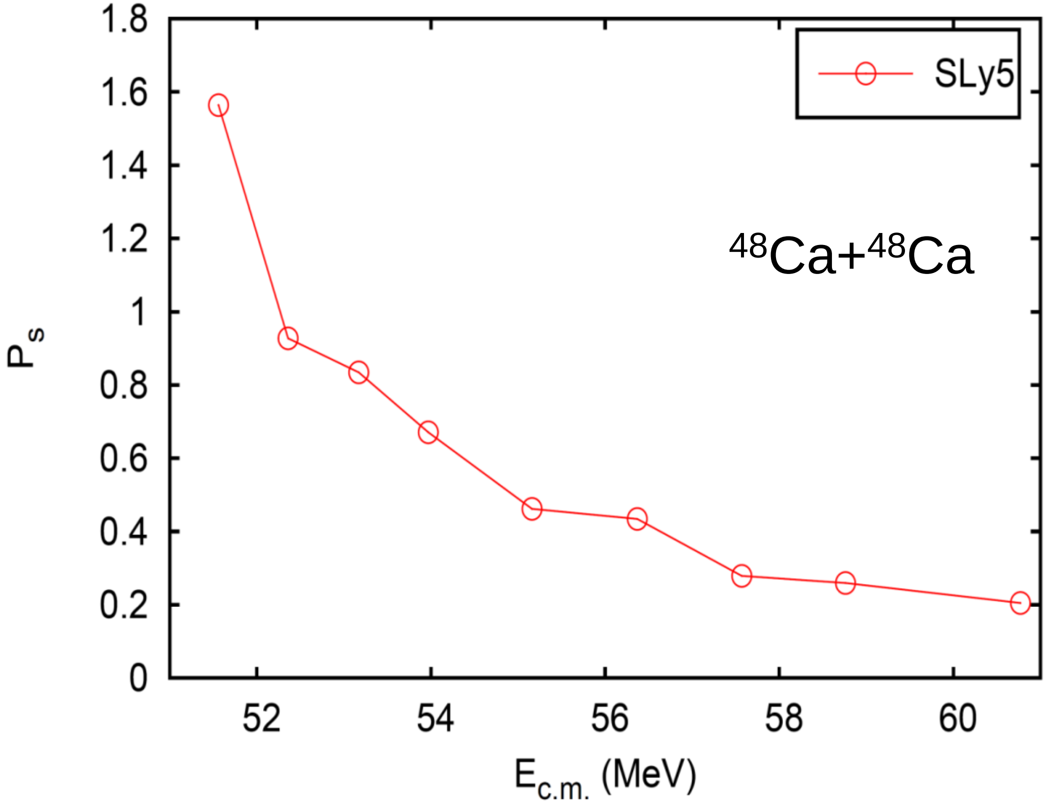


- Cross section with T26 are similar as SLy5, deviates quite large from experiment;
- Cross section with T62 are similar as SLy5t, in good agreement with experiment

Effect of tensor force in fusion dynamics

- Another important experimental observable

Parameter-free calculation



Deviation from experiments:

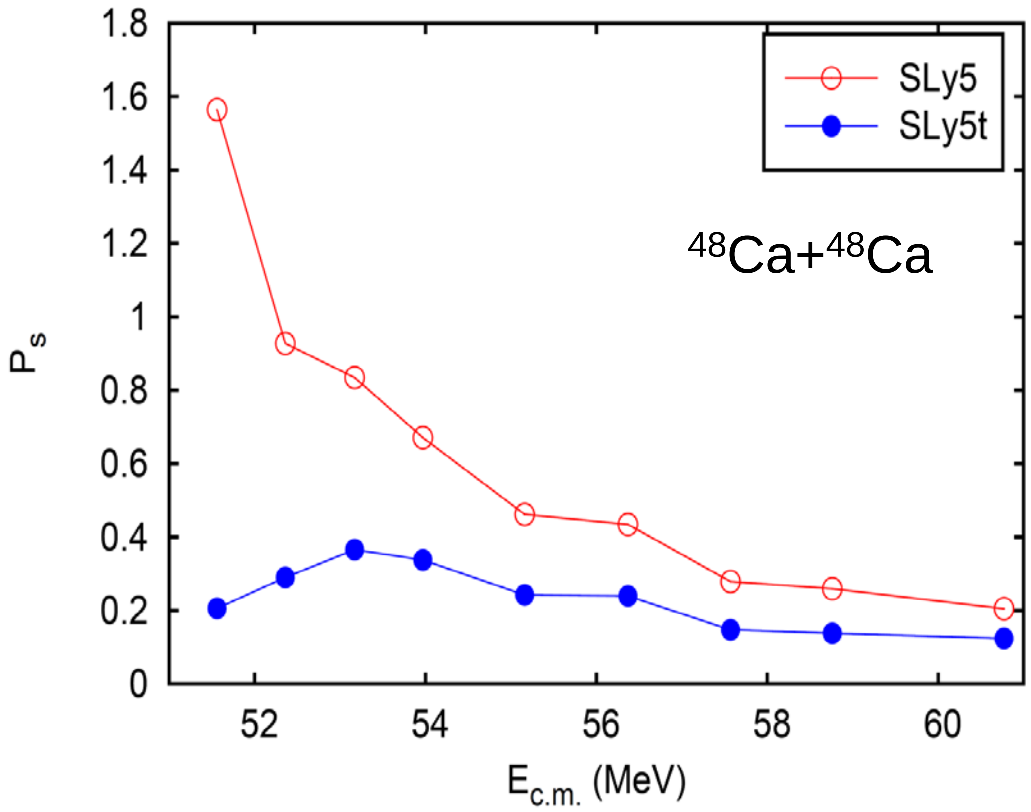
$$P_s = \left(\sigma_{TDHF} - \sigma_{\exp}\right) \Big/ \sigma_{\exp}$$

- the theoretical cross section overall overestimates the experiments.

Effect of tensor force in fusion dynamics

Another important experimental observable

Parameter-free calculation



Deviation from experiments:

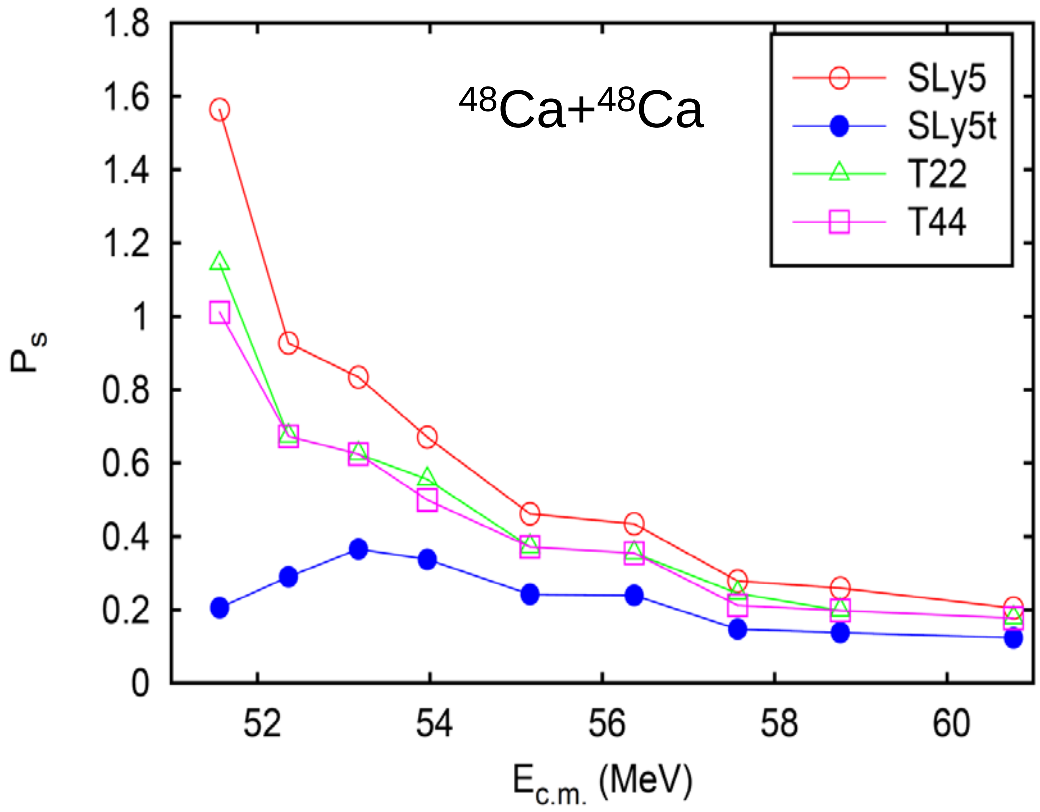
$$P_s = \left(\sigma_{TDHF} - \sigma_{\exp}\right) \Big/ \sigma_{\exp}$$

- with tensor force, the deviation decreases from 1.6 to 0.2 at Coulomb barrier;
- it improves the agreement dramatically;

Effect of tensor force in fusion dynamics

Another important experimental observable

Parameter-free calculation



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Effect of tensor force in fusion dynamics

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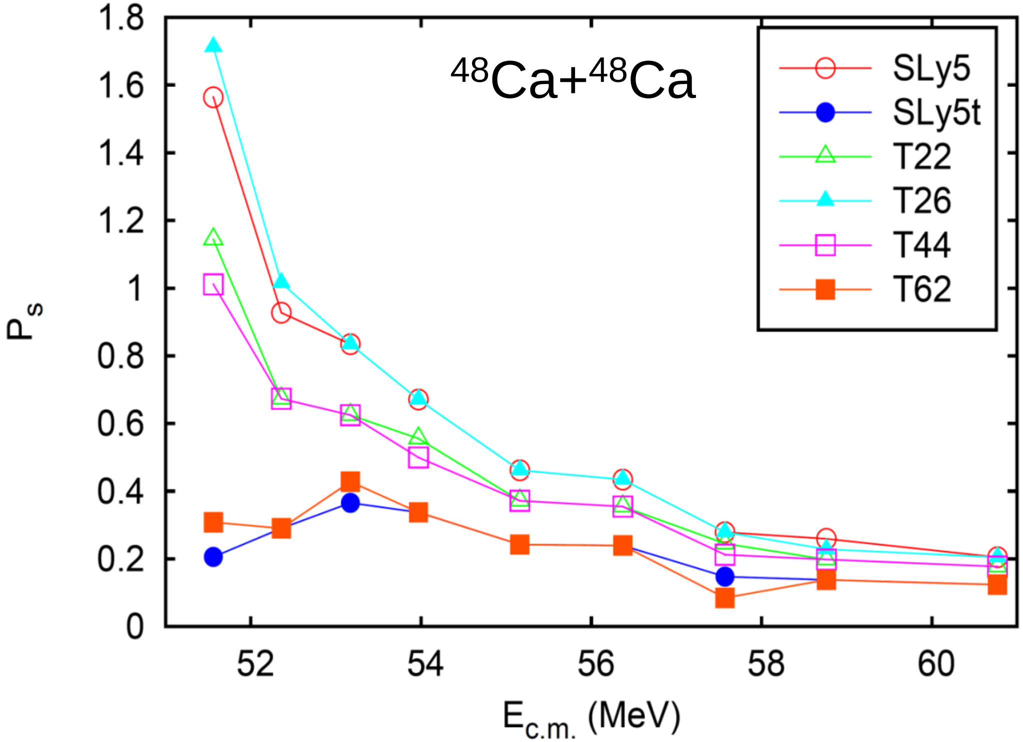
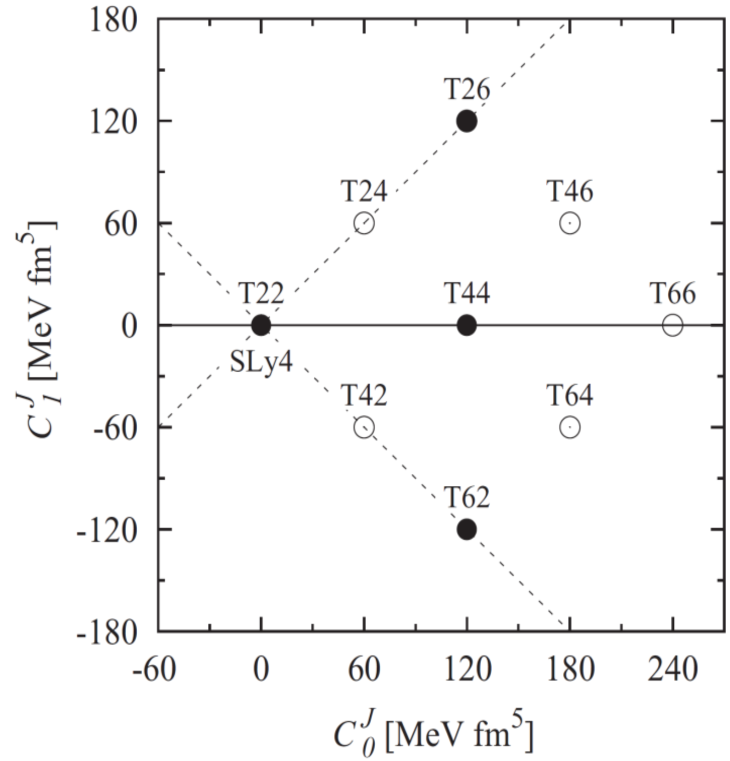


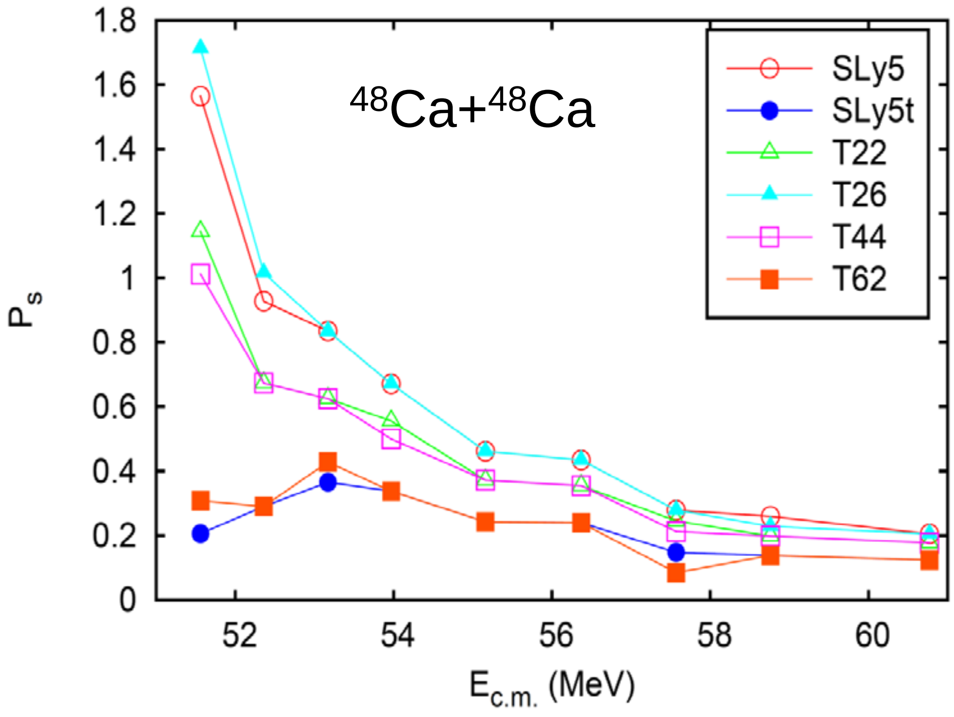


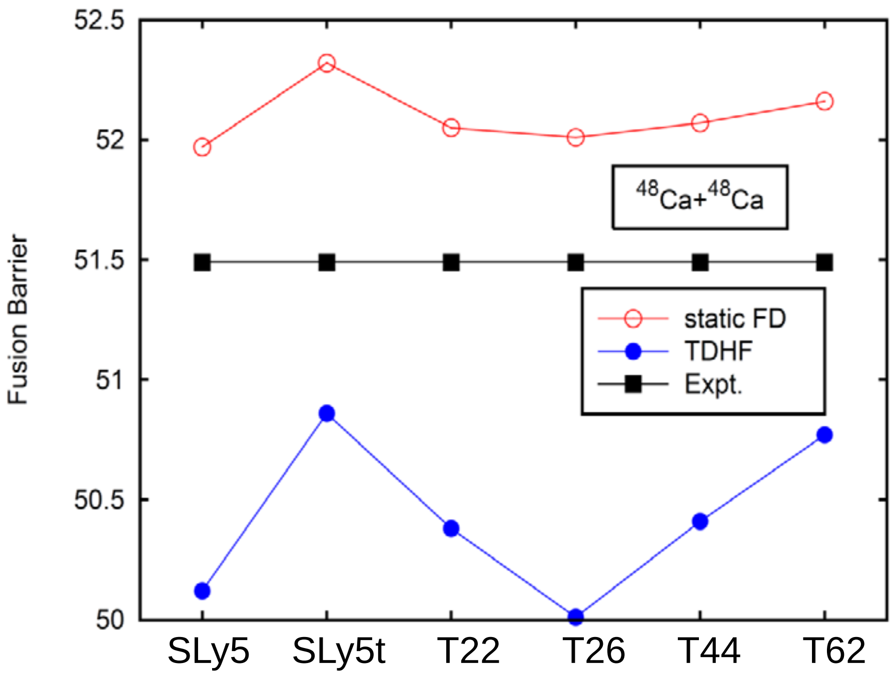
- ◻ deviation with T26 are similar as SLy5, deviates large from experiment;
- ◻ deviation with T62 are similar as SLy5t, in good agreement with experiment

Effect of tensor force in fusion dynamics

- Another important experimental observable

Parameter-free calculation





- the observations of cross section are consistent with the fusion barrier;
- SLy5t and T62 gives the best agreement, T44 and T22 mild, SLy5 and T22 the worst

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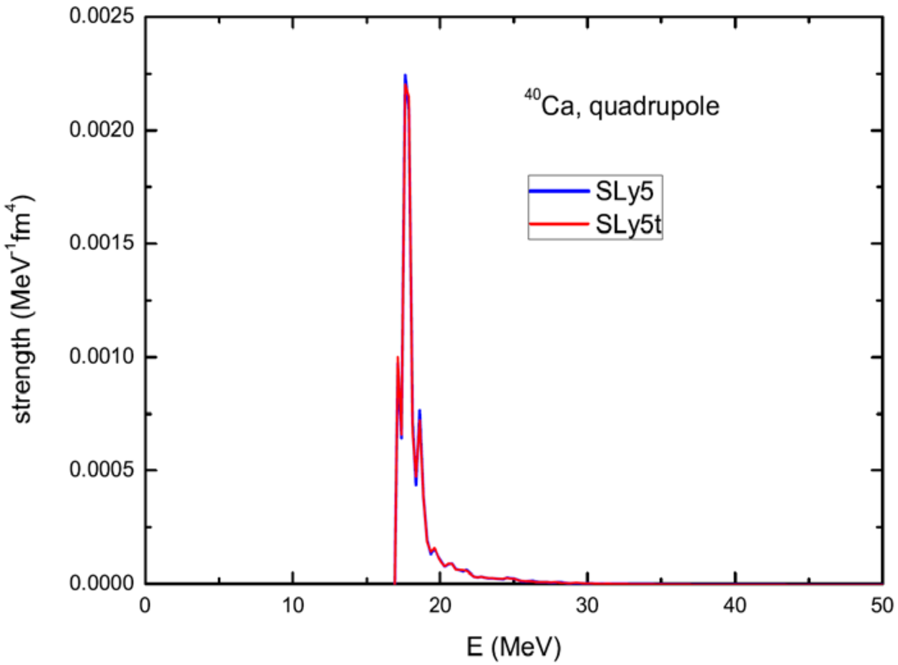
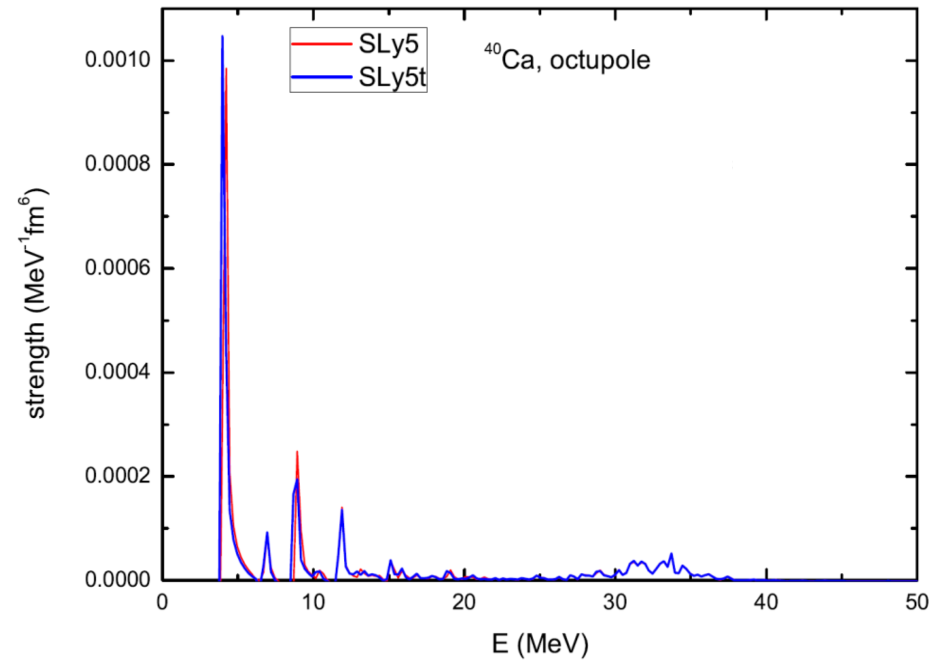
Effect of tensor force in vibration states



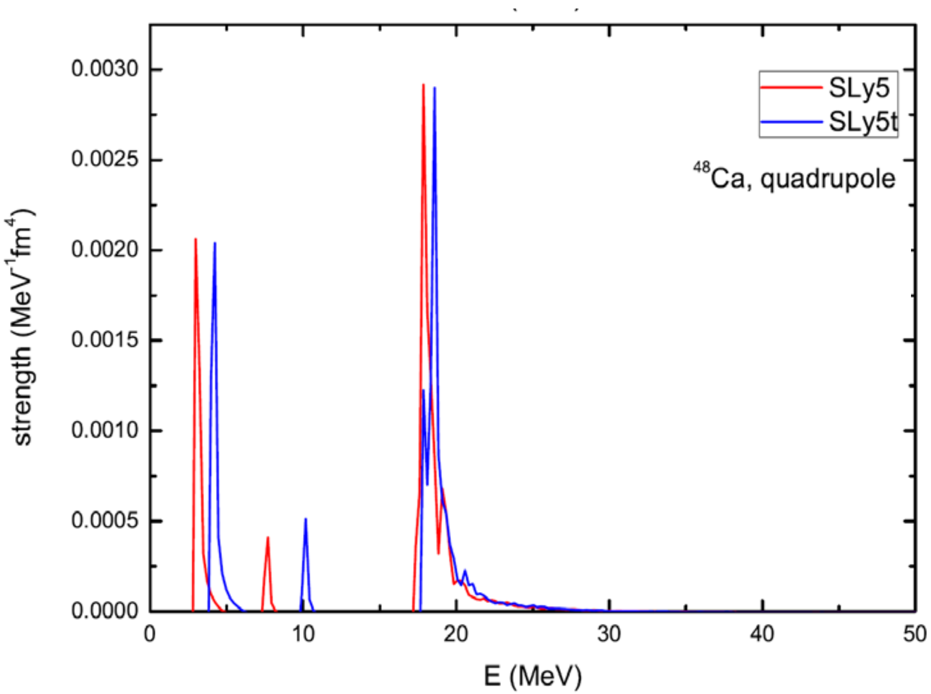


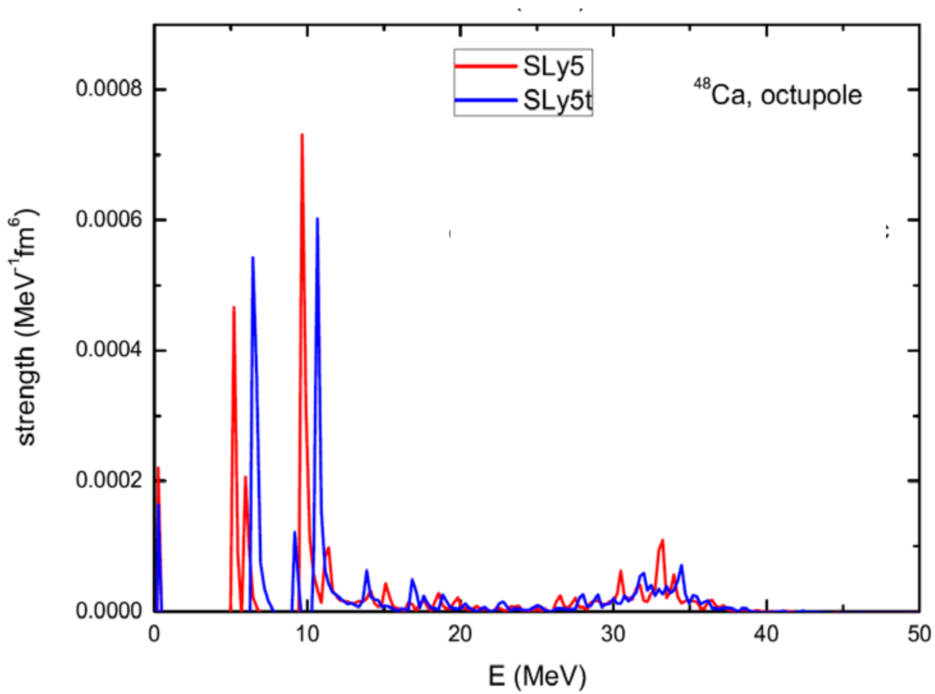
^{40}Ca

vibration stae	SLy5	SLy5t	Expt.
quadrupole	17.59	17.59	
3_1^-	4.21	3.97	3.74

- The octupole vibration state in ^{40}Ca is reasonably close to the experimental value;
- The 3_1^- state is expected to have a much stronger effect on near-barrier reaction mechanism than other octupole states;

Effect of tensor force in vibration states





^{48}Ca

vibration state	SLy5	SLy5t	Expt.
2_1^+	2.97	4.21	3.83
3_1^-	5.21	6.44	4.51

- The tensor has a quite important effect on low-lying vibrations in ^{48}Ca;
- The energy are pushed up with tensor force;
- This explains smaller fusion with tensor force because the coupling effects are weaker with high energy modes;

Summary

- The full tensor force has been incorporated in three-dimensional symmetry-unrestricted TDHF;
- The impact of tensor force in fusion dynamics has been systematically studied;
- The tensor force SLy5t increased barrier height, and hence decreases the FCS, much better agreement with experiments;
- The effect of tensor force depends on the isoscalar and isovector couplings;
- The effect of tensor force on low-lying vibration states;

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Thank you for your attention!