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Skyrme Tensor Force in ^{16}O+^{16}O Fusion Dynamics

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Abstract: The fusion dynamics of ^{16}O+^{16}O around Coulomb barrier has been studied in the time-dependent Hartree-Fock (TDHF) theory with the full Skyrme effective interaction. The calculations have been carried out in three-dimensional Cartesian basis without any symmetry restrictions. We have included the full tensor force and all the time-odd terms in Skyrme energy density functional (EDF). The Coulomb barrier obtained from the dynamical TDHF calculations and EDF with frozen density approximation has been compared with the available experimental data. The isoscalar tensor terms and the rearrangement of other terms are found to decrease the barrier height in the spin-saturated system ^{16}O+^{16}O, while the energy of Coulomb barrier tends to decrease as the isovector coupling constant decreases. The fusion cross section for ^{16}O+^{16}O collision has been calculated with and without the tensor force. We found that the tensor force has minor effect on the fusion dynamics of ^{16}O+^{16}O at the energies around Coulomb barrier.

Key words: time-dependent Hartree-Fock; tensor force; fusion; Coulomb barrier

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1 Introduction

It is well known that tensor force is essential to interpret the properties of the deuteron. There have been extensive studies on the effect of tensor force in the nuclear structure properties[1–4]. For example, the tensor force is observed to play a significant role in the evolution of shell structure of exotic nuclei[1], spin-orbit splitting[2, 3], Gamow-Teller and charge exchange spin-dipole excitations[4].

However, quite few studies have been done to investigate the role of tensor force in heavy-ion collisions due to the complexity of collision dynamics. In Ref. [5], the contribution of tim-even spin-current tensor has been demonstrated to become more important with the increase of the mass of the colliding systems. The effect of tim-even tensor force on the dissipation dynamics in deep-inelastic collisions has been investigated in Ref. [6]. In these studies, the inclusion of only time-even tensor terms led to the destruction of Galilean invariance. Recently the full tensor force has been included and found to have an effect on the upper fusion threshold of the order several MeV for ^{16}O+^{16}O collisions[7].

Microscopic theory is a good choice to study the role of tensor force in heavy-ion collisions. Time-dependent Hartree-Fock (TDHF) theory provides the microscopic foundation in nuclear large amplitude collective motion, *e.g.*, deep-inelastic collisions[8–11], fusion dyanmics[12–14], and giant resonances[15, 16]; for a review see Ref. [17].

In this paper, we will employ the microscopic TDHF theory with the full Skyrme tensor force to study the heavy-ion fusion dynamics in ^{16}O+^{16}O collision. Sec. 2 will present TDHF theory and Skyrme density functional (EDF). In Sec. 3, the Coulomb barrier and fusion cross section with and without tensor terms will be discussed and compared with the experimental data. Last is conclusions.

2 Theoretical framework

The time evolution of mean field is described by the TDHF equation

$$\mathrm{i}\hbar\frac{\mathrm{d}\rho}{\mathrm{d}t}=[h[\rho],\rho], \tag{1}$$

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where h is the single-particle Hamiltonian and ρ is the particle number density. In solving TDHF equation, the Skyrme force[18, 19] has been used for the nucleon-nucleon interaction. The full form of Skyrme EDF[3] is expressed as

$$\begin{aligned}E=\int \mathrm{d}^3r\sum_{t=0,1}\Bigg\{&C_t^{\rho}[\rho_0]\rho_t^2+C_t^S[\rho_0]\boldsymbol{S}_t^2+\\ &C_t^{\Delta\rho}\rho_t\Delta\rho_t+C_t^{\nabla S}(\nabla\cdot\boldsymbol{S}_t)^2+\\ &C_t^{\Delta S}\boldsymbol{S}_t\Delta\boldsymbol{S}_t+C_t^{\tau}(\rho_t\tau_t-\boldsymbol{j}_t^2)+\\ &C_t^T\Bigg(\boldsymbol{S}_t\cdot\boldsymbol{T}_t-\sum_{\mu,\nu=x}^{z}J_{t,\mu\nu}J_{t,\mu\nu}\Bigg)+\\ &C_t^F\Bigg[\boldsymbol{S}_t\cdot\boldsymbol{F}_t-\frac{1}{2}\Bigg(\sum_{\mu=x}^{z}J_{t,\mu\mu}\Bigg)^2-\\ &\frac{1}{2}\sum_{\mu,\nu=x}^{z}J_{t,\mu\nu}J_{t,\nu\mu}\Bigg]+C_t^{\nabla\cdot J}(\rho_t\nabla\cdot J_t+\\ &\boldsymbol{S}_t\cdot\nabla\times\boldsymbol{j}_t)\Bigg\}\ ,\end{aligned}\qquad(2)$$

where the central, spin-orbit and tensor force have been included. See Ref. [20] for the definition of coupling constants in the above equation. In the calculations, we set $C_t^{\nabla S}=C^{\Delta S}=0$ because the terms containing the gradient of spin-density may cause the spin instability both in nuclear structure and reaction studies as pointed out in Refs. [3, 7].

The interaction potential between projectile and target in the approaching phase can be expressed by the frozen density (FD) approximation[21] within the EDF theory as

$$V^{\mathrm{FD}}(R)=E[\rho_{\mathrm{P+T}}](R)-E[\rho_{\mathrm{T}}]-E[\rho_{\mathrm{P}}]\ .\qquad(3)$$

$\rho_{\mathrm{P+T}}=\rho_{\mathrm{P}}+\rho_{\mathrm{T}}$ is the sum of ground state density of projectile and target at the relative distance R, and $E[\rho_{\mathrm{P+T}}](R)$ is the Skyrme EDF as shown in Eq (2). Note that the Pauli principle has been neglected in FD approximation due to the overlap of projectile and target densities. When the overlap of two densities is small, *e.g.*, at the position of Coulomb barrier, EDF with FD approximation is a good tool to estimate the Coulomb barrier. However, at the smaller relative distance, since the Pauli effect is strong, FD approximation will not properly account for the interaction potential.

The fusion cross-section is obtained with the sharp cutoff approximation[22]

$$\begin{aligned}\sigma_{\mathrm{fus}}=&\frac{2\pi}{k^2}\sum_l(2l+1)\\ \approx&\pi(b_{\mathrm{max}}^2-b_{\mathrm{min}}^2)\ ,\end{aligned}\qquad(4)$$

where k is wave number, and the sum is for the even partial waves. b_{max} and b_{min} are the maximum and minimum impact parameter when fusion happens, respectively.

The numerical box in three dimensional Cartesian basis has been chosen as 32 fm×24 fm×24 fm for the ^{16}O+^{16}O collision with the grid spacing 1 fm. The initial distance between the two nuclei is taken as 20 fm, and the time step in dynamical calculations as 0.2 fm/c. The choice of these parameters guarantees that the particle number and total energy in dynamical calculations conserved quite well for all the cases studied here.

3 Results and discussion

In present work, the various Skyrme parametrizations SLy5[23], SLy5t[2], and the 36 sets of TIJ[3] have been used to study the effect of tensor force in fusion dynamics of ^{16}O+^{16}O reaction. Note that the parameters of Skyrme tensor force have been fitted in two ways. One is to adjust the parameters of tensor force based on the existing Skyrme parameters, *e.g.*, SLy5+T denoted as SLy5t. The other is to fit all the Skyrme parameters on the same footing, *e.g.*, the set of TIJ parametrizations with a wide range of isoscalar and isovector couplings. With such fitting procedure, different physical scenario will be taken into account. The effect of pure tensor force can be clarified by comparing the results with SLy5 and SLy5t. For the TIJ parametrizations, the calculations can figure out the implication of isoscalar and isovector tensor terms with a wide range of coupling constants.

The energy and radii of Coulomb barrier are listed in Table. 1 for ^{16}O+^{16}O with various Skyrme parametrizations SLy5[23], SLy5t[2], the 36 sets of TIJ[3], and the experimental data[24]. The calculations have been done with FD approximation within EDF theory as shown in Eq. (3). The energy and radii of Coulomb barrier with SLy5t are observed to be exactly same as those with SLy5 for ^{16}O+^{16}O, as we expected, because the tensor force has no contribution to the ground state EDF for the spin-saturated nucleus ^{16}O. There exist some differences among the different TIJ parameter sets. The radii of Coulomb barrier changes from 8.50 fm to 8.58 fm, while the barrier energy shifts from 9.96 MeV to 10.12 MeV. These differences, for the spin-saturated system, come from the rearrangement of other terms of Skyrme EDF in the fit of the parametrizations. One may see that the energy of Coulomb barrier is lower and the radii is larger than the experimental data for all the Skyrme parametrizations. This means the Coulomb barrier with theoretical calculations, comparing with experimental data,

Table 1 Energy (in MeV) and radii (in fm) of the Coulomb barrier obtained with the frozen density approximation and experimental data[24] for ^{16}O+^{16}O.

Parameters	R^{FD}/fm	V^{FD}/MeV	Parameters	R^{FD}/fm	V^{FD}/MeV	Parameters	R^{FD}/fm	V^{FD}/MeV
SLy5	8.51	10.09	T26	8.52	10.08	T51	8.57	10.00
SLy5t	8.51	10.09	T31	8.53	10.06	T52	8.57	10.00
T11	8.50	10.10	T32	8.53	10.06	T53	8.57	10.00
T12	8.50	10.11	T33	8.54	10.05	T54	8.57	9.99
T13	8.50	10.12	T34	8.53	10.06	T55	8.57	9.99
T14	8.50	10.10	T35	8.54	10.04	T56	8.57	9.99
T15	8.50	10.11	T36	8.53	10.05	T61	8.58	9.98
T16	8.51	10.08	T41	8.56	10.03	T62	8.58	9.97
T21	8.52	10.08	T42	8.56	10.01	T63	8.58	9.97
T22	8.52	10.08	T43	8.56	10.01	T64	8.58	9.98
T23	8.52	10.08	T44	8.55	10.02	T65	8.57	9.98
T24	8.52	10.08	T45	8.55	10.02	T66	8.58	9.96
T25	8.52	10.06	T46	8.55	10.01	Expt.	7.91	10.61

has been shifted to the larger relative distance in the curve of interaction potential. Interaction potential obtained with FD approximation for ^{16}O+^{16}O by using Skyrme parameter sets T1J is shown in Fig. 1, as an example. Slight difference among the interaction potential with Skyme T1J parametrizations is observed.

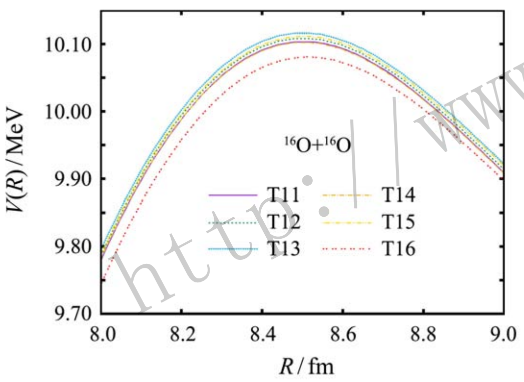

Fig. 1 (color online) Interaction potential as a function of relative distance obtained with the frozen density approximation for ^{16}O+^{16}O by using Skyrme parameter sets T1J.

Note that the Coulomb barrier obtained from FD approximation in Table 1 neglected the Pauli effect and the coupling between the collective motion and single particle degrees of freedom. These important quantum and dynamical effects have been automatically incorporated in the fully microscopic TDHF approach. Table 2 shows the Coulomb barrier from TDHF dynamical calculations for ^{16}O+^{16}O reaction with Skyrme parametrizations SLy5[23], SLy5t[2], four sets of T22, T26, T44 and T62[3]. The precision for the interval of energy has been selected as 0.05 MeV. The barrier with SLy5 and SLy5t is the same. This indicates that the pure tensor force for the spin saturated system ^{16}O+^{16}O has negligible effect at the energies around Coulomb barrier. The T22 and T44 have the same isovector coupling constant equal to 0 and isoscalar coupling constant with the value of 0 and 120 MeVfm^5. By the comparison of Coulomb barrier with T22 and T44, one may conclude that the isoscalar tensor terms and the rearrangement of other terms in the fit tend to decrease the barrier energy for ^{16}O+^{16}O reaction. The T26, T44, and T62 have the same isoscalar coupling constant, while the isovector coupling constant, respectively, takes the value of 120, 0, and 120 MeVfm^5. This indicates that the tensor terms with positive isovector coupling constant prefer to increase the barrier height, while those with negative coupling constants do not have notable effect on the dynamical barrier for ^{16}O+^{16}O reaction.

Table 2 Energy (in MeV) of the Coulomb barrier from TDHF dynamical calculations for ^{16}O+^{16}O reaction with Skyrme parametrizations SLy5[23], SLy5t[2], four sets of T22, T26, T44 and T62[3] within a precision of 0.05 MeV.

	SLy5	SLy5t	T22	T26	T44	T62
V^{TDHF}	10.05	10.05	10.05	10.00	9.90	9.90

In order to see the role of tensor force in dynamical collisions, Fig. 2 presents the fusion cross section calculated with the dynamical TDHF by using the Skyrme parametrization SLy5 and SLy5t, and the available experimental data[25–29]. Owing to the different experimental method and technique, the experimental fusion cross section for ^{16}O+^{16}O are quite different among the five sets of experimental data. For details, see Ref. [30]. One could see that the fusion cross section with SLy5 and SLy5t are quite similar. This means that the tensor force SLy5t has negligible impact on the fusion cross-section for ^{16}O+^{16}O collision. The paper[7] concluded that the maximum impact parameter for fusion in ^{16}O+^{16}O collisions was rather insensitive to the tensor parameter set for the center of mass energy of 34 MeV. This is consistent with our results. Although a minor effect of tensor force is observed in the fusion dynamics of ^{16}O+^{16}O collision, an obvious impact of tensor force on the upper fusion threshold is observed to be the order of several MeV for ^{16}O+^{16}O collision.

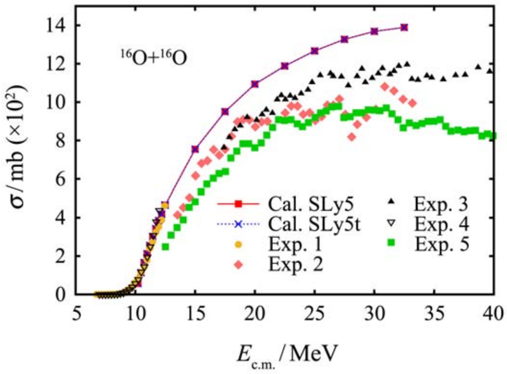

Fig. 2 (color online) Fusion cross section with TDHF calculations by using Skyrme parametrizations SLy5 and SLy5t, and the experimental data[25−29] for ^{16}O+^{16}O collisions.

4 Conclusions

We have studied the fusion dynamics of ^{16}O+^{16}O collision in the time-dependent Hartree-Fock theory with the full Skyrme force. The calculations have been done in three-dimensional Cartesian basis without any symmetry restrictions. The Coulomb barrier obtained from the dynamical TDHF calculations and the energy density functional with frozen density approximation has been compared with experimental data. We found, for the spin-saturated system ^{16}O+^{16}O, the isoscalar tensor terms and the rearrangement of other terms decrease the barrier height, while the energy of Coulomb barrier tends to increase with the increase of isovector coupling constant. We calculated the fusion cross sections for ^{16}O+^{16}O collision with and without the tensor force. The tensor force has minor effect on the fusion dynamics of ^{16}O+^{16}O at the energies of Coulomb barrier.

References:

[1] OTSUKA T, SUZUKI T, FUJIMOTO R, *et al.* Phys Rev Lett, 2005, **95**: 232502.

[2] COLO G, SAGAWA H, FRACASSO S, *et al.* Phys Lett B, 2007, **646**: 227.

[3] LESINSKI T, BENDER M, BENNACEUR K, *et al.* Phys Rev C, 2007, **76**: 014312.

[4] BAI C L, ZHANG H, SAGAWA H, *et al.* Phys Rev lett, 2010, **105**: 072501.

[5] IWATA Y, MARUHN J A. Phys Rev C, 2011, **84**: 014616.

[6] DAI G, GUO L, ZHAO E, *et al.* Sci China Phys, 2014, **57**: 1618.

[7] STEVENSON P D, SUCKLING E B, FRACASSO S , *et al.* Phys Rev C, 2016, **93**: 054617.

[8] MARUHN J A, REINHARD P G, STEVENSON P D, *et al.* Phys Rev C, 2006, **74**: 027601.

[9] GUO L, MARUHN J A, REINHARD P G. Phys Rev C, 2007, **76**: 014601.

[10] SIMENEL C. Phs Rev Lett, 2011, **106**: 112502.

[11] DAI G F, GUO L, ZHAO E G, *et al.* Phys Rev C, 2014, **90**: 044609.

[12] GUO L, MARUHN J A, REINHARD P G, *et al.* Phys Rev C, 2008, **77**: 041301(R).

[13] UMAR A S, OBERACKER V E, MARUHN J A, *et al.* Phys Rev C, 2010, **81**: 064607.

[14] GUO L, NAKATSUKASA T. EPJ Web of Conference, 2012, **38**: 09003.

[15] SIMENEL C, CHOMAZ P, DE FRANCE G. Phs Rev Lett, 2001, **86**: 2971.

[16] REINHARD P G, GUO L, MARUHN J. Eur Phys J A, 2007, **32**: 19.

[17] SIMENEL C. Euro Phys J A, 2012, **48**: 1.

[18] SKYRME T H R. Philos Mag, 1956, **1**: 1043.

[19] SKYRME T. Nucl Phys, 1958, **9**: 615.

[20] DAVESNE D, MARTINE M, BENNACEUR K, *et al.* Phys Rev C, 2009, **80**: 024314.

[21] DENISOV V Y, NORENBERG W. Eur Phys J A, 2002, **15**: 375.

[22] BONCHE P, GRAMMATICOS B, KOONIN S. Phys Rev C, 1978, **17**: 1700.

[23] CHABANAT E, BONCHE P, HAENSEL P, *et al.* Nucl Phys A, 1998, **635**: 231; 1998, **643**: 441.

[24] VAZ L C, ALEXANDER J M, SATCHLER G R. Phys Rep, 1981, **69**: 373.

[25] THOMAS J, CHEN Y, HINDS S, *et al.* Phys Rev C, 1986, **33**: 1679.

[26] TSERRUYA I, EISEN Y, PELTE D, *et al.* Phys Rev C, 1978, **18**: 1688.

[27] FERNANDEZ B, GAARDE C, LARSEN J. *et al.* Nucl Phys A, 1978, **306**: 259.

[28] WU S C, BARNES C. Nucl Phys A, 1984, **422**: 373.

[29] KOLATA J, FREEMAN R, HAAS F, *et al.* Phys Rev C, 1979, **19**: 2237.

[30] SIMENEL C, KESER R, UMAR A, *et al.* Phys Rev C, 2013, **88**: 024617.

张量力在^{16}O+^{16}O熔合动力学中的效应

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摘要： 利用时间相关Hartree-Fock理论和完整Skyrme有效相互作用研究了^{16}O+^{16}O碰撞在库仑位垒附近的熔合动力学。数值计算是在没有任何对称性约束的三维笛卡尔基下完成。将时间相关Hartree-Fock理论和冻结密度近似下的能量密度泛函方法给出的库仑位垒与实验结果进行了比较，发现同位旋标量的张量项能降低自旋饱和体系^{16}O+^{16}O的库仑位垒，而库仑位垒高度随着同位旋矢量的张量项的耦合常数减小而降低。并计算了包含和不包含张量力的^{16}O+^{16}O熔合截面，发现张量力对^{16}O+^{16}O碰撞在库仑位垒附近的熔合动力学影响较小。

关键词： 时间相关Hartree-Fock；张量力；熔合反应；库仑位垒

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