Two-body dissipation effects on the synthesis of superheavy elements

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Phys. Rev. C **93**, 034607 — Published 7 March 2016

DOI: 10.1103/PhysRevC.93.034607

Two-body dissipation effects on synthesis of superheavy elements

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To investigate the two-body dissipation effects on the synthesis of superheavy elements, we calculate low-energy collisions of the $N = 50$ isotones (^{82}Ge, ^{84}Se, ^{86}Kr and ^{88}Sr) on ^{208}Pb using the time-dependent density-matrix theory (TDDM). TDDM is an extension of the time-dependent Hartree-Fock (TDHF) theory and can determine the time evolution of one-body and two-body density matrices. Thus TDDM describes both one-body and two-body dissipation of collective energies. It is shown that the two-body dissipation may increase fusion cross sections and enhance the synthesis of superheavy elements.

PACS numbers: 21.60.-n,21.60.Jz,24.10.Cn,25.70.Jj

I. INTRODUCTION

The creation of new elements is one of the most novel and challenging research areas of nuclear physics [1–4]. The search for a region of the nuclear chart that can sustain the so called *superheavy elements* (SHE) has led to intense experimental activity resulting in the discovery and confirmation of elements with atomic numbers as large as $Z = 118$ [5–7]. The theoretically predicted *island of stability* in the SHE region of the nuclear chart is the result of new proton and neutron shell-closures, whose location is not precisely known [8–10]. The experiments to discover these new elements are notoriously difficult, with fusion evaporation residue (ER) cross-section in pico-barns.

The time-dependent Hartree-Fock theory (TDHF) provides us with a microscopic and self-consistent way to study nuclear dynamics and has extensively been used to study low-energy heavy-ion collisions [11, 12]. However, in such calculations approximations of any type limit the number of degrees of freedom accessible during a collision, and hence the nature and degree of dissipation [13–16]. The understanding of the dissipative mechanisms in the TDHF theory is vital for establishing the region of validity of the mean-field approximation and providing estimates for the importance of the mean-field effects at higher energies. In TDHF, the dissipation of the translational kinetic energy of the two ions is due to the collisions of single particle states with the walls of the time-dependent potential. This leads to the randomization of the motion characterized by the distribution of energy among all possible degrees of freedom of the system. The complete equilibration of the translational kinetic energy among all possible degrees of freedom is commonly accepted as being the definition of fusion whereas the incomplete equilibration results in inelastic collisions.

Recently TDHF simulations using symmetry unrestricted three-dimensional codes with full Skyrme effective interactions [16, 17] have been reported for fusion reactions [18–20], particle transfer reactions [21–24], quasi-fission processes [25–28],calculation of ion-ion interaction potentials [18, 29–31], and to dynamics of fission [32–34]. Even though TDHF simulations have become sophisticated, it is still plausible that additional dissipation of collective energies due to two-body mechanism plays an important role in critical situations like fusion processes. In this paper we study possible effects of the two-body dissipation on the synthesis of superheavy elements using the time-dependent density-matrix theory (TDDM) [35–38]. TDDM which is formulated by truncating the Bogoliubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy for reduced density matrices at a two-body level consists of the coupled equations of motion for one-body and two-body density matrices. The two-body dissipation is included through the coupling to the two-body density matrix. We consider so-called cold fusion [3] using ^{208}Pb as the target and the $N = 50$ isotones (^{82}Ge, ^{84}Se, ^{86}Kr and ^{88}Sr) as the projectiles. The nuclei ^{82}Ge and ^{84}Se are unstable but included to study the charge dependence of fusion reactions. Such unstable projectiles may be realized as radioactive beams [39]. We show that the two-body dissipation could enhance the synthesis of superheavy elements.

The impact of two-body dissipation on the capture process at near-barrier energies was studied in the past using various extended TDHF calculations as well as more phenomenological approaches such as the dissipative diabatic dynamics approach [40] and constrained molecular dynamics calculations that include two-body dissipations [41]. The heavy-ion fusion process has also been addressed within a transport approach that includes the two-body dissipation [42].

The paper is organized as follows. A brief outline of the TDDM formalism in connection to TDHF is given in Sec. II. Calculational details are given in Sec. III. Results are discussed in Sec. IV, followed by the conclusion in Sec. V.

II. FORMULATION

Here we give a brief outline of the TDDM formalism. Further details can be found in [36]. We start with a many-body Hamiltonian H consisting of a one-body part and a two-body interaction

$$H = \sum_{\alpha\alpha'} \langle\alpha|t|\alpha'\rangle a^\dagger_\alpha a_{\alpha'} + \frac{1}{2}\sum_{\alpha\beta\alpha'\beta'} \langle\alpha\beta|v|\alpha'\beta'\rangle a^\dagger_\alpha a^\dagger_\beta a_{\beta'} a_{\alpha'}, \tag{1}$$

where $a^\dagger_\alpha$ and a_α are the creation and annihilation operators of a particle at a time-dependent single-particle state α. TDDM gives the coupled equations of motion for the one-body density matrix (the occupation matrix) $n_{\alpha\alpha'}$ and the correlated part of the two-body density matrix $C_{\alpha\beta\alpha'\beta'}$. These matrices are defined as

$$n_{\alpha\alpha'}(t) = \langle\Phi(t)|a^\dagger_{\alpha'} a_\alpha|\Phi(t)\rangle, \tag{2}$$

$$\begin{aligned} C_{\alpha\beta\alpha'\beta'}(t) &= \langle\Phi(t)|a^\dagger_{\alpha'} a^\dagger_{\beta'} a_\beta a_\alpha|\Phi(t)\rangle \\ &- (n_{\alpha\alpha'}(t)n_{\beta\beta'}(t) - n_{\alpha\beta'}(t)n_{\beta\alpha'}(t)), \end{aligned} \tag{3}$$

where $|\Phi(t)\rangle$ is the time-dependent total wavefunction $|\Phi(t)\rangle = \exp[-iHt/\hbar]|\Phi(t=0)\rangle$. The single-particle wavefunctions ϕ_α satisfy a TDHF-like equation

$$i\hbar\frac{\partial\phi_\alpha}{\partial t} = h\phi_\alpha, \tag{4}$$

where

$$\langle\alpha|h|\alpha'\rangle = \langle\alpha|t|\alpha'\rangle + \sum_{\lambda_1\lambda_2} \langle\alpha\lambda_1|v|\alpha'\lambda_2\rangle_A n_{\lambda_2\lambda_1}. \tag{5}$$

Here the subscript A means that the corresponding matrix is antisymmetrized. The equations of motion for $n_{\alpha\alpha'}$ and $C_{\alpha\beta\alpha'\beta'}$ are written as [36]

$$\begin{aligned} i\hbar\dot{n}_{\alpha\alpha'} = \sum_{\lambda_1\lambda_2\lambda_3} &[\langle\alpha\lambda_1|v|\lambda_2\lambda_3\rangle C_{\lambda_2\lambda_3\alpha'\lambda_1} \\ &- C_{\alpha\lambda_1\lambda_2\lambda_3}\langle\lambda_2\lambda_3|v|\alpha'\lambda_1\rangle], \end{aligned} \tag{6}$$

$$i\hbar\dot{C}_{\alpha\beta\alpha'\beta'} = B_{\alpha\beta\alpha'\beta'} + P_{\alpha\beta\alpha'\beta'} + H_{\alpha\beta\alpha'\beta'}. \tag{7}$$

The matrix $B_{\alpha\beta\alpha'\beta'}$ in Eq. (7) does not contain $C_{\alpha\beta\alpha'\beta'}$ and describes two particle - two hole (2p-2h) and 2h-2p excitations:

$$\begin{aligned} B_{\alpha\beta\alpha'\beta'} = \sum_{\lambda_1\lambda_2\lambda_3\lambda_4} &\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle_A \\ &\times [(\delta_{\alpha\lambda_1} - n_{\alpha\lambda_1})(\delta_{\beta\lambda_2} - n_{\beta\lambda_2})n_{\lambda_3\alpha'}n_{\lambda_4\beta'} \\ &- n_{\alpha\lambda_1}n_{\beta\lambda_2}(\delta_{\lambda_3\alpha'} - n_{\lambda_3\alpha'})(\delta_{\lambda_4\beta'} - n_{\lambda_4\beta'})]. \end{aligned} \tag{8}$$

Particle - particle and hole-hole correlations are described by $P_{\alpha\beta\alpha'\beta'}$:

$$\begin{aligned} P_{\alpha\beta\alpha'\beta'} = \sum_{\lambda_1\lambda_2\lambda_3\lambda_4} &\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle \\ &\times [(\delta_{\alpha\lambda_1}\delta_{\beta\lambda_2} - \delta_{\alpha\lambda_1}n_{\beta\lambda_2} - n_{\alpha\lambda_1}\delta_{\beta\lambda_2})C_{\lambda_3\lambda_4\alpha'\beta'} \\ &- (\delta_{\lambda_3\alpha'}\delta_{\lambda_4\beta'} - \delta_{\lambda_3\alpha'}n_{\lambda_4\beta'} - n_{\lambda_3\alpha'}\delta_{\lambda_4\beta'})C_{\alpha\beta\lambda_1\lambda_2}]. \end{aligned} \tag{9}$$

The matrix $H_{\alpha\beta\alpha'\beta'}$ contains the particle-hole correlations:

$$\begin{aligned} H_{\alpha\beta\alpha'\beta'} = \sum_{\lambda_1\lambda_2\lambda_3\lambda_4} &\langle\lambda_1\lambda_2|v|\lambda_3\lambda_4\rangle_A \\ &\times [\delta_{\alpha\lambda_1}(n_{\lambda_3\alpha'}C_{\lambda_4\beta\lambda_2\beta'} - n_{\lambda_3\beta'}C_{\lambda_4\beta\lambda_2\alpha'}) \\ &+ \delta_{\beta\lambda_2}(n_{\lambda_4\beta'}C_{\lambda_3\alpha\lambda_1\alpha'} - n_{\lambda_4\alpha'}C_{\lambda_3\alpha\lambda_1\beta'}) \\ &- \delta_{\alpha'\lambda_3}(n_{\alpha\lambda_1}C_{\lambda_4\beta\lambda_2\beta'} - n_{\beta\lambda_1}C_{\lambda_4\alpha\lambda_2\beta'}) \\ &- \delta_{\beta'\lambda_4}(n_{\beta\lambda_2}C_{\lambda_3\alpha\lambda_1\alpha'} - n_{\alpha\lambda_2}C_{\lambda_3\beta\lambda_1\alpha'})]. \end{aligned} \tag{10}$$

The total number of particles $A = \sum_\alpha n_{\alpha\alpha}$ is conserved as easily understood by taking the trace of Eq. (6). Formally Eqs. (6) and (7) also conserve the total energy $E_{\rm tot}$ given by [36]

$$\begin{aligned} E_{\rm tot} &= \sum_{\alpha\alpha'}\langle\alpha|t|\alpha'\rangle n_{\alpha'\alpha} \\ &+ \frac{1}{2}\sum_{\alpha\beta\alpha'\beta'}\langle\alpha\beta|v|\alpha'\beta'\rangle(n_{\alpha'\alpha}n_{\beta'\beta} - n_{\alpha'\beta}n_{\beta'\alpha} \\ &+ C_{\alpha'\beta'\alpha\beta}). \end{aligned} \tag{11}$$

III. CALCULATIONAL DETAILS

Since our interest here is not in quantitative analysis of production rates of super-heavy elements but in exploration of possible effects of the two-body dissipation on their synthesis, we consider only the head-on collisions using the TDDM code [38, 43] which was developed based on the TDHF code [13] with axial symmetry restriction. The assumption of the axial symmetry is justified for the head-on collisions when the colliding system initially has axial symmetry with respect to the internuclear axis as is the case considered in this paper. We consider the collisions of the $N = 50$ isotones (^{82}Ge, ^{84}Se, ^{86}Kr and ^{88}Ge) on ^{208}Pb so that the total system has the charge $114 \leq Z \leq 120$. Although Nuclei ^{82}Ge and ^{84}Se are unstable, they are included in the calculations to cover the total charges $Z = 114$ and 116. The HF ground state is used as the initial ground states of the colliding nuclei. In the case of the projectiles which are open-shell nuclei it is assumed in the HF iteration process that the lowest-energy proton single-particle states in the $Z = 28 - 40$ subshell are fully occupied by the corresponding number of valence protons. The projectile nuclei thus prepared have slight deformation because not all single-particle states with different magnetic quantum numbers are equally occupied. The mesh sizes used in the TDHF code are $\Delta r = \Delta z = 0.5$ fm and the mesh points are $N_r \times N_z = 30 \times 90$. The time step size is $\Delta t = 0.75$ fm/c. We use the Skyrme III force [44] for the mean-field Hamiltonian Eq. (4). Since the Skyrme III has a large effective mass ($m^*/m \approx 0.9$), it is possible to obtain several bound single-particle states above the Fermi level which are needed to define $C_{\alpha\beta\alpha'\beta'}$. Since the number of $C_{\alpha\beta\alpha'\beta'}$ increases rapidly with increasing number of the single-particle states, we are forced to use a quite limited number of the single-particles states for the calculation of $C_{\alpha\beta\alpha'\beta'}$. To solve Eqs. (6) and (7), we take about 20 bound single states near the Fermi level both for protons and neutrons: The number depends on the projectile nucleus. As the residual interaction in Eqs. (6) and (7), which should in principle be consistent with the effective interaction used for the mean-field potential, we use a simple contact interaction $v(\boldsymbol{r}-\mathbf{r}') = v_0\delta^3(\boldsymbol{r}-\mathbf{r}')$ with $v_0 = -500$ MeV fm^3 to facilitate the time-consuming calculations of the matrix elements $\langle\alpha\beta|v|\alpha'\beta'\rangle$ at each time step. The value $v_0 = -500$ MeV fm^3 is similar to the strength of the contact interactions used in the study of the pairing correlations in tin isotopes [45]. We consider that the system fuses when the colliding nuclei stick together beyond $T_{\rm f} = 4000$ fm/c. This criterion for fusion seems reasonable as compared with the TDHF fusion study by Guo and Nakatsukasa [19] for a similar heavy system ^{70}Zn+^{208}Pb.

IV. RESULTS

The results for each projectile nucleus are summarized as follows:

i) ^{82}Ge: The total charge of this system is $Z = 114$. In TDHF fusion occurs in the three different energy regions, $E_{\rm cm} = 284\pm1$ MeV, 292 MeV $\leq E_{\rm cm} \leq$ 388 MeV and 468 MeV $\leq E_{\rm cm} \leq$ 626 MeV, where $E_{\rm cm}$ is the incident energy in the center-of-mass frame. Since the system barely escapes fusion in TDHF below and above these energy ranges, extra dissipation in TDDM results in a wider energy region for fusion, 281 MeV $\leq E_{\rm cm} \leq$ 655 MeV. In order to obtain the information about the capture barrier, we performed the TDHF and TDDM calculations at low energies and found that the barrier height is about 280 MeV both in TDHF and TDDM. This indicates that in the early stage of the collision the two-body dissipation operates inside the nucleus-nucleus potential pocket, resulting in trapping of the dinuclear system. The Coulomb barrier for the system ^{76}Ge+^{208}Pb which was estimated by Smolańczuk using the folding potential [46] is 257.5 MeV. If a similar value of the Coulomb barrier is applied to the system ^{82}Ge+^{208}Pb, the lowest energy for fusion in TDDM is about 24 MeV larger than the Coulomb barrier, which corresponds to so-called extra push. The above result shows that the extra push becomes slightly smaller due to the two-body dissipation. The density profiles in TDHF and TDDM at $E_{\rm cm} = 450$ MeV are shown in Fig. 1. In TDDM the system fuses whereas a projectile-like fragment appears on the left-hand side in TDHF after a rather large contact period. This process in TDHF may correspond to quasi fission. The collision pattern in TDHF changes at higher incident energies around $E_{\rm cm} = 600$ MeV beyond which a projectile-like profile appears on the right-hand side in the final state. Therefore, the fused system in TDHF and TDDM above $E_{\rm cm} = 600$ MeV has a shape similar to the lower part of Fig. 1 but reflected with respect to the plane perpendicular to the z axis.

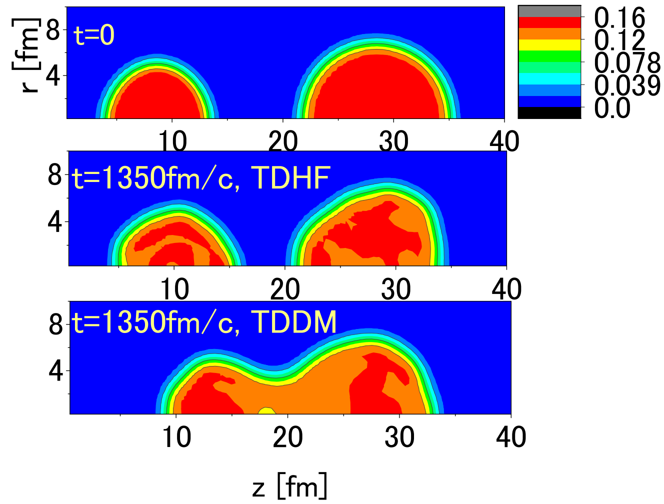

FIG. 1. Contour plot of the density $\rho(z,r)$ [fm^{-3}] in the head-on collision of ^{82}Ge+^{208}Pb at $E_{\rm cm} = 450$ MeV. The upper part shows the density profile at $t = 0$, the middle part that in TDHF at $t = 1350$ fm/c and the lower part that in TDDM at $t = 1350$ fm/c. The system fuses in TDDM at this incident energy.

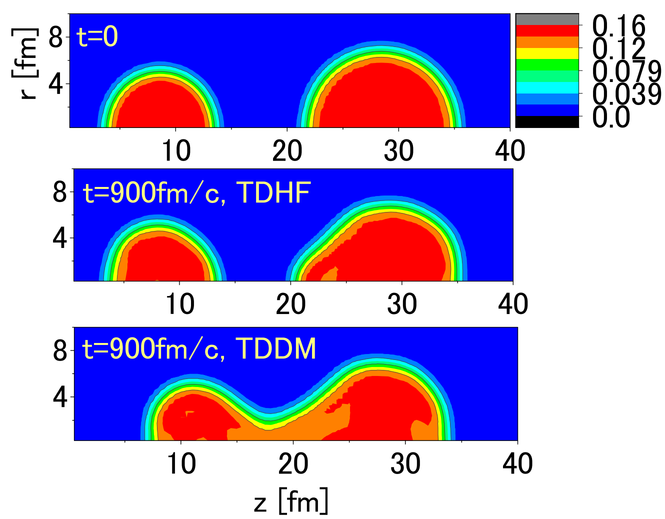

FIG. 2. Contour plot of the density $\rho(z,r)$ [fm^{-3}] in the head-on collision of ^{88}Sr+^{208}Pb at $E_{\rm cm} = 340$ MeV. The upper part shows the density profile at $t = 0$, the middle part that in TDHF at $t = 900$ fm/c and the lower part that in TDDM at $t = 900$ fm/c.

ii) ^{84}Se : The total charge of this system is $Z = 116$. The system fuses in TDHF in the quite narrow energy region $E_{\rm cm} = 299 \pm 1$ MeV, while fusion occurs in TDDM in the wider energy range 298 MeV $\leq E_{\rm cm} \leq$ 403 MeV. The change in the low-energy threshold due to the two-body dissipation is negligible in this system. The fusion threshold $E_{\rm cm} \approx 300$ MeV for ^{84}Se+^{208}Pb is about

30 MeV higher than the Coulomb barriers given by Smolańczuk [46, 47].

iii) ^{86}Kr: The total charge of this system is $Z = 118$. The system does not fuse in TDHF although the contact time of the colliding nuclei becomes large with increasing incident energy: It is about 2300 fm/c for ^{86}Kr+^{208}Pb at $E_{\rm cm} = 650$ MeV. We cannot find a high-energy fusion region around $E_{\rm cm} = 600$ MeV which has been predicted by an early TDHF calculation [48] for ^{84}Kr+^{209}Bi. This may be explained by the fact that they defined fusion using a smaller $T_{\rm f} \approx 1350$ fm/c. The system fuses in TDDM in the narrow energy range $E_{\rm cm} = 341 \pm 1$ MeV. The fusion threshold $E_{\rm cm} \approx 340$ MeV for ^{86}Kr+^{208}Pb is about 54 MeV larger than the Coulomb barriers given by Smolańczuk [46, 47]. The value of extra push is about half of the prediction of the Swiateki's macroscopic model [49] for the corresponding effective fissility $(Z^2/A)_{\rm eff} = 4Z_1Z_2/A_1^{1/3}A_2^{1/3}(A_1^{1/3} + A_2^{1/3})$, where Z_1, Z_2, A_1 and A_2 are proton and mass numbers of the colliding partners, but about twice larger than the result of the TDHF calculation by Guo and Nakatsukasa [19] for the system ^{100}Sn+^{132}Sn which has similar effective fissility.

iv) ^{88}Sr: The total charge of this system is $Z = 120$. Fusion does not occurs both in TDHF and TDDM. In TDDM the two fragments are further slowed down than in TDHF due to the two-body dissipation as shown in Fig. 2 for ^{88}Sr+^{208}Pb at $E_{\rm cm} = 340$ MeV. The fact that the system does not fuse in TDDM may be due to the truncation of the single-particle space to define $C_{\alpha\beta\alpha'\beta'}$. Since it is hard to increase the number of the single-particle states, we performed a TDDM calculation using a stronger residual interaction with $v_0 = -1000$ MeV fm^3 at $E_{\rm cm} = 340$ MeV and found that the system fuses. More elaborate calculations are needed for this system to conclude whether the system fuses or not in TDDM. The nucleon-nucleon collisions not only increase the dissipation of collective energies but also can enhance fluctuations of observables. To show this, we calculate the dispersion of the mass distribution $\sigma^2 = \langle \hat{N}_{\rm L}^2\rangle - \langle \hat{N}_{\rm L}\rangle^2$ for the projectile-like fragment shown in Fig. 2, where $\hat{N}_{\rm L}$ is the number operator that counts number of nucleons in the left-hand fragment [13]. We found only a small increase in the dispersion: The results of σ^2 calculated in TDHF at $t = 900$ fm/c and in TDDM at $t = 1155$ fm/c are 5.4 and 5.9, respectively.

V. SUMMARY

In summary, low-energy head-on collisions of the $N = 50$ isotones (^{82}Ge, ^{84}Se, ^{86}Kr and ^{88}Sr) on ^{208}Pb were studied using the time-dependent density-matrix theory (TDDM). TDDM is an extension of the time-dependent Hartree-Fock theory (TDHF) and can include the effects of the two-body dissipation which is missing in TDHF. It was shown that the two-body dissipation expands the fusion energy range for ^{84}Se+^{208}Pb and makes it possible for ^{86}Kr+^{208}Pb to fuse. Although our approach can only deal with the formation of an intermediate dinuclear complex, it was demonstrated that the two-body dissipation could play an important role in the synthesis of superheavy elements. The obtained results encourage further studies of the two-body dissipation effects based on the TDDM approach, though various refinements such as increase of the single-particle space and improvement of the residual interaction are needed to obtain more quantitative results.

ACKNOWLEDGMENTS

This work was supported in part by DOE grant No. DE-SC0013847 with Vanderbilt University.

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