Strong Orientation Dependence of Multinucleon Transfer Processes in $^{238}$U+$^{124}$Sn Reaction

Kazuyuki Sekizawa$^1$ and Kazuhiro Yabana$^{1,2}$

$^1$Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan
$^2$Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan

E-mail: sekizawa@nucl.ph.tsukuba.ac.jp

(Received September 30, 2014)

We theoretically investigate multinucleon transfer (MNT) processes in $^{238}$U+$^{124}$Sn reaction at $E_{\text{lab}} = 5.7$ MeV/A using the time-dependent Hartree-Fock (TDHF) theory. For this reaction, measurements of MNT processes have been reported, showing substantial MNT cross sections accompanying more than ten protons. From the calculation, we find that the amount of transferred nucleons depends much on the relative orientation between the deformation axis of $^{238}$U and the relative vector connecting centers of $^{238}$U and $^{124}$Sn nuclei. We find a formation of thick neck when the $^{238}$U collides from its tip with $^{124}$Sn. However, the neck formation is substantially suppressed when $^{238}$U collides from its side. We have found that a large number of protons are transferred in the tip collision. This is caused by the breaking of the neck and subsequent absorption of nucleons in the neck region. We thus conclude that the measured MNT processes involving about ten protons originate from the neck breaking dynamics in the tip collisions of a deformed $^{238}$U nucleus.

KEYWORDS: multinucleon transfer, low-energy heavy ion reactions, TDHF

1. Introduction

About 30 years ago, pioneering measurements of multi-nucleon transfer (MNT) cross sections in $^{238}$U-induced dissipative collisions were achieved [1]. In the measurements of $^{238}$U + $^{124}$Sn collisions, MNT processes accompanying more than ten protons from $^{238}$U have been reported. Possible structural effects have been advocated to explain the fact that lighter fragments with neutron number approximately equal to $N = 82$ are produced abundantly. Although there have been extensive efforts to clarify the reaction mechanism both experimentally and theoretically, the origin of the transfer of many protons has not yet been clear.

Recently, we have developed a theoretical method to investigate MNT processes in heavy ion reactions within the microscopic framework of the time-dependent Hartree-Fock (TDHF) theory. To calculate transfer probabilities from the TDHF wave function after collision, we have used a particle number projection (PNP) technique [3]. From the thorough analyses reported in Ref. [2], we have shown that the TDHF theory is capable of describing MNT processes quantitatively, in comparable accuracy to other existing theories. Since the TDHF calculation is microscopic treating nucleons’ degrees of freedom on equal footing and does not include any empirical parameter specific to colliding systems, we consider that it provides reliable microscopic pictures for the reaction dynamics.

We are undertaking investigations for the $^{238}$U+$^{124}$Sn in the TDHF theory to clarify the mechanism of MNT processes. In this short article, we will show tentative results of our calculation. We show that the MNT involving more than ten protons can be described by the TDHF calculation and that a deformed structure of $^{238}$U is crucial in the reaction dynamics.
2. Method and Results

To describe $^{238}\text{U}+^{124}\text{Sn}$ collisions, we use the computational code of TDHF calculations for nuclear collisions which we have developed recently [2]. We employ a uniform spatial grid in the three-dimensional Cartesian coordinates to represent single-particle wave functions. The grid spacing is taken to be 0.8 fm. For first and second derivatives, we use 11-point finite difference formula. The projectile and target nuclei are calculated using a box with $30 \times 30 \times 30$ grid points. For reaction calculations, we use a box with $70 \times 70 \times 30$ grid points for non-central collisions and $90 \times 40 \times 30$ grid points for central collisions. We choose the incident direction parallel to the $x$-axis, and the direction of the impact parameter vector parallel to positive-$y$ direction. The reaction plane is thus $xy$-plane. As the initial condition, we place wave functions of two nuclei separated by 24 fm in the incident direction. Because the total number of protons included in projectile and target nuclei is very large, $Z = 92 + 50 = 142$, no fusion reactions has been observed at any impact parameters. At the final stage of calculations, there always appear two fragments, a projectile-like fragment (PLF) and a target-like fragment (TLF). We continued time evolution calculations until the relative distance between the two fragments becomes larger than 28 fm. For all calculations reported in this article, we use Skyrme SLy5 parameter set [4], as in Ref. [2].

To calculate transfer probabilities, we define two spatial regions, $V$ and $\bar{V}$. The region $V$ is taken to be a sphere around the center-of-mass of a fragment with a radius of 14 fm. The region $\bar{V}$ is taken to be the rest of the space. Using the PNP technique, the probability to find $N$ nucleons with isospin $q$ ($= n$ or $p$) in the spatial region $V$ is given by [2,3]

$$P_N^{(q)} = \frac{1}{2\pi} \int_0^{2\pi} d\theta \ e^{iN\theta} \det\left\langle \langle \psi_i^{(q)} | \psi_j^{(q)} \rangle_V + e^{-i\theta} \langle \psi_i^{(q)} | \psi_j^{(q)} \rangle_{\bar{V}} \right\rangle. \quad (1)$$

Since the TDHF wave function is a direct product of two Slater determinants for protons and neutrons, the probability to find $N$ neutrons and $Z$ protons in the spatial region $V$ is given by a product of probabilities for neutrons and protons, $P_{N,Z} = P_N^{(n)} P_{Z}^{(p)}$. By integrating the probabilities over the impact parameter $b$, the production cross section for a fragment composed of $N$ neutrons and $Z$ protons is evaluated as

$$\sigma(N,Z) = 2\pi \int_0^\infty b P_{N,Z}(b) db. \quad (2)$$

We perform TDHF calculations of the $^{238}\text{U}+^{124}\text{Sn}$ collision for impact parameters from 0 to 10 fm. For an impact parameter region from 0 to 5 fm and from 5 to 10 fm, we achieve calculations in 0.5-fm and 1-fm steps, respectively. We evaluate the cross section by numerical quadrature according to Eq. (2).

The ground state of $^{238}\text{U}$ is prolately deformed with $\beta \sim 0.27$ and the ground state of $^{124}\text{Sn}$ is oblately deformed with $\beta \sim 0.11$. We performed TDHF calculations for three initial configurations characterized by different orientations of $^{238}\text{U}$: The symmetry axis of $^{238}\text{U}$ set parallel to the $x$-axis (parallel to the collision axis), $y$-axis (parallel to the impact parameter vector), and $z$-axis (perpendicular to the collision plane). The symmetry axis of a slightly deformed $^{124}\text{Sn}$ is always set parallel to the $z$-axis. For a quantitative comparison with the measured cross sections, we should average over all possible orientations. However, since the orientation average requires excessive computational costs, we have not yet performed it. Below, we show cross sections for each of the three initial conditions without the average, Eq. (2).

In Fig. 1, we show production cross sections of $^{124}\text{Sn}$-like fragments in the $A-Z$ plane. In Fig. 1 (a), (b), and (c), we show cross sections calculated by Eq. (2) for different initial configurations. From the results shown in the panels (a), (b), and (c), we find that the distributions of the calculated cross sections depend much on the initial orientations of the deformed $^{238}\text{U}$. 
Fig. 1. Production cross sections of \(^{124}\text{Sn}\)-like fragments in \(^{238}\text{U} + ^{124}\text{Sn}\) collisions at \(E_{\text{lab}} = 5.7\ \text{MeV}/\text{A}\) are shown in the \(A-Z\) plane. (a-c): Results of the TDHF calculations for three different relative orientations. (d): Experimentally measured cross sections (Figure has been taken from Ref. [1]).

When the symmetry axis of \(^{238}\text{U}\) is set parallel to the collision axis (\(x\)-direction in panel (a)), we find abundant cross sections widely spreading in the \(A-Z\) plane. For a fragment \(^{118}_{44}\text{Ru}_{72}\) produced by a transfer of two neutrons and six protons from \(^{124}\text{Sn}\) to \(^{238}\text{U}\), we find a cross section of \(10^{-3}\ \text{mb}\). For a fragment \(^{150}_{64}\text{Gd}_{86}\) produced by a transfer of twelve neutrons and fourteen protons to \(^{124}\text{Sn}\), the cross section is again the same order of magnitude, \(10^{-3}\ \text{mb}\).

When the symmetry axis of \(^{238}\text{U}\) is set perpendicular to the collision axis (symmetry axis in \(y\) - and \(z\)-directions, shown in panels (b) and (c), respectively), the calculated cross sections do not so much extend in the \(A-Z\) plane compared to the case of \(x\)-direction shown in panel (a). Cross sections producing lighter nuclei in the transfer from \(^{124}\text{Sn}\) to \(^{238}\text{U}\) are almost the same as those in the \(x\)-direction case. However, cross sections to produce heavier nuclei in the transfer from \(^{238}\text{U}\) to \(^{124}\text{Sn}\) is substantially suppressed compared to the \(x\)-direction case. For example, we find a cross section of \(10^{-3}\ \text{mb}\) for the production of \(^{134}_{56}\text{Ba}_{78}\), which corresponds to a transfer of four neutrons and six protons to \(^{124}\text{Sn}\). The number of transferred nucleons with the similar magnitude of cross section is much smaller than the cross section shown in panel (a).

To obtain intuitive pictures for the reaction dynamics, we show in Fig. 2 time evolutions of the calculated density distribution in the collision plane (\(xy\)-plane). We show results of head-on collisions \((b = 0\ \text{fm})\) with two different initial orientations. In the \(x\)-direction case, the symmetry axis of \(^{238}\text{U}\) is set parallel to the collision axis. In the \(y\)-direction case, symmetry axis of \(^{238}\text{U}\) is set perpendicular to the collision axis. The top panels show initial configurations. We show several snapshots below.

In both \(x\)- and \(y\)-direction cases, two nuclei touch at around \(320\ \text{fm}/\text{c}\). In the \(x\)-direction case (right panels), a thick neck is developed between the two colliding nuclei forming an elongated di-nuclear system (480-800 \(\text{fm}/\text{c}\)). When the di-nuclear system dissociates (\(\sim 928\ \text{fm}/\text{c}\)), the neck is
cut at a position closer to the larger fragment. Consequently, a lot of nucleons in the neck region are absorbed by the smaller fragment. Since the neck region is composed of both neutrons and protons, the absorption of nucleons in the neck region results in the transfer of both neutrons and protons in the same direction. We find that about eleven neutrons and seven protons are transferred in average in this reaction, producing fragments resembling $^{142}_{57}$La$_{85}$ and $^{219}_{85}$At$_{134}$. In the $y$-direction case (left panels), on the other hand, the neck is not so much developed compared to the $x$-direction case (320-640 fm/c). As a result, only one-neutron and one-proton are transferred on average from $^{238}$U to $^{124}$Sn.

In Fig. 1 (d), we show measured production cross sections for $^{124}$Sn-like fragments in the $^{238}$U+$^{124}$Sn collisions reported in Ref. [1]. As seen in Fig. 1 (d), measured cross sections extend to the mass number $A \sim 148$ and the proton number $Z \sim 64$. It corresponds to a transfer of eight neutrons and fourteen protons from $^{238}$U to $^{124}$Sn. As seen in Fig. 1 (a), (b), and (c), the large number of transferred nucleons from $^{238}$U to $^{124}$Sn in the measurement can only be explained by the $x$-direction configuration, the tip collision of a deformed $^{238}$U, among the examined three configurations. Our TDHF calculations strongly suggest that the large number of transferred nucleons, more than ten protons, from $^{238}$U to $^{124}$Sn in the measured MNT processes can only be explained in the tip-collision-induced transfer, associated with the formation and absorption of the elongated thick neck during the collision.

3. Concluding Remarks

We have investigated MNT processes in $^{238}$U+$^{124}$Sn collisions at around the Coulomb barrier employing the TDHF theory with the particle-number projection method. For this reaction, substantial cross sections of MNT processes accompanying more than ten protons were measured experimentally. Since $^{238}$U is a prolately deformed nucleus, we performed reaction calculations for three initial orientations of the deformed $^{238}$U. The symmetry axis of $^{124}$Sn, which is slightly deformed in oblate shape, is always set perpendicular to the collision plane. From the calculation, we have found that the MNT processes accompanying more than ten protons can only be explained in the tip collision in which the symmetry axis of $^{238}$U is parallel to the incident direction. An extended neck is formed in the tip collision, and the breaking of the neck is responsible for the MNT accompanying a large number of protons. To clarify reaction mechanisms further, more detailed investigations such as projectile-target combination and/or incident energy dependence as well as effects of particle evaporation should be considered. A study along this line is now in progress and results will be discussed in a forthcoming paper.

Acknowledgments

This research used computational resources of the HPCI system provided by Information Initiative Center, Hokkaido University, through the HPCI System Research Project (Project ID: hp140010). A part of calculations was carried out using computational resources of the COMA (PACS-IX) system at the Center for Computational Sciences at the University of Tsukuba. This work was supported by the Japan Society of the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research Grant Numbers 23340113 and 25104702, and by the JSPS Grant-in-Aid for JSPS Fellows Grant Number 25-241.

References

[1] W. Mayer, G. Beier, J. Friese, W. Henning, P. Kienle, H.J. Körner, W.A. Mayer, L. Müller, G. Rosner, and W. Wagner: Phys. Lett. B152 (1985) 162.
[2] K. Sekizawa and K. Yabana: Phys. Rev. C 88 (2013) 014614.
[3] C. Simenel: Phys. Rev. Lett. 105 (2010) 192701.
[4] E. Chabanat, P. Bonche, P. Haensel, J. Meyer and R. Schaeffer: Nucl. Phys. A635 (1998) 231; A643 (1998) 441.