DYNAMICS OF NEAR-BARRIER COLLISIONS OF STATICALLY DEFORMED NUCLEI*

V.V. Saiko, A.V. Karpov

Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
and
Dubna State University, Dubna, Russia

(Received December 5, 2017)

Dynamics of collisions of heavy nuclei deformed at their ground states is considered within a multidimensional dynamical approach based on Langevin equations. The orientation effects and their energy dependence were investigated on example of the ^{160}Gd + ^{186}W reaction. Initial mutual orientations of colliding nuclei influence the distributions of reaction products at near-barrier energies. This should be taken into account when such combinations are used for production of new nuclei in multinucleon transfer reactions.

DOI:10.5506/APhysPolB.49.307

1. Introduction

In the recent decade, an interest in studying the low-energy heavy-ion collisions has been renewed mainly due to the predicted possibility of producing the neutron-rich heavy nuclei with a quite large cross sections in Deep-Inelastic (DI) collisions [1, 2]. Corresponding experiments confirmed that the multi-nucleon transfer (MNT) accompanying DI collisions indeed allows one to populate unstable nuclei far from initial projectile and target, especially towards the neutron-rich region of the nuclear chart [3–5]. Particularly, properties of neutron-rich isotopes of heavy elements are of great interest for modeling the astrophysical r-process.

That is why development of theoretical approaches for investigating the MNT processes in collisions of heavy ions is an important task. First, these approaches may shed light on understanding the mechanism of collisions of heavy nuclei at near-barrier energies. In particular, the orientation effects in

* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

collisions of statically deformed nuclei and their energy dependence may significantly influence the reaction cross sections. Second, reliable predictions of production cross sections of neutron-rich heavy and superheavy nuclei are of great importance. Nowadays, one of the most powerful theoretical approaches for analyzing low-energy heavy-ion collisions is the Langevin-type approach (see, *e.g.*, [6–8]). It allows one to obtain a rather complete information on nuclear dynamics itself as well as to study the characteristics of primary and final reaction products. In the present work, the multidimensional dynamical approach based on the Langevin equations was used to analyze DI collisions of ^{160}Gd and ^{186}W. The model was proposed in [8] where collisions of heavy spherical nuclei were analyzed.

2. Model

The model has eight degrees of freedom that describe a system of two colliding nuclei. Four of them define the nuclear shape: distance between geometrical centers of two nuclei r, two independent ellipsoidal surface deformations $\delta_{1,2}$ and mass asymmetry η_A. In order to account for formation of nuclei with different atomic numbers, there is an additional variable — the charge asymmetry η_Z. Two angles of rotation of the nuclei $\varphi_{1,2}$ and the angle between the symmetry axis and the beam direction θ are included in the model as well.

A set of eight coupled Langevin equations is solved numerically

$$\dot{q}_i = \sum_j \mu_{ij} p_j \,, \tag{1}$$

$$\dot{p}_i = T \left(\frac{\partial S}{\partial q_i}\right)_{E_{\rm tot}} - \sum_{j,k} \gamma_{ij}\mu_{jk}p_k + \sum_j \theta_{ij}\xi_j(t)\,, \tag{2}$$

where $q_i = \{r, \delta_1, \delta_2, \eta_A, \eta_Z, \theta, \varphi_1, \varphi_2\}$ and $p = \{p_r, p_{\delta_1}, p_{\delta_2}, p_{\eta_A}, p_{\eta_Z}, L, l_1, l_2\}$ are collective degrees of freedom and their conjugate momenta, correspondingly. S is the entropy of excited system, $\mu_{ij} = [m_{ij}]^{-1}$ is the inverse inertia tensor, γ_{ij} is the friction tensor, θ_{ij} are the amplitudes of the random force. The terms in the second equation represent correspondingly the driving, friction and random forces. A more detailed description of the model can be found in [8].

Solution of Eq. (1) starts from the initial distance between nuclei $\approx$50 fm. A projectile approaches a target nucleus at a given impact parameter b with a certain center-of-mass energy $E_{\rm cm}$. The calculations are terminated when the products are formed and separated again by the initial distance. The obtained solution is a trajectory in multidimensional space of the collective degrees of freedom that carries complete information about a single collision.

A large number of trajectories for different impact parameters are simulated. Then the statistical model [8–10] is used to obtain final reaction products from the primary excited ones. The cross sections are then calculated as

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Z\mathrm{d}A\mathrm{d}E\mathrm{d}\Omega}(Z,A,E,\theta) = \int\limits_0^{b_{\max}} \frac{\Delta N(b,Z,A,E,\theta)}{N_{\mathrm{tot}}(b)} \frac{b\,\mathrm{d}b}{\Delta Z\Delta A\Delta E\sin\theta\Delta\theta}\,, \quad (3)$$

where ΔN is a number of trajectories in a given bin and N_{tot} is the total number of simulated trajectories for each impact parameter. Integration of Eq. (3) allows one to obtain different distributions of reaction products.

In this paper, we discuss the first attempt to extend the model of Ref. [8] to the case of collisions of statically deformed nuclei with arbitrary mutual orientation. There are several difficulties on the way to solve this task. Particularly, the calculation of the potential energy for arbitrarily oriented nuclei is rather complicated and yet-unsolved problem. In order to avoid these difficulties, reasonable approximations are needed. At the first step, we restrict ourselves to the case of fixed mutual orientations of colliding nuclei: the so-called tip-to-tip, side-to-side, and tip-to-side collisions.

The orientation effects can be easily taken into account for separated nuclei, where the potential energy is calculated using the double-folding procedure. After the contact, the potential energy depends on the interaction time. In particular, the axial symmetry should be restored if the interaction time is long enough. The corresponding axially-symmetric shapes are chosen assuming that the nuclear system preserves its compactness during the transition from axially-asymmetric configuration (*e.g.*, side-to-side one) to the axially-symmetric one.

The reaction cross section is estimated according to standard averaging procedure

$$\langle\sigma(Z,A,E,\theta)\rangle = \int\limits_0^{\frac{\pi}{2}}\int\limits_0^{\frac{\pi}{2}} \sigma(Z,A,E,\theta,\varphi_1,\varphi_2)\sin\varphi_1\sin\varphi_2\mathrm{d}\varphi_1\mathrm{d}\varphi_2\,, \quad (4)$$

where the cross section $\sigma(Z,A,E,\theta,\varphi_1,\varphi_2)$ is calculated at the limit orientations of colliding nuclei $\varphi_i = 0,\pi/2$ and it is assumed to be linearly dependent on the angles φ_1 and φ_2.

3. Results

The ^{160}Gd + ^{186}W reaction was considered as a system for studying the orientation effects. Both colliding nuclei have prolate deformations in their ground states $\beta_2(^{160}\mathrm{Gd}) = 0.28$ and $\beta_2(^{186}\mathrm{W}) = 0.22$, thus there are four limit orientations: tip-to-tip, tip-to-side (symmetry axis of the target nucleus is perpendicular to the reaction axis), side-to-tip, and side-to-side ones. For these configurations, we performed calculations of the total kinetic energy loss (TKEL), mass, and angular distributions of primary products of the ^{160}Gd + ^{186}W reaction at several energies shown in Fig. 1. The angular distributions were calculated for target-like fragments (TLFs) with masses $A > 200$.

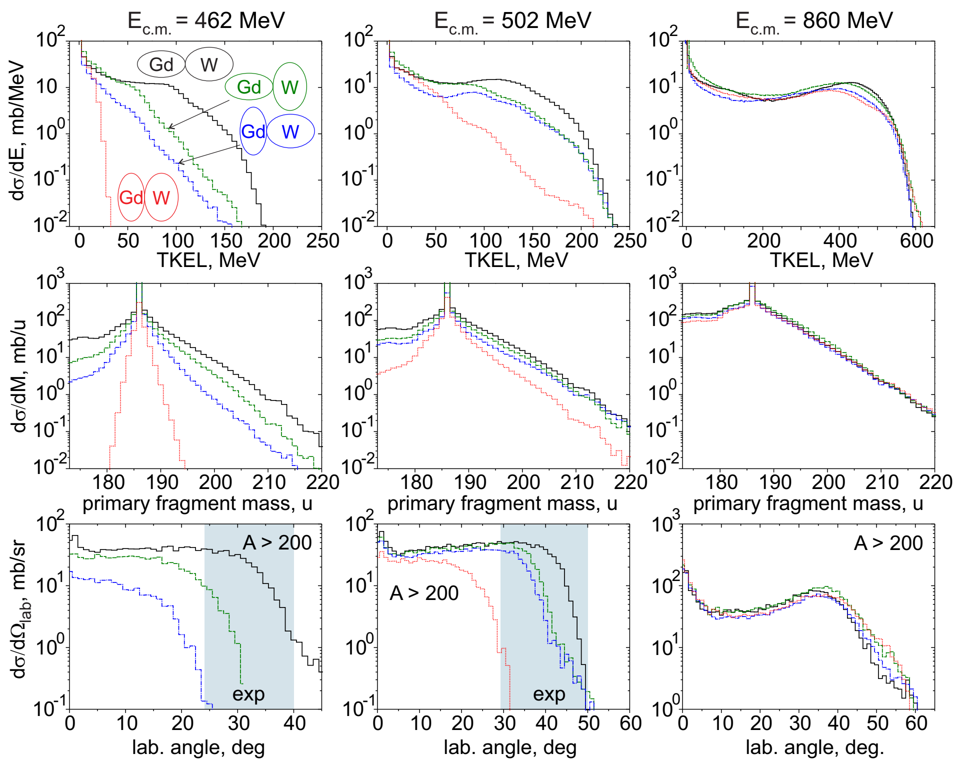

Fig. 1. Total kinetic energy loss, mass, and angular distributions of primary products of the ^{160}Gd + ^{186}W reaction calculated at three energies $E_{\rm cm} = 462$, 502, and 860 MeV. Solid, dashed, dash-dotted, and dotted histograms correspond to tip-to-tip, tip-to-side, side-to-tip, and side-to-side collisions. Shaded areas in the angular distributions show the angular ranges covered in the experiment [11].

A significant role of the initial orientation of nuclei in collision dynamics is clearly seen at the lowest near-barrier energy. The tip-to-tip collisions have the largest contribution to reaction cross section and the side-to-side collisions have the lowest one. The reason of this behavior is the variation of the Coulomb barrier heights for this system for different orientations. They are $V_{\rm C} = 412$ MeV for tip-to-tip, $V_{\rm C} = 447$ MeV for tip-to-side, $V_{\rm C} = 454$ MeV for side-to-tip, and $V_C = 492$ MeV for side-to-side collisions. When the collision energy increases, the difference between cross sections calculated for different orientations gradually disappears.

Orientation of the colliding nuclei changes their distance of the closest approach. In particular, for more compact systems, it leads to decreasing the angle of grazing collisions of TLFs in the laboratory frame (see Fig. 1).

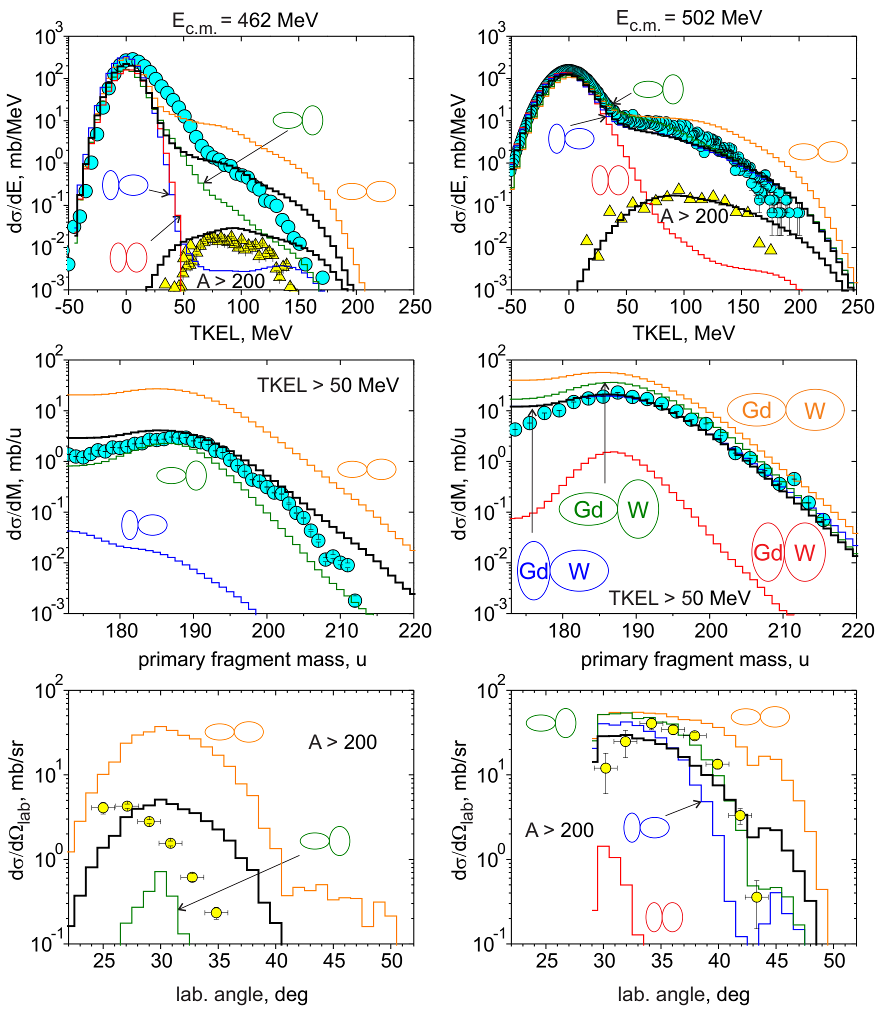

Fig. 2. TKEL, mass, and angular distributions of primary products obtained in the ^{160}Gd + ^{186}W reaction at two energies $E_{\mathrm{cm}} = 462$ and 502 MeV. Symbols are the experimental data [11], thin lines are the calculations for tip-to-tip, side-to-tip, tip-to-side and side-to-side collisions, and the thick lines show the total cross sections averaged over the projectile–target orientations.

The experimental study of the ^{160}Gd + ^{186}W reaction at two energies $E_{\rm cm} = 462$ and 502 MeV has been done at CORSET setup [11]. The binary reaction products were measured in coincidence mode, and the TLFs were detected in the angular ranges shaded in Fig. 1. The TKEL, mass, and angular distributions of reaction products obtained in the experiment and the calculated ones are shown in Fig. 2. The experimental energy and mass resolutions (FWHM) of 12 MeV and 3 u were taken into account in the theoretical calculations.

All the four configurations have a significant contribution to the reaction cross section at $E_{\rm cm} = 502$ MeV, while the distributions at $E_{\rm cm} = 462$ MeV are mainly formed by the tip-to-tip and tip-to-side configurations. Actually, the other orientations at the lower reaction energy miss the angular range of the experimental measurements and, therefore, their contribution in the reaction cross section were inhibited.

4. Summary

The orientation effects play a significant role in dynamics of collisions of deformed nuclei at near-barrier energies. Contribution of each configuration of oriented nuclei into the reaction cross section strongly depends on the collision energy. The difference between different mutual orientations gradually disappears when the collision energy increases. Further clarification of the role of the mutual orientations of statically deformed nuclei in their low-energy collisions is an important and challenging task.

REFERENCES

[1] V. Zagrebaev, W. Greiner, *J. Phys. G: Nucl. Part. Phys.* **34**, 1 (2007).
[2] V. Zagrebaev, W. Greiner, *Phys. Rev. C* **87**, 034608 (2013).
[3] E.M. Kozulin *et al.*, *Phys. Rev. C* **86**, 044611 (2012).
[4] J.V. Kratz, M. Schädel, H.W. Gäggeler, *Phys. Rev. C* **88**, 054615 (2013).
[5] Y.X. Watanabe *et al.*, *Phys. Rev. Lett.* **115**, 172503 (2015).
[6] V. Zagrebaev, W. Greiner, *J. Phys. G: Nucl. Part. Phys.* **31**, 825 (2005).
[7] Y. Aritomo, M. Ohta, *Nucl. Phys. A* **744**, 3 (2004).
[8] A.V. Karpov, V.V. Saiko, *Phys. Rev. C* **96**, 024618 (2017).
[9] Nuclear Reaction Video project, `http://nrv.jinr.ru/nrv/`
[10] A.V. Karpov *et al.*, *Phys. At. Nucl.* **79**, 749 (2016).
[11] E.M. Kozulin *et al.*, *Phys. Rev. C* **96**, 064621 (2017).