ANALYSIS OF MULTI-NUCLEON TRANSFERS IN COLLISIONS OF ACTINIDES*

Vyacheslav Saiko, Alexander Karpov

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

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Collisions of actinides are analyzed in the paper on the basis of the multidimensional dynamical model based on the Langevin equations as the method of production of neutron-enriched isotopes of heavy elements.

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1. Introduction

The Langevin-type dynamical models are powerful tool for describing the nuclear processes occurred in collisions of heavy ions at low energies. They provide reliable results for fusion, fission, deep inelastic and quasifission phenomena [1–5].

The dynamical model based on the Langevin equations [6] allows one to consider the collision dynamics of statically deformed heavy nuclei at different initial mutual orientations. Particularly, analysis of the ^{160}Gd+^{186}W reaction with two heavy prolate nuclei shows the strong influence of the initial mutual orientation on differential cross sections mainly at near-barrier collision energies [7].

Collisions of actinides are of special interest due to the possibility for production of neutron-enriched isotopes of heavy and superheavy elements. Actinides have prolate shape in the ground state and the orientational effects must be taken into account in calculations of differential cross sections. The isotopic yields of transuranium elements produced in multinucleon transfer reactions ^{238}U+^{238}U/^{248}Cm/^{254}Es have been discussed in this work.

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2. Model

The main degrees of freedom of the model originate from the Two-Center Shell Model parametrization [8]. The elongation r, two ellipsoidal deformations $\delta_{1,2}$ and mass asymmetry η_A describe the shapes of the nuclear system. The charge asymmetry η_Z had been also considered in order to calculate the proton transfer, as well as rotation angles of the nuclear system θ and both fragments $\varphi_{1,2}$ relative to the beam direction.

The Langevin equations are solved to consider the evolution of the set of degrees of freedom included into the model $q_i = \{r, \delta_1, \delta_2, \eta_A, \eta_Z, \theta, \varphi_1, \varphi_2\}$:

$$\begin{aligned} \dot{q}_i &= \sum_j \mu_{ij} p_j \, , \\ \dot{p}_i &= T \left(\frac{\partial S}{\partial q_i} \right)_{E_{\mathrm{tot}}} - \sum_{j,k} \gamma_{ij} \mu_{jk} p_k + \sum_j \theta_{ij} \xi_j(t) \, . \end{aligned} \tag{1}$$

Here, $p_i = \{p_r, p_{\delta_1}, p_{\delta_2}, p_{\eta_A}, p_{\eta_Z}, L, l_1, l_2\}$ are the momenta corresponding to the collective degrees of freedom. The first term in Eq. (1) is the driving force, S is the entropy and T is the temperature of the system. The second term is the friction force, where $\mu_{ij} = {m_{i,j}}^{-1}$ and γ_{ij} are the inverted mass and the friction tensors, respectively. The third term is the random force with the amplitudes θ_{ij} derived from the Einstein relation $\theta_{ik}\theta_{kj} = \gamma_{ij} T$, and ξ_i are the normalized random variables with zero mean value $\langle \xi_i(t) \rangle = 0$ and the correlation function $\langle \xi_i(t), \xi_j(t') \rangle = 2\delta_{ij}\delta(t - t')$. A more detailed description of the model can be found in [6].

Equations (1) are solved numerically under initial conditions: a projectile with a given impact parameter b and a certain center-of-mass energy E_{cm} approaches a target nucleus starting from the distance ≈ 50 fm. A dinuclear system is formed if the nuclei come into contact, then it evolves and decays into two excited reaction fragments. The calculations are terminated when the products are separated again by the initial distance. The obtained solution is a trajectory in the multidimensional space of the collective degrees of freedom that carry complete information about a single collision.

A large number of trajectories for different impact parameters are simulated. Then the statistical model [6, 9] is used to obtain final reaction products from the primary excited ones. Usually, the Monte-Carlo method of simulation is used in calculations, but for highly-fissile reaction products, the method of nested integrals is applied under the assumption that final products are formed in neutron evaporation channels (up to four neutrons). The GEF code is employed for simulation of sequential fission (SeqF) fragment distribution [10].

When collisions of statically deformed nuclei are considered in a shape-dependent approach, some difficulties are arisen due to the broken axial symmetry of dinuclear shapes. In particular, calculation of the potential energy for the corresponding shapes is rather complicated and yet unsolved problem. Therefore, next assumptions have been employed in the model:

1. System of two oriented touching nuclei restores its axial symmetry as the interaction time increases with exponential form-factor;
2. Nuclei keep the distance between the nuclear surfaces as well as centres of nuclei, while the relaxation process proceeds in perpendicular direction;
3. We have considered only limit initial orientations of two deformed colliding nuclei: the so-called tip-to-tip ($\varphi_1^0 = \varphi_2^0 = 0$), side-to-side ($\varphi_1^0 = \varphi_2^0 = \pi/2$), tip-to-side ($\varphi_1^0 = 0, \varphi_2^0 = \pi/2$), and side-to-tip ($\varphi_1^0 = \pi/2, \varphi_2^0 = 0$) collisions.

The cross sections for a given initial orientation are calculated as

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Z\mathrm{d}A\mathrm{d}E\mathrm{d}\Omega}(Z,A,E,\theta) = \int\limits_0^{b_{\max}} \frac{\Delta N(b,Z,A,E,\theta)}{N_{\mathrm{tot}}(b)} \frac{b\,\mathrm{d}b}{\Delta Z\Delta A\Delta E\sin\theta\Delta\theta}\,, \quad (2)$$

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. (2) allows one to obtain different distributions of reaction products. Finally, the cross sections are averaged over initial mutual orientations with the corresponding weights [7].

3. Results

The collisions of actinides were investigated in late 1970s in order to see the prospects of synthesizing superheavy elements [11, 12]. Radiochemical methods were used for identification of above-target products obtained in the ^{238}U+^{238}U/^{248}Cm reactions. Before discussing the yields of the heaviest reaction products, we consider the variety of all reaction products obtained in damped collisions of two actinides. Recent measurements of the ^{238}U+^{238}U reaction at several collision energies were performed at GANIL [13]. The data on the mass distributions of final-reaction products from this work are shown in Fig. 1 for the lowest and the highest incident energies studied in [13]. The distributions consist of the elastic, the multinucleon transfer, and the sequential fission components. The histograms are the results of the calculations in the experimentally covered angular range $30^\circ \leq \theta_{\mathrm{lab}} \leq 40^\circ$ averaged over mutual orientations. The experimental uncertainty of 6 mass units was taken into account.

Note, the cross sections of multinucleon transfer products as well as sequential fission fragments increase significantly with increasing the collision energy and the calculations describe this behaviour well. Particularly, the tremendous decrease of the production cross section of reaction products heavier than uranium due to the sequential fission process can be seen in the calculated primary distributions.

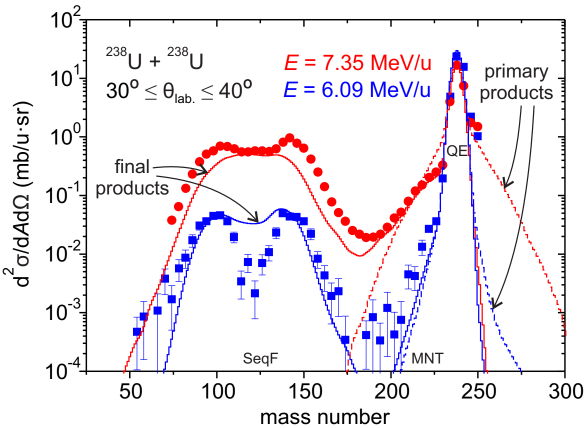

Fig. 1. Mass distributions of fragments formed in the ^{238}U+^{238}U reaction at 6.09 and 7.35 MeV/u. The symbols are the experimental data. The solid and dashed histograms are the calculations for primary and final fragments, respectively.

We aimed to describe the multinucleon transfer component, namely, the slope of the distributions. It can be achieved by varying the nucleon transfer rates $\lambda^0_{A,Z}$ responsible in our model for the proton and neutron transfer probabilities in the vicinity of the contact point (see Eqs. (26) and (27) of Ref. [6]). A rather good agreement is achieved if $\lambda^0_{A,Z}$ were increased twice comparing to a lighter system like ^{160}Gd+^{186}W. Preliminarily, we found that the transfer rates should depend on the system mass as $\sim A^2_{\mathrm{CN}}/1.2\times 10^5$.

When we ensured the correct description of the multinucleon transfer process in collisions of two uranium nuclei, let us return to the problem of synthesizing heavy nuclei. We have calculated the yields of above-target nuclei in the ^{238}U+^{238}U/^{248}Cm/^{254}Es reactions to compare them with the available experimental data [11, 12]. Note that the thick target was used in the ^{238}U+^{238}U experiment and the collision energy was smoothly distributed in the range of $E \leq 7.5$ MeV/u [11], while the calculations were performed for the fixed value of the energy $E = 7.5$ MeV/u. The $0^\circ \leq \theta_{\mathrm{lab}} \leq 55^\circ$ angular range covered in the experiment on the ^{238}U+^{248}Cm collisions at $E = 7.4$ MeV/u [12] was taken into account in the calculations.

The calculated isotopic yields for the ^{238}U+^{238}U/^{248}Cm collisions agree well with the experimental data. Irregularities in the results of the calculations for low cross sections are due to poor statistics. The yields of primary fragments are rather large. For example, excited Rf and Db nuclides can be produced with the cross sections exceeding 1 mb in the ^{238}U+^{254}Es reaction [see Fig. 2 (b)]. Nevertheless, high excitation energies and angular momenta lead to rather low probabilities of their survival. Exponential drop of the final cross sections with increasing atomic number of the products is observed experimentally in all reactions shown in Fig. 2. As a rule, the transfer of each proton towards the heavier reaction partner leads to the decrease of the corresponding production cross section by an order of magnitude. Our calculations shown in Fig. 2 confirm this tendency.

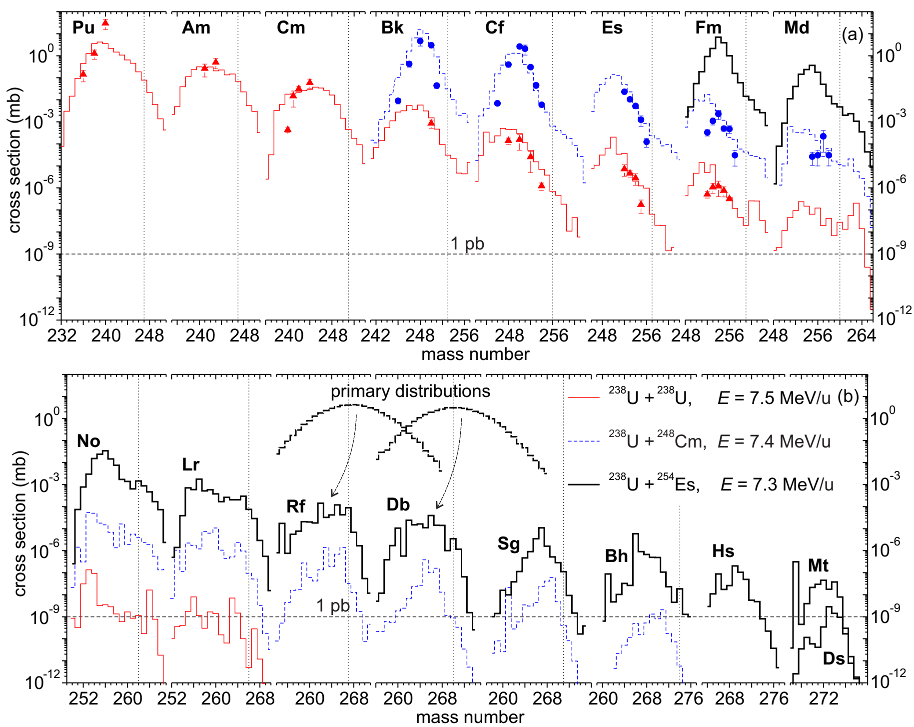

Fig. 2. Isotopic distributions of transuranium elements obtained in the ^{238}U+^{238}U/^{248}Cm/^{254}Es reactions. The symbols are the experimental data. The histograms are the calculations. The vertical dotted lines indicate the heaviest known isotope of a given element. More details are in the text.

The vertical dotted lines in Fig. 2 indicate the heaviest known isotopes for each chemical element, thus, we can see the production cross sections of yet unknown isotopes of transuranium nuclides. The strong exponential drop of the isotopic yields with increasing atomic number limits the possibility of synthesis of unknown superheavy nuclides in collisions of actinides. However, in some cases, the yields of the neutron-enriched isotopes of heavy actinides are sufficiently large for their experimental identification. For example, a number of neutron-enriched isotopes of Fm and Md can be produced with submicrobarn cross sections in the ^{238}U+^{254}Es reaction. This can be better seen in Fig. 3, where the final cross sections for products with $Z > 91$ formed in this reaction are shown on the nuclear chart of the known nuclides. A large area of unknown neutron-enriched isotopes of elements from U to Md can be explored with the cross sections exceeding 1 μb.

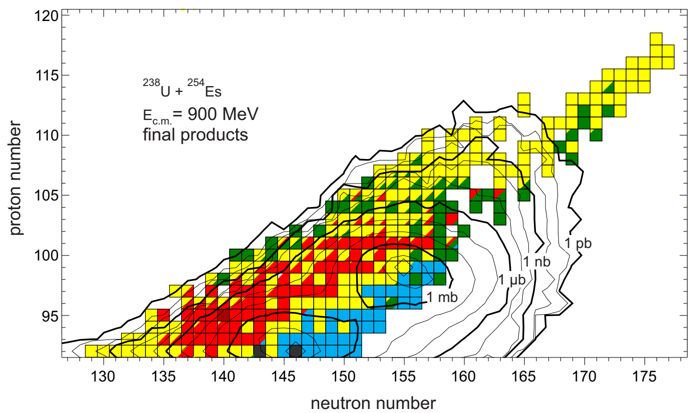

Fig. 3. Cross sections of the ^{238}U+^{254}Es reaction products with $Z > 91$.

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