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Угловые, энергетические и зарядовые распределения в реакции $^{238}U + ^{238}U$

Развита динамическая модель, описывающая диссипацию и статистические флюктуации в глубоконеупругих столкновениях тяжелых ионов. Модель учитывает эффект деформации ядер в выходном канале. Изучены угловые и энергетические распределения продуктов, а также выход элементов в столкновении U + U (E = 7,42 МэВ/А). Дана оценка сечения образования сверхтяжелых элементов и их средней энергии возбуждения.

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Angular, Energy and Element Distributions in the Collision $^{238}U + ^{238}U$

The angular, energy and element distributions in the collision U + U (E = 7.42 MeV/A) are studied within a dynamical model which accounts for dissipation and statistical fluctuations and includes the deformation degree of freedom. The production cross section of superheavy elements and their average excitation energy are estimated.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1. *INTRODUCTION*

Recently, the reaction $^{238}U + ^{238}U$ (E = 7.42 *MeV/A*) has been studied at the UNILAC accelerator in Darmstadt /1/ to investigate the gross features of the reaction products associated with their charge, total kinetic energy and angular distributions. The search for the production of superheavy elements has yielded an upper cross section limit of $2 \cdot 10^{-32}$ cm^2 /1/. For the surviving U-like fragments, at a given energy dissipation more particle diffusion was found than in other systems.

Theoretical considerations of the mass and charge transfer in the U + U collision have been made in the framework of the fragmentation theory /2/ and a simple diffusion model /3-5/. In both cases a remarkable large production cross section for the primary reaction products of superheavy elements was found but the decay of the superheavy nuclei due to the remaining excitation energy diminishes the production cross section noticeably.

It is the aim of this paper to study the charge, angular and total kinetic energy distributions in the U+U collision within a theory including both dissipation and statistical fluctuations /6/.

The theory /6/ has been successfully applied to describe various cross sections of DIC, as $d\sigma/d\Theta$, $d^2\sigma/d\Theta dE$, $d^2\sigma/d\Theta dM$ and recently $d^3\sigma/d\Theta dZ dE$ /7-10/. Deformation effects on the angular distributions and some kind of evolutions in the shape of the angular distributions of DIC products as a function of the bombarding energy and the initial mass number of the colliding nuclei have been studied within another model-formulation of [6] including the deformation degree of freedom implicity [11,12].

In this paper we extend the dynamical model [12] as to include the charge asymmetry degree of freedom and apply this model to the U+U reaction. In contrast to [8,10] we use microscopically calculated diffusion parameters [3] which allow us to estimate the production cross section of superheavy elements within a dynamical calculation without additional free parameters.

2. *THE MODEL*

Deep inelastic collisions can be investigated in terms of the time evolution of a few collective degrees of freedom. In ref. [6] it has been shown how statistical fluctuations in the highly excited internal degrees of freedom lead necessarily to fluctuations in the collective degrees. An internal relaxation time small compared to a characteristic time for the collective motion and a temperature of the internal system larger than a typical collective frequency are assumed. Using linear response theory and performing the classical limit a Fokker-Planck equation for the density distribution $d(Q^{\ell}, P_{\ell}, t)$ in the phase space of the collective degrees is obtained. Its Gaussian type solution is determined completely by the first moments (mean values) and by the second moments (statistical fluctuations) of the collective coordinates Q^{ℓ} and their conjugate momenta P_{ℓ}. The equations of motion for the first moments are Newton-type equations including frictional terms, while the corresponding equations for the second moments fulfil a coupled set of first order differential equation. Both types of equations have to be solved simultaneously and, as a result, the density distribution is obtained. This solution of the Fokker-Planck equation can be used to calculate those cross sections which can be expressed as functions of the collective coordinates and their momenta.

In refs. [11,12] we have restricted our considerations to two collective coordinates $Q^{\ell}=\{R,\Theta\}$, the polar coordinates of the relative motion. The large deformation of the two ions produced mainly in the exit channel is taken into account by correcting the ion-ion interaction potential in the exit channel for an appropriate deformation energy term. Such a model allows one to compute only mass- and charge integrated cross sections of deep inelastic collisions. The model used in the present paper is exactly the same as developed in refs. [11,12] but includes an additional collective coordinate Z which describes the charge asymmetry between the two ions. In order to do this, we use the experimental fact that the relaxation time of the charge diffusion is much larger than that of the kinetic energy loss in the relative motion [19]. Therefore we write the total density distribution as a product

$$d(R,\Theta,Z,P_R,P_\Theta,P_Z,t) = d_1(R,\Theta,P_R,P_\Theta,\bar{Z},t)\cdot d_2(Z,P_Z,t). \tag{1}$$

That means, we have to solve simultaneously two separable Fokker-Planck equations,where the coupling between the relative motion and the charge diffusion process is taken into account through the mean value $\bar{Z}(t)$ in d_1 and the time variable t in d_2. Next, we neglect the P_Z-dependence in d_2 and write the Fokker-Planck equation for d_2

$$\frac{\partial d_2(Z,t)}{\partial t} = -\frac{\partial}{\partial Z} V(Z)\, d_2 + \frac{\partial}{\partial Z} D(Z) \frac{\partial}{\partial Z} d_2 . \tag{2}$$

This form is often used to describe the mass- or charge diffusion process during the course of a deep inelastic collision [4,5,13]. Eq. (2) can be derived from the Fokker-Planck equation in the phase space $\{Z, P_Z\}$ by integrating over P_Z and assuming a large friction force for this process [14,6]. Instead of phenomenological "friction forces" for the Z-motion [8,10] we use diffusion coefficients $V(Z)$ and $D(Z)$ calculated microscopically [3]. Neglecting angular momentum effects these coefficients can be written for a nearly symmetric initial fragmentation as [5]

$$V(Z) = a(1 - \frac{2 \cdot Z}{Z_{12}}), \quad D(Z) = \text{const.} \tag{3}$$

For the U + U reaction the constants $a = 2{,}78 \cdot 10^{22}$ (Z units$\cdot s^{-1}$) and $D = 1.29 \cdot 10^{22}$ (Z units$^2 \cdot s^{-1}$) have been calculated in ref. /3/. Thus, the model is completely determined from the calculated density distribution (1) it is possible now to obtain multidimensional cross sections of the type

$$d^3\sigma/d\Theta dEdZ = 2\pi\lambda^2 \int dL \cdot L \sqrt{\frac{\mu}{2E}} \int dR\, dP_{\Theta} d(t \to \infty). \tag{4}$$

and others by integrating (4) over the corresponding variables (E - the kinetic energy of the products, μ - the reduced mass).

3. RESULTS

Experimentally, the fission process of one or both colliding nuclei is found to dominate /1/, and hence, it is not possible to measure the angular distribution of all the primary products. The theoretically predicted mass- and energy integrated angular distribution $d\sigma/d\Omega$ of the primary products shows a very anisotropic behaviour (*Fig. 1*). All the reaction products come out at angles greater than $\Theta \approx 85°$. The abrupt decreasing of $d\sigma/d\Omega$ near the grazing angle points out the classical character of this reaction between very heavy nuclei. Due to the strong Coulomb repulsion only backward scattering occurs, the deflection function increases monotonously with decreasing angular momentum and reaches 180° for $L = 0$.

Calculated energy-integrated angular distributions $d^2\sigma/d\Theta dZ$ for reaction fragments with different Z-values are plotted in *fig. 2*. Though the general form of the angular distribution is not changed, the pronounced peak near $\Theta \approx 85°$ is reduced and shifted to larger angles. The reason is that for products with Z-values far away from that of the projectile low partial waves contribute mainly

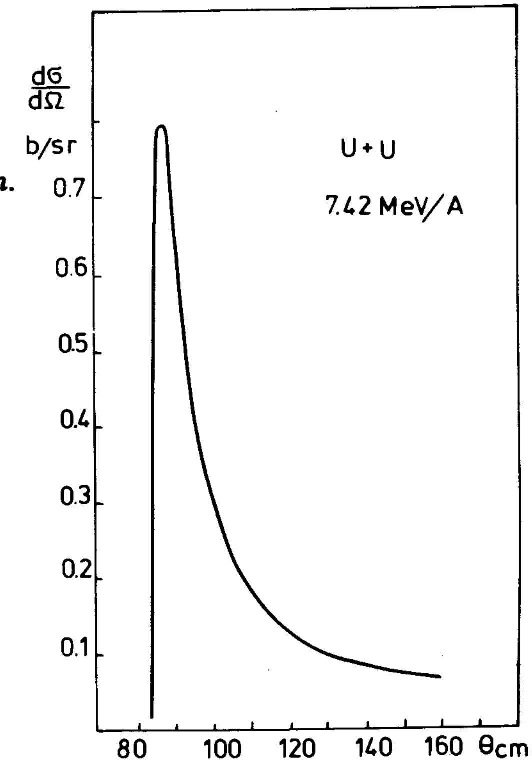

Fig. 1. Calculated angular distribution of deep inelastic reaction products in the U+U (E= *7.42 MeV/A) collision.*

to the cross section. These partial waves are scattered to larger angles due to the increasing Coulomb repulsion with decreasing wave numbers. Furthermore, low partial waves are scattered with a large energy dissipation and hence, the increased angle-dispersions (second moments) smooth out the pronounced peak in $d^2\sigma/d\Theta dZ$.

The calculated mass-integrated double differential cross section $d^2\sigma/dEd\Theta$ (the so-called Wilczynski plot) is shown in *fig. 3*. On the one hand, the pattern reflects the strong Coulomb forces acting within this system which do not allow trajectories to angles smaller than the grazing one. On the other hand, the large kinetic energy loss for backward scattered products indicates a larger penetration of the surfaces of the two ions. The widths of

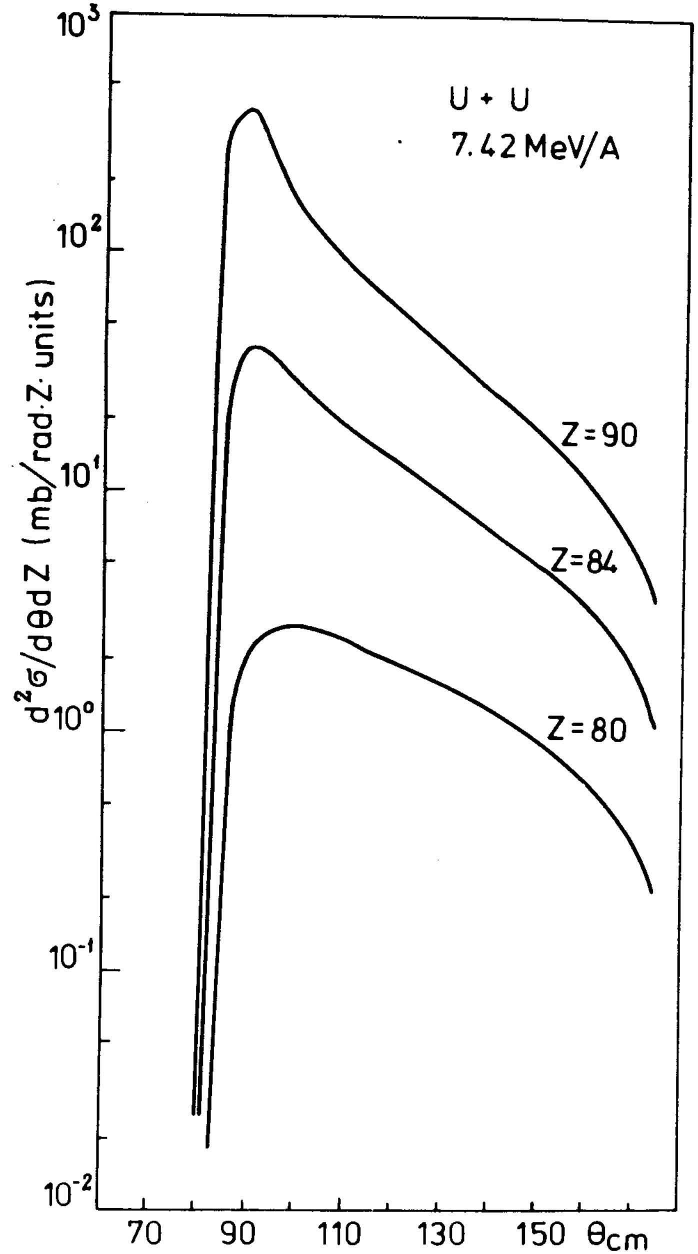

Fig. 2. Calculated angular distributions of various elements with proton numbers Z = *90, 84 and 80.*

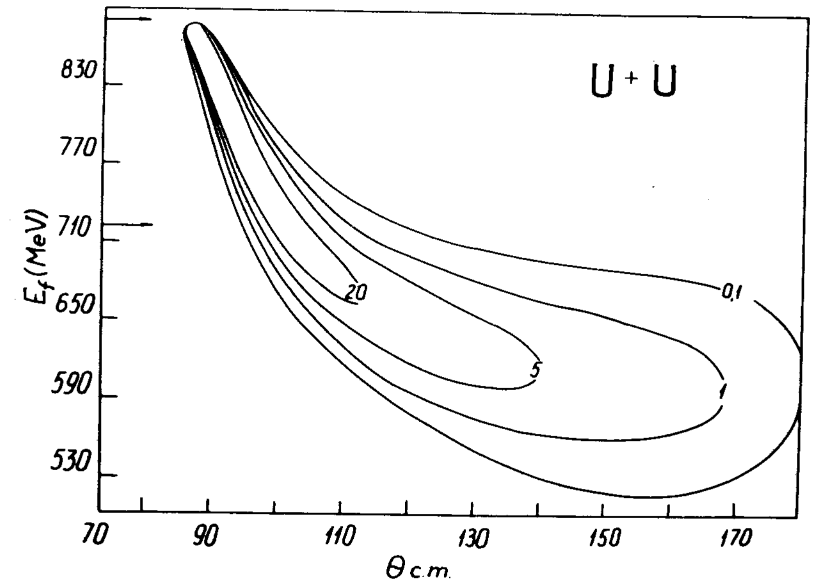

Fig. 3. Calculated double differential cross section $d^2\sigma/dEd\Theta$,

the angular distributions at a fixed final energy increase with increasing energy loss. The same behaviour of the energy-integrated angular distributions was found with increasing transferred proton numbers (fig. 2).

Of a special interest of the reaction U+U is the element distribution. *Fig. 4* gives the calculated charge distribution of the primary products as well as the experimental points for the measured secondary products /15/. The strong asymmetry with respect to Z=92 of the Z-distribution of the secondary products is a consequence of the large fission probability of nuclei heavier than uranium. A preliminary attempt to reconstruct the primary charge distribution from the experimental points /1/ is also shown in *fig. 4*. As our model gives the mean excitation energy of the nuclear system, we have tried to recalculate the yield of the secondary products from the curve of the primary ones. For a given fragmentation we determine the mean excitation energy of the whole system.

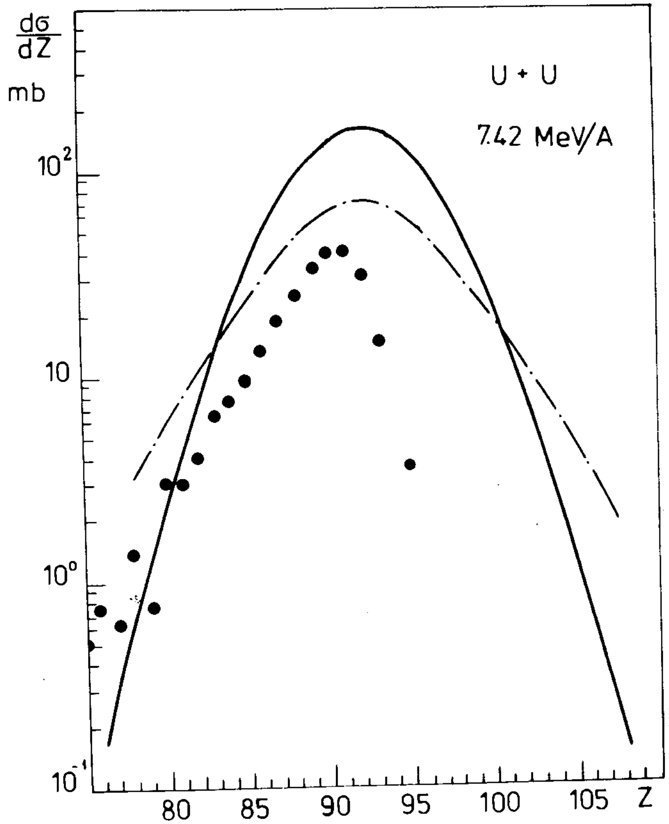

Fig. 4. Calculated element distribution of the primary reaction products (solid line). The experimental points for the secondary reaction products are from ref. /15/. The experimental reconstructed distribution (dashed-dotted line) is taken from ref. /5/.

The excitation energy of the individual fragments is assumed to be proportional to its mass. Using the known systematics of Sikkeland /16/ for the ratios Γ_n/Γ_f, we evaluate the yield of the final products. The *table* shows the results of the calculation for various elements.

The theoretical production cross section of $_{95}$Am, the heaviest among all experimentally, directly observed elements /1/, somewhat exceeds the experimental value

Table

Z	$\bar{N}$	σ^{DIC} (mb)	$\overline{E^*}$ (MeV)	$\log \frac{\Gamma_n}{\Gamma_f}$	$\sigma_{theor.}$ (μb)	σ_{exp} (μb)
95	151	120	82	+0.50	$1.2\cdot10^{4}$	$\sim0.4\cdot10^{4}$ /15/
100	159	22	100	−0.42	$5.5\cdot10^{-2}$	$>0.7\cdot10^{-2}$ /17/
102	162	7.9	105	−0.82	$4\cdot10^{-6}$	-
112	178	$5.7\cdot10^{-3}$	126	-	-	-
114	181	$8.9\cdot10^{-4}$	129	-	-	-
116	184	$1.2\cdot10^{-4}$	130	-	-	-

Calculated and experimental production cross sections for elements in the collision U+U(E = 7.42 *MeV/A*). $\overline{E^*}$ is the average excitation energy of the fragment with the proton number Z and the average neutron number $\bar{N}$. The Γ_n/Γ_f values are from ref. /16/. σ_{theor} and σ_{exp} are the theoretical and experimental cross sections for the secondary reaction products, respectively. σ^{DIC} is the theoretical production cross section for the primary products.

~4 *mb* (see *fig. 4*). It should be noted that the element $_{95}$Am differs from the initial U nuclei by 3 charge units only and therefore in the calculation of σ^{DIC} quasi-elastic events may lead to an overestimation of the cross section σ^{DIC}, especially as we include partial waves up to $L_{max} = 512\hbar$ in the calculation.

By using chemical methods, three isotopes of $_{100}$Fm have been found as reaction products in the same reaction /17/. The obtained production cross section of the element $_{100}$Fm can be looked at a lower limit which is in good agreement with our results.

For the element $_{102}No$ the production cross section is still lowered by four orders. In the *table* the calculated σ^{DIC} of superheavy elements are given, too. Our results are close to but somewhat lower than the estimate of Nörenberg [4]. At present it is impossible to estimate the Γ_n/Γ_f ratios for these elements with a sufficient accuracy. A doubtful extrapolation of the systematic of Sikkeland gives vanishing yields for these elements if the mean excitation energy $\overline{E^*}$ is used [18]. However, realistic values of Γ_n/Γ_f and the distribution of the excitation energy are needed to get a realistic estimation of the production yields of the superheavy elements in the U + U reaction.

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