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Comparison of the description of heavy-ion fragmentation reactions in different models

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Heavy-ion-induced projectile fragmentation reactions at energies about 35 MeV per nucleon are of interest because they are a tool to produce new isotopes far from stability line. They are also used to obtain secondary beams, which are necessary for scientific investigations. Because of these it is very important to be able to make explicit prediction of cross-sections of fragments produced in such type of reactions. In this report, we compare calculations with transport-statistical approach with the three frequently used models: empirical EPAX, geometrical-macroscopic Abrasion-Ablation and phenomenological HIPSE models, and experimental data obtained in collisions of ^{18}O projectile on ^{181}Ta and ^{9}Be targets at 35 MeV per nucleon obtained at COMBAS set-up in FLNR, JINR. Difficulties of reproducing the experimental ratio of cross-sections obtained in the reactions on heavy ^{181}Ta and light ^{9}Be target in the collision with the same projectile at the same energy are discussed and the results of model calculations are presented.

Key words and phrases: computer science, mathematical modeling, fragmentation reactions, conference proceedings.

1. Introduction

Heavy-ion collisions at different energies are a tool to obtain nuclides far from stability line, which can be used as secondary beams to get even more exotic isotopes. For such experiments to be successful one has to choose the most favorite partners of the reaction and the collision energy. This is why it is so important to have appropriate models to describe this kind of processes. Energy range between 20 MeV and 100 Mev per nucleon (sometimes called Fermi energy range) is known to be transitional from fusion (central collisions, small impact parameter b) and deep-inelastic (peripheral collisions, range of overlap of target and projectile is small, the impact parameter b is large) collisions to high energy collisions at which relativistic models are applied. The experiments [Gelbke [1], Lahmer [2]] have shown at least to components in the velocity spectra of the isotopes moving in beam direction, the left one having dissipative character and the right one resembling those occurring at relativistic energies. Hence the models applied to describe collisions of ions at relativistic energies, empirical model EPAX [3]and geometric-statistical Abrasion-Ablation (AA) [4] model, were applied and it was shown that they describe the cross-section of stable fragments quite well. Also phenomenological Hipse [5] model was sometimes used to describe peripheral collisions at Fermi energies. In our previous papers [6, 7] we described transport-statistical (BNV-SMM) model developed in our group and its application to modeling the dynamics of heavy-ion peripheral collisions. In this report we compare calculations of the isotope distributions performed in a frame of BNV-SMM with Epax, Hipse and A-A model calculations for the peripheral collision of ^{18}O projectile on ^{181}Ta and ^{9}Be targets at 35 MeV per nucleon and also with the experimental data obtained at COMBAS set-up in FLNR, JINR. We present the experimental ratio of fragment cross-sections at heavy ^{181}Ta and light ^{9}Be targets, which reveal considerable increase for the production of neutron-rich nuclides in the reactions with heavy target. We show that standard EPAX and AA models doesn't explain this feature, HIPSE model represents quite chaotic behaviour of this parameter and discuss what we can learn to explain this phenomena from BNV-SMM calculations

2. Transport-Statistical approach

The BNV-SMM model consists of two steps: transport approach describing the time evolution of the one-body phase space distribution function $f(\vec{r}, \vec{p}, t)$ under the influence of a self-consistent mean field $U([f])$ and a Boltzmann two-body collision term, which includes the effect of Pauli blocking [8] and statistical de-excitation of fragments produced in BNV calculations. Transport equation for the one-body phase space distribution function had the following form:

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\nabla_{\vec{r}} f - \nabla_{\vec{r}} U \nabla_{\vec{p}} f = I_{coll}$$

Here $\vec{r}, \vec{v} = \vec{p}/m$ are coordinates and velocities, and m is the nucleon mass. The solution of this non-linear integro-differential equation is achieved by simulations using the test particles (TP) method, where the distribution function is represented in terms of finite elements, having gaussian or sometimes triangle shape. It can be shown [8] that between collisions the test particles propagate according to Hamilton equations of motion

$$\frac{\partial \vec{p}_i}{\partial t} = -\nabla_r U(\vec{r}_i, t) \quad ; \quad \frac{\partial \vec{r}_i}{\partial t} = \vec{p}_i/m \quad .$$

The collision term is treated in a stochastic after each time step of calculations, choosing the collision probability according to the total cross section, and the collision angle according to the angular dependence and is responsible for the main part of the energy dissipation occurred during the collisions. To start the solution of the set of eqs.(3) for colliding nuclei of the mass A_1, A_2, charge Z_1, Z_2, the initial coordinates r_i and the momenta p_i, charge and iso-spin of all test-particles are found. Then the collision for kinetic energy E_{kin} and impact parameter b is set up. Equations (3) are solved by the second-order leapfrog method. The positions of r_i and p_i of test-particles are written down in file with a time interval of 10 fm/c to be able to follow the dynamics of the collision.

Fragments are identified in terms of a coalescence criterion in coordinate and momentum space. The time evolution of the reaction is followed until the freeze-out time $t = t_{freeze-out}$ when the different fragments are sufficiently isolated so that nuclear forces between them become negligible. Then the Coulomb trajectories are attached and excitation energy is calculated in self-consistent way, using the same potentials as were used for dynamics calculations. The projectile fragments produced in the transport calculation at the freeze-out configuration are still considerably excited. The de-excitation of the primary fragment is important when comparing to experiments which measure the final cold fragments. It cannot be described by the transport approach because the detailed pathway of de-excitation depends on quantum structures in the excited nuclei, which are not contained in the semi-classical description of the nuclei and fragments. We employ a statistical model to describe the de-excitation and cooling of the primary fragments, namely the Statistical Multifragmentation Model (SMM) [9].

This model uses as an input mass A, charg Z, coordinates and excitation energy E_{exc} of projectile-like fragments obtained in transport calculations. Calculations with SMM model are fulfilled using two different assumptions on how the cooling of the hot fragment take place: if it can de-excite through evaporation (Ev-Mode) only or also the statistical fragmentation (Frag+Ev-Mode) take place. BNV calculations are repeated 50 times for each value b_i, starting from b_{min} to b_{max} with the step db =0.25 fm. For each value of db_i the matrixes of isotope distributions with their yields, velocities and angle distributions are calculated. The excitation energy is averaged over all nuclides produced at this particular value of db_i and its dispersion is calculated. These data are transported to SMM code, for each value of impact parameter $N * b_i * db$ runs of SMM code were fulfilled to make it possible to compare the

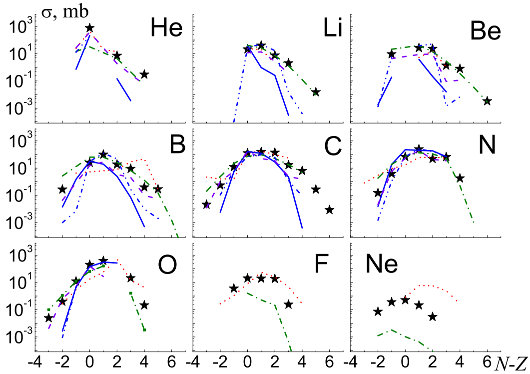

Figure 1. Isotope yields for isotopes from He to Ne produced in reaction ^{18}O on ^{181}Ta at 35 MeV per nucleon: stars - experiment, curves - predictions of different model calculations, see text

results with experimental data. The present implementation of the BNV codes is derived from the version of BNV code developed in Catania [10], with particular emphasis on the calculation accuracy and rapidity of calculations.

In figure 1 isotope yields for nuclides from He to Ne produced in reaction ^{18}O on ^{181}Ta at 35 MeV per nucleon: stars - experiment, curves - predictions of different model calculations,namely: solid curves BNV-SMM (Ev-Mode) calculations, dash-dot-dot BNV-SMM (Frag+Ev-Mode), dash-dot - EPAX 3 model, dash-AA model and short dash - HIPSE model. In Fig. 2 isotope distributions for nuclides from He to Ne are shown for the reaction ^{18}O on ^{9}Be at 35 MeV per nucleon, the notations are the same as in Fig. 1. One can see that the best coincidence with the experimental data in both cases gives the parametrization model EPAX. This model was suggested to predict the cross-sections of fragments produced in nuclear collisions at relativistic energies but was shown to work quite well at lower energies. As was discussed in our previous papers BNV-SMM model describes dissipative processes and so it can't predict the yields of fragments whenever the capture processes are involved. Comparing (Frag+Ev-Mode) and (Ev-Mode) one can see that the first has has wider isotope distributions and hence it look preferable to make model predictions. Abrasion-Ablation model was one of the first attempts to describe the yields of fragments produced in nuclear collisions at relativistic energies, from what we can conclude looking at the figures 1 and 2 it doesn't work well for energies of the order of 40 MeV per nucleon. One can see that HIPSE model over-estimates the outcome of isotopes heavier that the projectile for heavy target ^{181}Ta and make reasonable predictions for these isotopes in case of light target ^{9}Be while EPAX model under-estimates their yields.

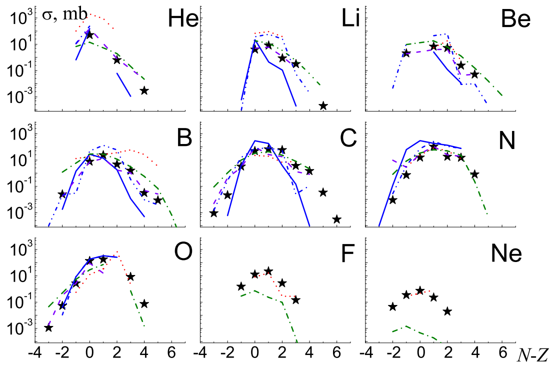

Figure 2. Isotope yields for isotopes from He to Ne produced in reaction ^{18}O on ^{9}Be at 35 MeV per nucleon: stars - experiment, curves - predictions of different model calculations, see text

3. Results

To be able to discover new nuclides situated far from stability line one has to choose correctly the projectile nucleus, its energy and the target nucleus. From kinematical point of view the lighter the target nucleus the more fragments are moving in forward directions, because Coulomb deflection is small in this case. In the experiments [13, 14] the ratio of the yields of the isotopes produced in the reactions with the same projectile on heavy and light targets was measured. It revealed considerable enhancment of neutron-reach isotopes in the reaction with heavy target. Here we show the same value for the reaction of ^{18}O on ^{181}Ta and ^{9}Be targets at 35 MeV per nucleon. In figure 3 this ratio is shown: a - experiment; b - BNV-SMM (Frag+Ev mode); c - BNV-SMM (Ev mode); d - EPAX3 model; e -AA model; f -HIPSE model. The dotted lines show the ratio of the sum of the radii of two partners of the reactions

$$R1 = \frac{1.2(A_O^{1/3} + A_{Ta}^{1/3})}{1.2(A_O^{1/3} + A_{Be}^{1/3})}. \quad ;$$

One has to take into account that the lighter is the fragment the smaller is the impact parameter of the collision, this implies the smaller distance between the centers of two colliding nuclei. one can obtain the approximate formula:

$$R1 = \frac{1.2(A_O^{1/3} + A_{Ta}^{1/3} - \varkappa(18 - x))}{1.2(A_O^{1/3} + A_{Be}^{1/3} - \varkappa(18 - x))} \quad ;$$

the results of its calculations is presented in Fig3a as the short-dooted curve, where $\varkappa$=0.4 is an arbitrary parameter. As in [13, 14] Fig. 3a shows that the yields of neutron reach isotopes are larger for the reactions with heavy target. If one compare the model predictions of this ratio one can see that BNV-SMM (Ev mode) has more resemblance to experimental results than the other ones.

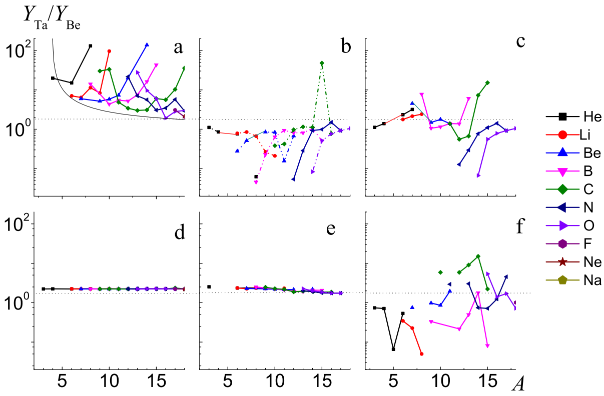

Figure 3. Ratio of yields of isotopes in the reactions of ^{18}O projectile on ^{181}Ta and ^{9}Be targets at 35 MeV per nucleon

4. Conclusion

In this report the comparison of modeling of isotope distributions produced in nuclear collision at energies of the order of 40 MeV per nucleon in frames of a microscopic transport approach of the Boltzmann-type, followed by a statistical decay code for the de-excitation of the primary hot fragments and three well known codes: EPAX, AA and HIPSE and comparison to experimental data are discussed. The ratio of isotope yields produced in the collision with the same projectile at the same energy with heavy and light targets was calculated (Ratio). It is shown that EPAX code predicts very well the yields of isotopes not far from stability line, but it fails to describe the Ratio. BNV-SMM calculations give reasonable predictions for elements with $Z \leq 8$ especially in the case when fragmentation (Frac Ev mode)is allowed at the stage of de-excitation. But if the Ratio is concerned this mode can't explain the experimental results while (Ev mode) does show the increase of yields of neutron-reach isotopes in the reaction with heavy target.

The further work to improve the model calculations of nuclear collisions at energies of the order of 40 MeV per nucleon is necessary.

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Сравнение описания реакций фрагментации тяжелых ионов в различных моделях

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Реакции фрагментации тяжелых ионов интересны тем, что они позволяют получать новые изотопы удаленные от линии стабильности. Так же они используются для получения вторичных пучков необходимых для научных исследований. Вследствие этого необходимо иметь возможность точно предсказывать сечения фрагментов, образованных в реакциях данного типа. В данном докладе мы сравниваем вычисления в рамках транспортно-статистического подхода с результатами широко используемых моделей: эмпирическая модель EPAX, геометрически-эмпирическая

АА и феноменологическая модель HIPSE, а также с экспериментальными данными полученными в столкновении ионов пучка 18O на мишенях 181Ta и 9Be при энергии пучка 35 МэВ на нуклон, данные получены на установке КОМБАС, ФЛЯР, ОИЯИ. Обсуждаются трудности воспроизведения измеренных в эксперименте отношений сечений одинаковых изотопов , полученных на тяжелой 181Ta и легкой мишенях 9Be и результаты расчетов данной величины в разных моделях.

Ключевые слова: информационные технологие, математическое моделирование, реакции фрагментации, конференционные материалы.