THE IMPORTANCE OF THE NUCLEAR POTENTIAL FORM IN THE STOCHASTIC TWO STAGE REACTION MODEL

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The importance of the nuclear potential shape in the entrance channel heavy ion collision as well as in the process of cluster formation is discussed. For more central collisions it is specially important for multiplicity distributions of intermediate mass fragments and for the parallel velocity distribution of reaction products. For peripheral collisions the entrance channel nuclear interaction is mainly responsible for the deflection angle.

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1. Introduction

The heavy ion reactions for collisions around the Fermi energy are characterized by a relatively high multiplicity of different ejectiles, which are emitted not only from the projectile-like fragment (PLF) and the target-like fragment (TLF), but also from an intermediate velocity source (IVS) located between PLF and TLF. In the collision, nucleons are exchanged between colliding heavy ions or clusters are formed. Energy is dissipated in both above processes. Energy dissipation depends on the impact parameter and is expected to be rather one-body for lower energies, because of Pauli blocking, and should become two-body at higher energies, when Pauli blocking is less effective. Near the Fermi energy a competition of both energy dissipation scenarios may be expected. Various models have been used to describe the heavy ion reactions (see *e.g.* [1, 2] and references cited herein). One of them is the stochastic two stage reaction model (STSRM) [1] which successfully describes peripheral and mid-peripheral collisions for relatively light systems. In the present paper a new version of the model (STSRM2) of

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extended applicability is discussed. In Sec. 2 basic features of the old STSR model are explained. Sec. 3 proposes modifications leading to a new version of the model. Results and conclusions are presented in Secs. 4 and 5.

2. The STSR model

The STSR model describes a heavy ion collision as a two-stage process. Some of the nucleons become "active" reaction participants in the first stage by mean field effects or by nucleon–nucleon (NN) interactions and are transferred in the second stage to the target remnant, or to the projectile remnant. Alternatively, they may form clusters located in the region between colliding ions, or escape to the continuum. The two stages of the reaction do not represent here a time sequence, but a parameterization of probabilities. The nucleon transfer process is treated as a chain of steps. In every step the considered system consists of the projectile remnant, the target remnant, some number of equilibrated excited clusters and other participating nucleons. According to the Fermi gold rule the nucleon transfer probabilities are governed by the state densities. Here we assume that the square of the T matrix is roughly constant. Under the assumption that acting objects do not interact very strongly we can write the density of states for the total system as a product of densities associated with internal degrees of freedom of the considered objects multiplied by density of states related to the relative motion of the projectile and target nucleus remnants. For every step one needs some assumption related to division of the reaction heat (Q value). It is divided among all the involved subsystems having masses $A > 4$, with a probability proportional to the corresponding densities of states. The various hot fragments created in the second reaction stage decay afterwards by particle emission, which is simulated by the GEMINI code [3]. Clusters and other final fragments (particles) are accelerated by Coulomb forces. For more central collisions, after formation of all the fragments, the PLF and TLF may fuse. In the STSR model this happens when due to the dissipation of energy and relative angular momentum a "pocket" appears in the PLF–TLF interaction potential and the energy of the system is smaller than the potential barrier. The fusion process in a strict sense is expected for lower collision energies.

2.1. First reaction stage — generation of reaction participants

In the STSR model some nucleons escape from their bounded states in the interacting ions and become virtually free (active) reaction participants. Two mechanisms are considered. In the first mechanism one of the nucleons of the projectile nucleus (P) or target nucleus (T) becomes a participant when runs across a potential window which opens in the region between

the colliding heavy ions. The P and T trajectories are calculated using a sum of the proximity and of the Coulomb potentials. Here the P and T nucleons are treated as a Fermi gas and the potential barrier transmission coefficients are calculated. In this mean field activation mechanism, more important for lower collision energies, the active nucleons "remember" momentum distributions which they had in the mother P or T nuclei. In the second mechanism two nucleons, one from the P and the second from the T, collide in the overlap zone of the P and T nuclei, where for larger collision energies and/or larger collision parameters the Pauli principle becomes less restrictive. These reaction participants practically do not "remember" their initial momentum distributions. The overlap zone of the P and T nuclei exists along some section of the heavy ion collision trajectory calculated for the input channel potential. But it is easier to assume that generation of participating nucleons takes place at the closest approach point. Such procedure is justified because in the second reaction stage we consider a chain of nucleon transfers without considering their time sequence. Therefore, we are allowed to shift positions of propagating nucleons in order to get their "activation" in the closest approach point.

2.2. Second reaction stage — clustering

In the STSR model the cluster–cluster interaction potential was taken in a simple form:

$$\begin{aligned} V_{ij}(r) &= \frac{Z_i Z_j}{r} \qquad \text{for } r \geq R_{\text{int}}\,, \\ V_{ij}(r) &= \frac{Z_i Z_j}{R_{\text{int}}} \qquad \text{for } r < R_{\text{int}}\,, \end{aligned} \tag{1}$$

$$R_{\text{int}} = r_{\text{int}} \left(A_i^{1/3} + A_j^{1/3} \right), \tag{2}$$

where r_{int} was a free parameter.

The nuclear attractive interaction was simulated there by cutting off the Coulomb interaction for $r < R_{\text{int}}$. Such form of the cluster–cluster potential allowed avoiding singularities for $r = 0$. Predictions of the STSR model were compared with experimental data obtained at SARA (Grenoble) for the peripheral and mid-peripheral collisions in the ^{40}Ca+^{40}Ca, and ^{40}Ca+^{197}Au reactions at 35 AMeV. The reaction mechanism and properties of the three observed sources of emitted particles, PLF, TLF, and IVS were properly reproduced and explained [4–6].

3. The STSRM2 — modified version of the STSR model

The STSR model, successful in describing details of heavy ion reactions for relatively light systems and for peripheral and mid-peripheral collisions, was found to have difficulties in application to heavier systems and more central collisions. We discuss here the importance of different factors responsible for these difficulties and a new version of the model (STSRM2) which is able to overcome them.

3.1. Modifications proposed for the first reaction stage

In order to get the PLF and the TLF trajectories which properly reproduce the experimental ones (*e.g.* in the Wilczynski plot), the proximity [7] potential had to be replaced by the following one, where both: the attractive, negative potential $V_s(R)$, and the repulsive, positive potential $V_{\rm comp}(R)$ have Woods–Saxon form factors:

$$\begin{aligned} V_n(R) &= V_{\rm comp}(R) + V_s(R) \\ &= \frac{U_{\rm comp}}{1+\exp\left(\frac{R-R_{\rm comp}}{a_{\rm comp}}\right)} + \frac{U_s}{1+\exp\left(\frac{R-R_s}{a_s}\right)}, \end{aligned} \tag{3}$$

where $U_{\rm comp}$, $R_{\rm comp}$, $a_{\rm comp}$ are energy dependent, and U_s, R_s, a_s should in principle be more universal.

The $V_s(R)$ potential is mainly responsible for the proper deflection of heavy ions and the $V_{\rm comp}(R)$ potential simulates to some extend consequences of the nuclear matter incompressibility.

Fig. 1 presents shapes of the "old" STSRM and of the "new" STSRM2 potentials for the case ^{107}Ag+^{58}Ni at 52 AMeV for which $U_{\rm comp} = 300\,$MeV, $R_{\rm comp} = 0.5\left(A_P^{1/3} + A_T^{1/3}\right)$ fm, $a_{\rm comp} = 1.36\,$fm and $U_s = -100\,$MeV, $R_s = 1.23\left(A_P^{1/3} + A_T^{1/3}\right)$ fm, $a_{\rm comp} = 0.8\,$fm. This new nuclear potential modifies slightly the potential window between colliding heavy ions and the number of mean field active nucleons. For more central, higher energy collisions of heavier ions, the overlap zone may include the majority of the colliding system, with the matter density exceeding considerably the normal nuclear matter density. In such a situation one can expect a complete multi-fragmentation (prompt multi-fragmentation [8]) without the formation of a composite system in a strict sense. To simulate this effect for collisions where the number of activated nucleons exceeds some critical value (*e.g.* 70%) we assume that all nucleons of the system are activated. Fig. 2 presents the position (left part), and the momentum (right part) distributions obtained according to the above procedure for nucleons activated in

the reaction ^{107}Ag+^{58}Ni at 52 AMeV and for the input angular momentum $L < 300\,\hbar$. The projectile and the target ions are located in the z–y plane and consequently the r_y distribution is a broader one.

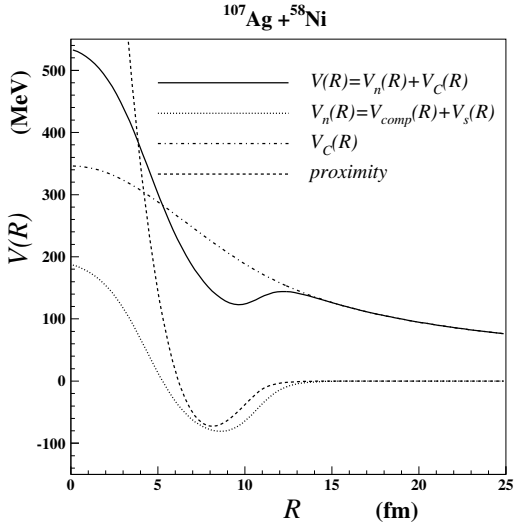

Fig. 1. The "old" STSRM (dashed line) and the "new" STSRM2 (dotted line) nuclear potentials for the case ^{107}Ag+^{58}Ni at 52 AMeV. The solid line presents the sum of the nuclear and Coulomb potential. The Coulomb potential is presented by the dashed–dotted line.

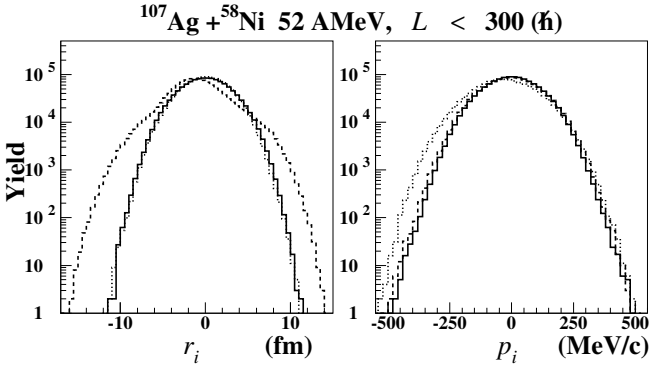

Fig. 2. Position (left part), and momentum (right part) distributions of "active" nucleons for the reaction ^{107}Ag+^{58}Ni (52 AMeV) and for the input angular momentum $L < 300\,\hbar$. They are given in the reaction CM system. Here solid lines represent r_x and p_x distributions, dashed lines r_y and p_y distributions, dotted lines r_z and p_z distributions.

3.2. Modifications proposed for the second reaction stage

In this section we discuss the influence of the nuclear potential shape on the clustering process. This influence is important particularly for more central collisions where a large number of participants is created. The situation here is to some extend similar to the binary decay described by the transition state method [9,10]. The splitting probability is there determined by the density of states reached by the system at the potential saddle point. This density quite strongly depends on the value of the potential energy at this point and on the shape of the nuclear potential. Reversing direction of the time one can discuss in a similar way the probability of cluster formation in a nucleon–cluster or cluster–cluster interaction. In our case the nuclear interaction which can compensate the Coulomb interaction energy can increase the reaction Q value and increase the probability of a given configuration.

In the STSRM2 the Coulomb interaction of two colliding clusters is supplemented by an attractive nuclear potential with the Woods–Saxon form factor:

$$V_{kl}(r) \;=\; \frac{V_0\,(A_k \cdot A_l)^{1/3}}{1+\exp\left(\frac{r-r_{kl}}{a}\right)} + V_{kl}^{\mathrm{Coul}}\,, \tag{4}$$

$$r_{kl} \;=\; r_0\left(A_k^{1/3}+A_l^{1/3}\right)\,, \tag{5}$$

where V_0, r_0 and a are free parameters. The Coulomb potential is calculated as for two overlapping charged spheres. As an example Fig. 3 presents a t–α cluster interaction in the STSRM and in the STSRM2 versions. As one can see, the flat top Coulomb potential used in the STSR model was quite similar to the new potential of two overlapping charged spheres. The total potential presented in Fig. 3 ($r_0 = 1.4\,\mathrm{fm}$, $a = 0.5\,\mathrm{fm}$, $V_0 = -1.5\,\mathrm{MeV}$) properly describes the creation of different possible clusters; in this particular case a production of the ^{7}Li clusters. A repulsive nuclear potential ($V_0 > 0$) could simulate a situation when the interaction of two particles is not able to produce a bond cluster. The influence of the cluster–cluster nuclear potential shape on the multiplicity of the primary $A > 1$ and $A > 4$ particles, generated in the clustering process, is presented in Fig. 4. For $V_0 = 0$ one gets the multiplicity *versus* angular momentum distribution presented by the dashed line. This distribution corresponds more or less to the STSRM prediction, which finally, after cooling the system by the GEMINI code, was not in agreement with the experimental data. For a slightly attractive nuclear potential $V_0 = -1.5\,\mathrm{MeV}$ the multiplicity of particles increases, specially for heavier ejectiles, $A > 4$ (solid line). This can be explained by the increasing

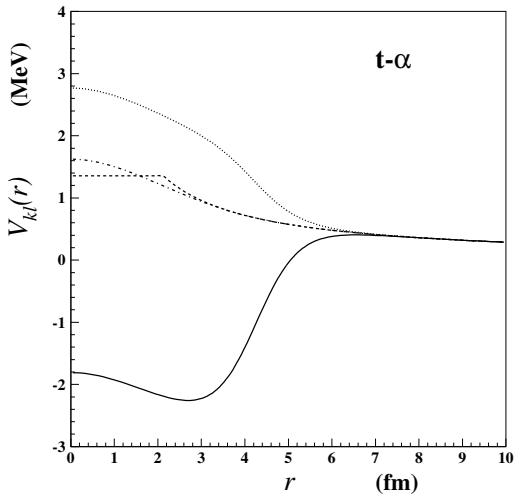

Fig. 3. The "old" STSRM (dashed line) and the "new" STSRM2 (solid line) t–α cluster interaction potentials. The Coulomb contributions to the STSRM2 potential is given by the dashed–dotted line. The dotted line presents the $V_0 = 0.5\,\mathrm{MeV}$ case.

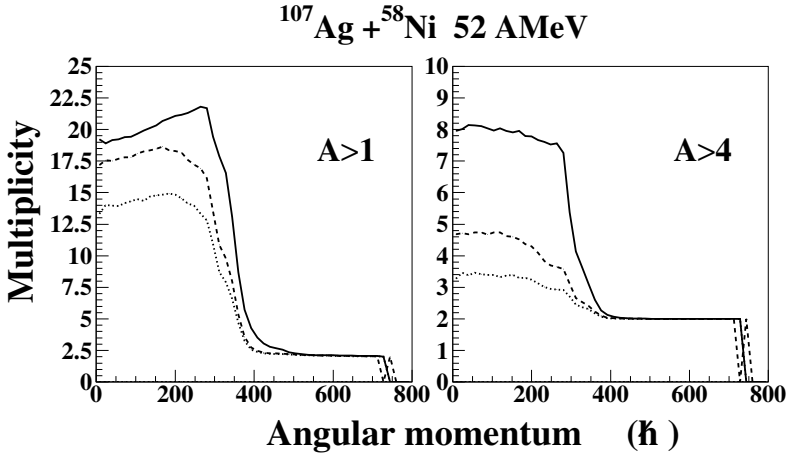

Fig. 4. Influence of the cluster–cluster nuclear potential shape on the multiplicity of the primary particles: $A > 1$ left part, $A > 4$ right part. The solid line corresponds to the attractive potential (new version of the model). The case with the Coulomb interaction only is presented by a dashed line, the case with the repulsive potential by a dotted line.

of the reaction Q value. An opposite effect is observed for a slightly repulsive nuclear potential $V_0 = 0.5\,\mathrm{MeV}$ (dotted line). As seen in Fig. 4 the nuclear cluster–cluster potential influences mostly the more central collisions.

4. The confrontation of the STSRM2 predictions with experimental data

Predictions of the modified STSR model, the STSRM2 one, are presented in Fig. 5 for the total multiplicity distribution of charged particles, and in Fig. 6 for the charge distribution. For comparison the STSR model predictions are also presented.

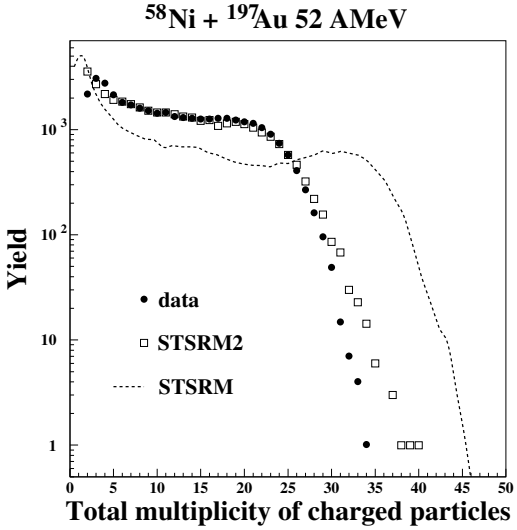

Fig. 5. The total multiplicity distribution of charged particles for the ^{58}Ni+^{197}Au reaction at 52 AMeV [11].

The experimental data were taken from the ^{58}Ni+^{197}Au experiment performed at GANIL for 52 AMeV ^{58}Ni ions [11]. It is obvious that the STSR model is not able to reproduce properly the data, and modifications proposed in the STSRM2 version are justified. It has been shown recently that the new version of the STSR model is also successful in describing experimental data from the ^{107}Ag+^{58}Ni reaction for ^{107}Ag ions at 52 AMeV (GANIL [12, 13]). As an example Fig. 7 presents the TLF velocity distributions. For reversed kinematics the target like fragment can attain large velocities for more central collisions only, where the STSRM2 predicts a practically complete multi-fragmentation and the TL fragment has a rather small probability to survive. Consequently, the yield of the large velocity TLF's must be very small.

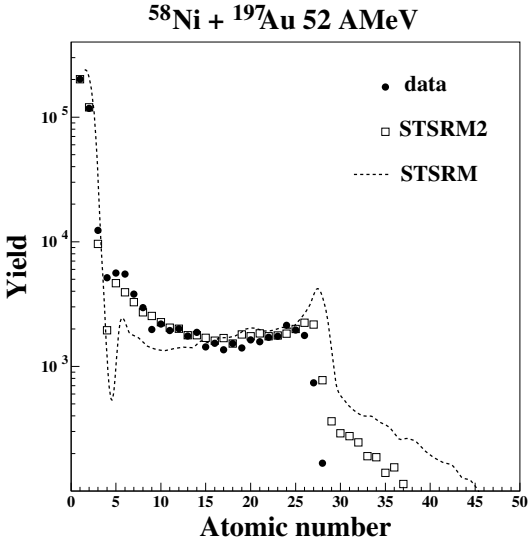

Fig. 6. The charge distribution of charged particles for the ^{58}Ni+^{197}Au reaction at 52 *A*MeV [11].

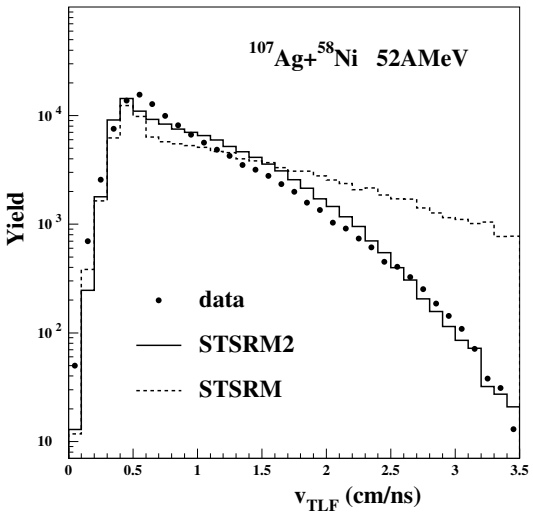

Fig. 7. The TLF velocity distribution for the ^{107}Ag+^{58}Ni reaction at 52 *A*MeV. See text for details [12, 13].

5. Summary and conclusions

The paper presents a modified version of the STSR model which can be used for collisions of heavier ions and at relatively higher collision energy. Modifications are mainly concentrated on different forms of nuclear interac-

tions in the first and in the second reaction stage. A particular shape of the nuclear interaction in the entrance reaction channel is specially important for heavier systems and higher collision energy, because of the deflection angle determination. The proximity potential was giving here a too high value of the grazing angle and in the new version of the model had to be replaced by a sum of the attractive negative potential with the Woods–Saxon form factor, and the repulsive positive potential simulating incompressibility of the nuclear matter. The final reaction picture depends on the clusterization process, governed by the attained densities of states, which in turn depend on the generated reaction heat. What seems to be the most important for peripheral and mid-peripheral collisions is the kinetic energy dissipation. For more central collisions, however, the cluster–cluster interactions and the ground state binding energy of all participating objects become the most important. The modified version of the STSR model gives a considerably better description of different reaction observables, such as multiplicity and Z distributions. In the future, some farther modifications of the model are possible. One of them could be *e.g.* inclusion of the isospin dependent interactions.

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