Production of cold fragments in nucleus-nucleus collisions in the Fermi-energy domain

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Abstract

The reaction mechanism of nucleus-nucleus collisions at projectile energies around the Fermi energy is investigated with emphasis on the production of fragmentation-like residues. The results of simulations are compared to experimental mass distributions of elements with Z = 21 - 29 observed in the reactions $^{86}$Kr+$^{124,112}$Sn at 25 AMeV. The model of incomplete fusion is modified and a component of excitation energy of the cold fragment dependent on isospin asymmetry is introduced. The modifications in the model of incomplete fusion appear consistent with both overall model framework and available experimental data. A prediction is provided for the production of very neutron-rich nuclei using a secondary beam of $^{132}$Sn where e.g. the
reaction $^{132}$Sn$+^{238}$U at 28 AMeV appears as a possible alternative to the use of fragmentation reactions at higher energies.

**Introduction**

Nucleus-nucleus collisions in the Fermi energy domain exhibit a large variety of contributing reaction mechanisms and reaction products (see e.g. [1]) and offer the principal possibility to produce mid-heavy to heavy neutron-rich nuclei in very peripheral collisions. In the reactions of massive heavy ions such as $^{124}$Sn$+^{124}$Sn [2] and $^{86}$Kr$+^{124}$Sn [3], an enhancement was observed over the yields expected in cold fragmentation which is at present the method of choice to produce neutron-rich nuclei. In this case the neutron-rich nuclei are produced in damped symmetric nucleus-nucleus collisions with intense nucleon exchange leading to the large width of isotopic distributions. Further enhancement of yields of n-rich nuclei was observed in the reaction $^{86}$Kr$+^{64}$Ni [4] in the very peripheral collisions, thus pointing to the possible importance of neutron and proton density profiles at the projectile and target surfaces. In [5], the model of deep-inelastic transfer [6] was supplemented with a phenomenological correction introducing the effect of shell structure on nuclear periphery. A consistent agreement with experimental data was achieved in the reactions of a 25 AMeV $^{86}$Kr beam with three different target nuclei, specifically allowing to describe the deviation of the nucleon exchange from the path toward isospin equilibration.

In this article, we present an investigation of the reaction mechanism of the nucleus-nucleus collisions with an emphasis on the production of fragmentation-like residues at projectile energies around the Fermi energy. The fragmentation-like residues with mass and charge below the projectile can be, according to calculation [1], produced at projectile energies around the Fermi energy in the process of incomplete fusion. The difference to high-energy fragmentation as assumed in standard abrasion-ablation model ([7,8]) is that here the participant zone fuses with one spectator, thus creating a very hot multifragmentation source and the other spectator remains cold. The cold projectile-like fragment is not emitted at zero angle but due to classical Coulomb trajectory along which the collision evolves it appears at larger angles. The existence of such a cold fragment can be deduced e.g. from the data of Casini et al. [9] where mass and excitation energy of the projectile-like fragment (PLF) were kinematically reconstructed and it was established
that the products lighter than the projectile are cold and heavier ones are hot. Such dependence can not be explained using the concept of nucleon exchange as represented by the model of deep-inelastic transfer [10]. The simulation using the incomplete-fusion (ICF) code [1] reproduces such behavior reasonably well, due to low excitation energy of fragmentation-like residues with masses below projectile and considerably higher excitation energy of ICF-like residues heavier than projectile. Furthermore, a large amount of detailed data on hot multifragmentation source in various reactions was reproduced, including detailed experimental studies of the mid-velocity source [11] and single fusion-like source [12]. The reaction \(^{124}\text{Sn}+^{27}\text{Al}\) was used to verify the ICF model using heavy residues with masses \(A=60-90\) measured with high precision using a fragment separator at forward angles [13] and both the production cross sections and the N/Z trend were reproduced well for these products originating from hot projectile-like ICF source. However, little is known on N/Z trend of the cold fragments, which can be produced in symmetric reactions of heavy nuclei. In the present paper we examine such a trend using the experimentally observed heavy residues in reactions \(^{86}\text{Kr}+^{112,124}\text{Sn}\) at projectile energy 25 AMeV and refine the model description in order to improve the prediction of the production of exotic (neutron-rich) nuclei in nucleus-nucleus collisions around Fermi energy.

Production of heavy residues in reactions \(^{86}\text{Kr}+^{112,124}\text{Sn}\) at projectile energy 25 AMeV

According to the incomplete fusion model [1], in order to study the production of cold fragmentation-like residues around the Fermi energy it is necessary to study symmetric nucleus-nucleus collisions of two massive nuclei (with target comparable or heavier than projectile). The products of interest will be produced at angles away from zero degrees and the measurement at these angles is necessary to observe such products. Furthermore, according to the calculation, the cold fragmentation-like residues should be increasingly dominant products for the channels with the number of stripped protons exceeding seven to eight. Thus the products of primary interest are the heavy residues considerably lighter than the initial projectile, which due to the removal of a significant number of protons can be also considerably neutron-rich.
In order to examine the prediction of the ICF code [1], the results of simulations were compared to experimental mass distributions of elements with Z = 21 - 29 observed within the separator acceptance in the reaction $^{86}$Kr+$^{124,112}$Sn at 25 AMeV [3]. Figs. 1, 2 show the comparison of experimental mass distributions (symbols) to the results of the simulation (dashed line) for the reactions of $^{86}$Kr with two tin targets. The simulation uses either the model of deep-inelastic transfer [6, 5] for peripheral collisions or the model of pre-equilibrium emission and incomplete fusion (ICF) for violent (central) collisions, combined with the de-excitation code SMM [14]. The simulated yields were filtered for angular acceptance of the separator positioned at 4° with appropriate azimuthal corrections [3].

The model of incompleteness fusion [1], used in the calculation, considers a spectator-participant scenario evolving along the classical Coulomb trajectory, followed by fusion of the participant zone with one spectator, typically the heavier one due to larger contact area and thus larger attractive force. The charge of spectator zones is determined using the combinatorial probabil-
ity, which is a standard approach in fragmentation codes \cite{8}. The excitation energy of the cold fragment is determined considering the two-body collisions of participant and spectator nucleons along the separation plane \cite{1}. The concept of combinatorial probability explores the available statistical phase space and allows a rather wide range of isospin asymmetries. From a dynamical point of view, however, the spectator-participant scenario implies an instantaneous separation and thus preservation of isospin asymmetry of the initial nucleus in the ground state, with homogeneous density in the interior of the nucleus. Thus, the two concepts seem to be in contradiction, which can be resolved when assuming that the change of isospin asymmetry is dynamically consistent with transfer of certain amount of nucleons across the separation plane. Simultaneously, the relative velocity between the participant and spectator zone increases from zero to maximum value corresponding to final incomplete-fusion scenario and thus the transferred nucleons should carry this relative velocity which will be transferred into excitation energy of the acceptor. Thus a component of excitation energy dependent on isospin asymmetry can be deduced. It can be assumed that, due to absence of Coulomb barrier, the nucleons transferred will be predominantly neutrons. The formula for such isospin dependent component of excitation energy of a cold spectator (acceptor) can be written as

$$E^*_S(A_s, Z_s) = x \left( A_s - A_0(Z_s) \right) \left( \frac{v_{ICF}}{v_{proj}} \right)^2 \frac{E_P - V_C}{A_P}$$

(1)

where $E_P$, $A_P$ are the projectile kinetic energy and mass, $V_C$ is the Coulomb barrier, $v_{proj}$, $v_{ICF}$ are the projectile velocity and the final relative velocity between hot and cold fragment in the incomplete-fusion scenario, evaluated at the Coulomb barrier, $A_s$, $Z_s$ are mass and charge of the spectator (cold fragment), $A_0(Z_s)$ is the spectator mass corresponding to N/Z of initial nucleus and $x$ is a random number between zero and one, generated for each collision. The random number is introduced due to uncertainty concerning the exact moment of transfer and represents an zero-th order estimate allowing to reproduce the mean value of extra excitation energy due to transfer of neutrons. The excitation energy is evaluated only in the case when the cold fragment is acceptor (and thus neutron-rich). For the loss of neutrons no such component is evaluated, thus assuming that neutrons close to the Fermi level are lost and no enhancement of intrinsic excitation occurs.

The results of modified calculation employing the formula (1) are shown in Figs. 1, 2 as solid lines. One can see that the overall agreement with the
experimental data is improved in the modified calculation compared to the standard one. The calculation with modification, which is fully consistent with overall description of the nucleus-nucleus collisions and introduces no free parameters, describes the trend of the experimental yields of the most neutron-rich products below nickel for the reaction $^{86}$Kr+$^{124}$Sn, which the initial calculation overpredicts. The situation improves also for the reaction $^{86}$Kr+$^{112}$Sn. For the most neutron-rich products below chromium nuclei occasionally appear less populated than it is predicted by the model. This however can be caused by missing yield in the experiment due to high background from the initial beam, because of increasing overlap of the charge states (in terms of magnetic rigidity) with charge states of the scattered beam. The effect is more pronounced for the reaction $^{86}$Kr+$^{112}$Sn due to lower experimental yields.

It is worthwhile to mention that both the original and modified calculations correctly reproduce the experimental cross sections of heavy residues with $Z = 25 - 30$ for the reaction $^{86}$Kr+$^{64}$Ni at 25 A MeV [4], measured at angles below $3^\circ$, as documented in Fig. 3 (dashed and solid line represent original and modified calculation). The discrepancies at the proton-rich side are caused by restricted $B_\rho$-coverage for such products in the experiment focused primarily on neutron-rich products. The situation in Fig. 3 and its comparison with reactions $^{86}$Kr+$^{112,124}$Sn shows that indeed measurement at larger angles and use of heavier target is necessary in order to observe the experimental cross section of cold fragmentation-like residues.

In general, the modifications in the model of incomplete fusion appear consistent with both overall model framework and experimental data and thus one can expect improved predictive power which can be used to predict production of exotic mid-heavy to heavy neutron-rich nuclei in the reactions around the Fermi energy, and possibly identify under which conditions such approach can be more effective than other methods. From the point of view of reaction dynamics, the modified model of incomplete fusion is consistent with the formation of a neutron-rich region between cold and hot fragment (or participant zone as its precursor). Similar effect was reported in the literature [15] as a possible consequence of the evolution of nuclear mean field. The number of transferred neutrons can then be determined by a mechanism similar to the random neck rupture, as established in nuclear fission [16], which can justify the applicability of a combinatorial (and thus essentially statistical) probability in the description of dynamical reaction mechanism such as the incomplete fusion.
Production of neutron-rich nuclei around $N=82$

A great deal of attention was paid in recent years to production of the secondary beams of exotic nuclei. One of the most promising ways to produce extremely neutron-rich nuclei around the neutron shell $N=82$ is fragmentation of a secondary beam of $^{132}$Sn. Nevertheless, based on the results of the previous section, one can in principle consider also the reaction in the Fermi-energy domain at energies below 50 AMeV. The comparison of production cross sections for the reaction $^{132}$Sn+$^{238}$U at 28 AMeV with fragmentation cross section of $^{132}$Sn beam with Be target is provided in Fig. 4. For the reaction $^{132}$Sn+$^{238}$U the modified DIT code [5] was used for peripheral collisions together with original model of incomplete fusion [1] (dashed lines) and its modification presented in this article (solid lines) for central collisions, while for the fragmentation of $^{132}$Sn beam the codes COFRA [17] (dotted lines) and EPAX [18] (dash-dotted lines) were used. The production cross sections calculated using both the original and modified model of incomplete fusion for $Z=46$ are comparable with results of EPAX and COFRA, while for elements with lower atomic numbers the reaction $^{132}$Sn+$^{238}$U leads, according to both the original and modified model of incomplete fusion, to still more favorable cross sections exceeding both COFRA and even EPAX cross sections. The high cross sections for proton-stripping channels with $^{238}$U target were observed recently in reaction $^{58}$Ni+$^{238}$U by Corradi et al. [19] at energies about 1 AMeV above Coulomb barrier. The proton-stripping cross sections were reproduced using the calculation analogous to the one used here after minor readjustment (increase by 0.5 fm) of diffuseness reflecting mean-field effects at such low energy [20]. When looking at the calculated cross sections for $^{132}$Sn+$^{238}$U in Fig. 4 one can see that the trend of the shapes of mass-distributions calculated using original model of incomplete fusion is quite similar to EPAX (since the assumptions are essentially similar) while trend of the elemental yields differs due to assumed classical Coulomb trajectories vs straight movement assumed in fragmentation model. The validity of EPAX code concerning the trend of n-rich products is a matter of discussion and based on the results of the present work one can expect that experimental production cross sections of very n-rich nuclei in fragmentation reactions will be significantly lower than the prediction of EPAX parametrization. The magnitude of such effect needs to be verified (a dedicated experiment on fragmentation of $^{132}$Sn secondary beam is planned at GSI [21]), one can nevertheless expect that the code with more realistic treatment of specta-
tor excitation energy, such as COFRA, will provide better predictions. It is interesting to note that the difference of predictions of fragmentation cross sections by EPAX and COFRA is similar to difference of predictions of production cross sections in reaction $^{132}\text{Sn} + ^{238}\text{U}$ by the original and modified model of incomplete fusion. Despite different processes, the amount of excitation energy of the spectator appears to be comparable in both cases and the success of modified model of incomplete fusion in the present work may imply that COFRA will be successful in the fragmentation reactions.

The in-target yields calculated using the production cross sections from Fig. 4 are shown in Fig. 5. For the fragmentation of $^{132}\text{Sn}$ secondary beam an energy 100 AMeV was used, which is the maximum foreseen for post-accelerator envisioned for future European RNB facility Eurisol [22]. The achievable in-target reaction rate was determined using code AMADEUS [23]. For the reaction $^{132}\text{Sn} + ^{238}\text{U}$ at 28 AMeV a target thickness 40 mg/cm$^2$ was assumed. For the intensity of $^{132}\text{Sn}$ secondary beam a value of $10^{12}$ s$^{-1}$ was adopted from Eurisol RTD Report [22]. Due to larger target thickness, the in-target yield for fragmentation option calculated using both COFRA and EPAX dominate for elements $Z=44$ and above, for lighter nuclei nevertheless the larger production cross sections in the Fermi-energy domain lead also to larger in-target yields despite relatively thin target and for $Z=40$ the in-target yield calculated using the modified model of incomplete fusion exceeds the COFRA value (and the EPAX value is exceeded by original model of incomplete fusion). To answer on viability of Fermi-energy option, a crucial question is which calculation of fragmentation cross sections is realistic. Recent measurement carried out at MSU [24] has shown that experimental fragmentation cross section of neutron-rich Ni isotopes are overpredicted by EPAX by up to two orders of magnitude. If the situation is analogous in the fragmentation of $^{132}\text{Sn}$ the Fermi-energy option can become interesting. However, the angular distribution of reaction products at 28 AMeV would require a large-acceptance separator with angular coverage up to 10 degrees and a highly efficient gas-cell in order to form a secondary beam.

Conclusions

The reaction mechanism of the nucleus-nucleus collisions at projectile energies around the Fermi energy was investigated with emphasis on the production of fragmentation-like residues. The results of simulations were compared
to experimental mass distributions of elements with Z = 21 - 29 observed around 4° in the reaction $^{86}$Kr+$^{124,112}$Sn at 25 AMeV. The model of incomplete fusion was modified and a component of excitation energy of the cold fragment dependent on isospin asymmetry was introduced. The modifications in the model of incomplete fusion appear consistent with both overall model framework and available experimental data. Prediction is provided for the production of very neutron-rich nuclei using a secondary beam of $^{132}$Sn where e.g. the reaction $^{132}$Sn+$^{238}$U at 28 AMeV appears as a possible alternative to the use of fragmentation reactions at higher energies.

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Figure 1: Comparison of the simulations to experimental mass distributions (symbols) of elements with $Z = 21$ - $29$ observed around $4^\circ$ in the reaction $^{86}$Kr+$^{124}$Sn at 25 AMeV [3]. Dashed line - results of the standard simulation [1, 5] combined with the de-excitation code SMM [14], Solid line - results of simulation using modified model of incomplete fusion (eq. [1]).
Figure 2: Comparison of the simulations to experimental mass distributions (symbols) of elements with $Z = 21 - 29$ observed around $4^\circ$ in the reaction $^{86}\text{Kr} + ^{112}\text{Sn}$ at 25 AMeV \cite{3}. Solid, dashed lines - as in Fig. 1.
Figure 3: Comparison of the simulated ( lines ) and experimental ( symbols ) cross sections of heavy residues with $Z = 25 - 30$ for the reaction of $^{86}$Kr+$^{64}$Ni at 25 A MeV [4], measured at angles below 3 $^\circ$. Dashed and solid line represent standard and modified calculation.
Figure 4: Comparison of production cross sections for reaction $^{132}$Sn+$^{238}$U at 28 AMeV using standard (dashed lines) and modified simulation (solid lines) with fragmentation cross sections of $^{132}$Sn beam with Be target using COFRA [17] (dotted lines) and EPAX [18] (dash-dotted lines).
Figure 5: The in-target yields (for the intensity of $^{132}$Sn beam $10^{12}$ s$^{-1}$) calculated using the production cross sections from Fig. 4. Meaning of lines is analogous to Fig. 4.