Investigation of isotope composition of nuclear fragments with angular momentum and Coulomb effects in peripheral ^{84}Kr+^{112,124}Sn collisons at 35 *A* MeV*

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New theoretical calculations are performed to investigate the Coulomb proximity and angular momentum effects on multifragmentation picture for ^{84}Kr+^{112,124}Sn collisions at an incident beam energy of 35 MeV/nucleon. Charge and isotopic distributions and the mean neutron-to-proton ratios of the fragments are reproduced within the microcanonical Markov chain calculations on the basis of Statistical Multifragmentation Model. It is shown that the Coulomb interactions and angular momentum effects are very important to reproduce isotopic composition of nuclear fragments in peripheral heavy-ion collisions at Fermi energies. Our results imply that it is possible to investigate in laboratories the modification of structure parameters of fragments, such as the symmetry energy coefficient, at subnuclear densities in dense environment of other species.

Keywords: Multifragmentation, Angular momentum, Coulomb effect

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I. INTRODUCTION

During the peripheral heavy-ion collisions at Fermi energies (20–50 MeV per nucleon), a considerable amount of angular momentum could be transferred from the interaction region to the excited projectile and target residual nuclei, and this can lead to significant changes in their multifragmentation [1–6]. Additional long-range forces caused by the complicated Coulomb interaction between the target and projectile-like sources are essentially involved in the process [3, 7]. The multifragmentation in the presence of the external Coulomb field offers a possibility to study, experimentally, the effects of this long-range force, which are very important for disintegration of matter [2]. This is also necessary for construction of a reliable equation of state (EoS) of nuclear matter at subnuclear densities. Another motivation of these studies is that similar conditions for nuclear matter take place during the collapse and explosion of massive stars and in the crust of neutron stars [8, 9], where the Coulomb interactions of dense electron environment change the fragmentation picture. It is generally assumed that the statistical equilibrium regarding the fragment composition at subnuclear densities should be established in these astrophysical cases. Therefore, the analysis of the observables obtained in laboratory experiments with statistical models is a proper way to obtain knowledge on stellar matter. Previous studies of isospin composition of the produced fragments were found to be especially important for determining the strength of the symmetry energy during fragment formation in hot and diluted environments [10–15]. In central heavy-ion collisions at Fermi energies (20–50 MeV per nucleon), high excitation and high densities can be reached [16]. They become a suitable tool to study EoS of hot nuclear matter and the nuclear liquid-gas phase transitions at subnuclear densities. As shown previously, one can study the properties of hot fragments in the vicinity of other nuclear species by means of multifragmentation [15]. The angular momentum effect is usually neglected in this case, since the impact parameters are small.

As demonstrated by several studies [12, 17–21], using statistical ensemble approach within Statistical Multifragmentation Model (SMM) [22], charge and isotope yields, fragment multiplicities and temperatures, and correlations of various fragment properties were successfully analyzed using ALADIN data. This was also achieved in the analysis of the experimental data [23] obtained at the MSU laboratory at 50 MeV/nucleon [24–26], and in the analysis of TAMU data [27, 28]. In these studies, the symmetry energy of fragments was one of the main model parameters governing the mean $\langle N\rangle/Z$ values, the isoscaling parameters, and the isotopic composition of the fragments. In our theoretical interpretations [12, 24–26] for ALADIN and MSU experiments, we considered the formation and decay of single thermalized source and the averaged Coulomb interaction of fragments (the Wigner-Seitz approximation), since a direct positioning of fragments in the freeze-out volume has minor influence on their charge and isotope distributions. We have justified the assumption of the formation and decay of single thermalized sources for relativistic peripheral collisions, and central collisions of heavy nuclei around the Fermi energy with our successful predictions for ALADIN and MSU data. We believe that it is possible to extract important information on multifragmentation and properties of fragments in peripheral collisions at Fermi energies as well. The new fragment partitions can be obtained by including the Coulomb effects caused by the proximity of colliding target and projectile nuclei, as well as the effects by large angular momentum transfer to the multifragmenting sources. We believe that a long-range Coulomb

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interaction of the target- and projectile-like sources changes the fragmentation pattern and leads to a predominant midrapidity (neck–like) emission of light and intermediate mass fragments (IMF, with charge numbers Z =3–20). In Refs. [28, 29], such experiments have already been analyzed with statistical models. However, there were no systematic theoretical investigations of the Coulomb and angular momentum effects on multifragmentation picture at these reactions, especially on the isotope yields which are crucial for astrophysical applications. The angular momentum may lead to more neutron-rich IMF production and to anisotropic emission with respect to the projectile and target sources, as it was reported in Refs. [3, 7]. In this paper, we theoretically investigate the influence of angular momentum and Coulomb interactions on the charge yields, the neutron to proton ratios of particles for peripheral ^{84}Kr+^{112,124}Sn collisions at 35 MeV per nucleon. This is a quite typical reaction, and our selection is partly motivated by recent FAZIA experiments [30]. Our investigation on interpretation of FAZIA experiment is underway. For the simulation of the reactions, we consider the break-up of a single source ^{84}Kr in the proximity of a secondary source ^{112,124}Sn. The calculations are carried out within the Markov chain version of the statistical multifragmentation model (SMM), which is designed for a microcanonical simulation of the decay modes of nuclear sources [3, 31]. This method is based on producing the Markov chain of partitions which characterize the whole statistical ensemble. In this method the individual fragment partitions and coordinate positions of fragments in the freeze-out volume are generated. They are selected by the Metropolis algorithm and we can take into account the influences of angular momentum and Coulomb interactions for each spatial configuration of primary fragments in the freeze-out volume, similar to Refs. [1, 2].

II. STATISTICAL METHOD FOR MULTIFRAGMENTATION CALCULATIONS

In the microcanonical SMM, a statistical equilibrium at low density freeze-out region is a basic assumption. Nucleons and nuclear fragments are included in the breakup channels, and the laws of conservation of energy E_x, momentum, angular momentum, mass number A and charge number Z are considered. The breakup channels and the compound-nucleus channels are also included, and competition between all channels is permitted. The SMM includes the conventional evaporation and fission processes occurring at low excitation energy as well as the transition region between the low and high energy de-excitation regimes. In the thermodynamic limit, SMM is consistent with liquid-gas phase transitions when the liquid phase is represented by infinite nuclear clusters [32], that allow connections for the astrophysical cases [6, 33]. The statistical weights of all breakup channels partitioning the system into various species are calculated. The decay channels are generated by Monte Carlo method according to their statistical weights. In the Markov chain SMM [3, 31], we use ingredients taken from the standard SMM version developed in [22, 34, 35] which was successfully used for comparison with various experimental data: Light fragments with mass number $A \leq 4$ and charge number $Z \leq 2$ are considered as elementary particles with the corresponding spins (nuclear gas) that have translational degrees of freedom. The fragments with mass number $A > 4$ are treated as heated nuclear liquid drops. Therefore it is possible to study the nuclear liquid-gas coexistence in the freeze-out volume. Free energies $F_{A,Z}$ of each fragment are parameterized as a sum of the bulk, surface, Coulomb and symmetry energy contributions

$$F_{A,Z} = F^{B}_{A,Z} + F^{S}_{A,Z} + E^{C}_{A,Z} + E^{sym}_{A,Z}. \quad (1)$$

The bulk contribution is given by $F^{B}_{A,Z} = (-W_0 - T^2/\varepsilon_0)A$, where T is the temperature, the parameter ε_0 is related to the level density, and $W_0 = 16\,\text{MeV}$ is the binding energy of infinite nuclear matter. Contribution of the surface energy is $F^{S}_{A,Z} = B_0 A^{2/3}[(T_c^2 - T^2)/(T_c^2 + T^2)]^{5/4}$, where $B_0 = 18\,\text{MeV}$ is the surface energy term, and $T_c = 18\,\text{MeV}$ is the critical temperature of the infinite nuclear matter. In the standard SMM version the Coulomb energy contribution is $E^{C}_{A,Z} = cZ^2/A^{1/3}$, where c denotes the Coulomb parameter obtained in the Wigner-Seitz approximation, $c = (3/5)(\mathrm{e}^2/r_0)(1 - (\rho/\rho_0)^{1/3})$, with the charge unit e, $r_0 = 1.17$ fm, and ρ_0 is the normal nuclear matter density (0.15 fm^{-3}). However, within this Markov-chain SMM we directly calculate the Coulomb interaction of non-overlapping fragments in the freeze-out by taking into account their real coordinate positions. The symmetry term is $E^{\text{sym}}_{A,Z} = \gamma(A - 2Z)^2/A$, where $\gamma = 25\,\text{MeV}$ is the symmetry energy parameter. All the parameters given above are taken from the Bethe-Weizsaecker formula and correspond to the assumption of isolated fragments with normal density unless their modifications in the hot and dense freeze-out configuration follow the analysis of experimental data. Since our previous analysis [13] confirms the trend of a decreasing symmetry energy as one approaches conditions comparable to the multifragmentation regime in agreement with previous findings [11, 12, 15, 24, 26, 28], we have used $\gamma = 14\,\text{MeV}$ for $Z \leq 9$, $\gamma = 16\,\text{MeV}$ for $Z = 10 - 17$, and $\gamma = 18 - 19\,\text{MeV}$ for $Z \geq 18$. In this work, we use $\rho = \rho_0/6$ to freeze out density for better evaluation of Coulomb and angular momentum effects. Usually, we generate about 10^5 Monte Carlo events to provide sufficient statistics.

III. CALCULATIONS WITH ANGULAR MOMENTUM AND COULOMB INTERACTIONS

In this study, we investigate peripheral nucleus-nucleus collisions at 35 MeV/nucleon with corresponding relative velocities of the projectile and target around 45–70 mm/ns. At the initial dynamical stage of such a collision, the projectile nucleons interact with target nucleons and some energetic products of this interaction can leave the nuclei as pre-equilibrium particles. The kinetic energy of colliding nuclei can also be converted into the excitation energy of projectile and target residues. Therefore, the relative velocity between the residues decreases as well. These excited target and projectile-like sources decay afterwards.

Table 1. Values for the sources assumed to be formed according to the peripheral collisions for ^{84}Kr+^{112,124}Sn reactions.

E_x (A MeV)	Z_s	A_s (^{112}Sn)	A_s (^{124}Sn)	Weight	ang. mom.
2	34	77	82	0.13	30
3	33	75	80	0.19	30
4	32	73	77	0.32	40
5	30	68	73	0.25	50
6	29	66	70	0.08	60
7	28	64	68	0.03	70

The projectile and target-like sources will not be far from each other before disintegration since nuclear multifragmentation is a fast process within a characteristic time around 100 fm/c. We believe that at these short distances the long range Coulomb field of one of the sources affects the break up of the other one. In this way, we can deal with the multifragmentation in a double nuclear system, since it is a new physical situation with respect to the standard multifragmentation of a single isolated source.

According to our estimates from the energy conservation, their relative velocity should decrease to ∼60 mm/ns, at an excitation energy around 5 MeV/nucleon transferred to the residues. In this case, the first and second source will be separated by ≈15 fm in a time of 100 fm/c. The decay of the two excited sources in such a double system is determined by the short-range nuclear forces. However, the presence of an external Coulomb field (for each source) may influence the composition of the produced fragments and their relative positions. Especially, an additional Coulomb barrier will prevent disintegration of the sources into many small pieces. It should be noted that during the evolution of a double system we must take into account its total center of mass conservation without a separate constraint in the freeze-out volumes of disintegrating sources. On the other hand, we include the angular momenta (rotation) of the separate sources, which can be transferred after the collision. It will also influence the positions and sizes of the fragments at the freeze-out [1, 3, 7].

We show the results for multifragmentation of the projectile-like source (the first source ^{84}Kr) by assuming the Coulomb field coming from the center of the target source (the second source ^{112,124}Sn). We have assumed that the first source flies along the Y-axis, and the second one flies in the opposite direction (related to the center of mass of the double system). This separation axis may slightly deviate from the initial beam axis. The location of the second source is taken as R_Y= -15 fm and R_Z=15 fm with respect to the first source. The peripheral collision is assumed to take place in the $Y-Z$ plane. The coordinates in Z-axis are determined by the sizes of colliding nuclei, as well as by their possible repulsion after the collision. The angular momentum axis is assumed to be X-axis. We believe that this relative space configuration of the sources is suitable for investigating the Coulomb and angular momentum effects. The pre-equilibrium emission of few nucleons during the dynamical stage may decrease the excitation energy and relative velocity of the residues. One may take into account these effects in the statistical approach by changing the corresponding input and by using the ensemble of the sources [12, 13] with adequate parameters. We also know from many theoretical and experimental works [17, 22, 36], that the relative yields of IMF do not depend much on the size of the sources in the multifragmentation regime. But in our previous work [37], we also investigated the behavior of sources of the same size and isospin content as the colliding nuclei (^{84}Kr).

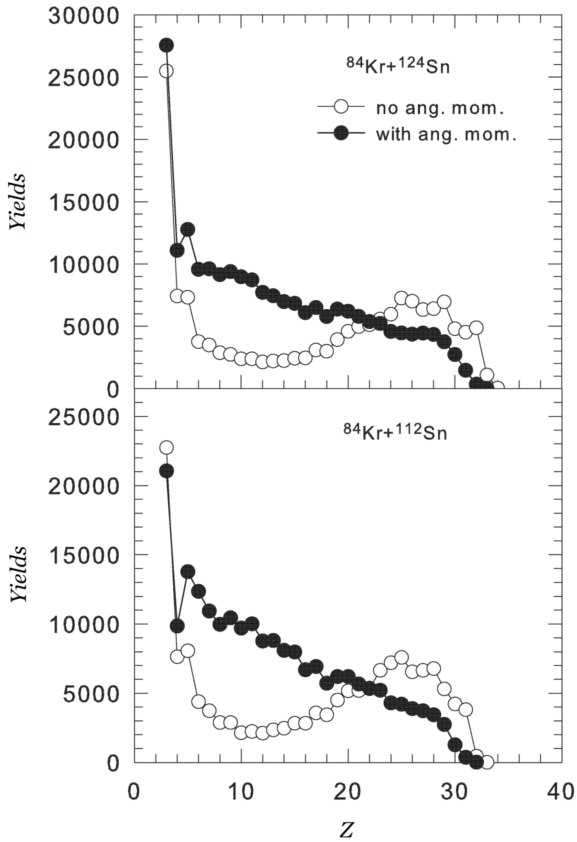

Fig. 1. The charge yield of fragments, in the cases of without (full circles) and with angular momentum (open circles), after multifragmentation of the projectile ^{84}Kr source. These sources are assumed to be formed in the peripheral ^{84}Kr + ^{112,124}Sn collision at 35 MeV/nucleon, and its disintegration is affected by the Coulomb field of the target source as shown in Table 1.

A. Charge and isotope distributions, and neutron to proton ratios

We have investigated the angular momentum and Coulomb field influences on the charge and isospin contents of the produced fragments. It is important to analyze the new characteristics of fragment distributions, which are crucial for interpretation of many experiments on heavy-ion collisions at Fermi energies. After the break-up of the sources we calculate the Coulomb propagation of produced hot fragments by taking into account the Coulomb interactions of particles in the double system. In order to clarify the modification of the multifragmentation picture caused by the new effects and

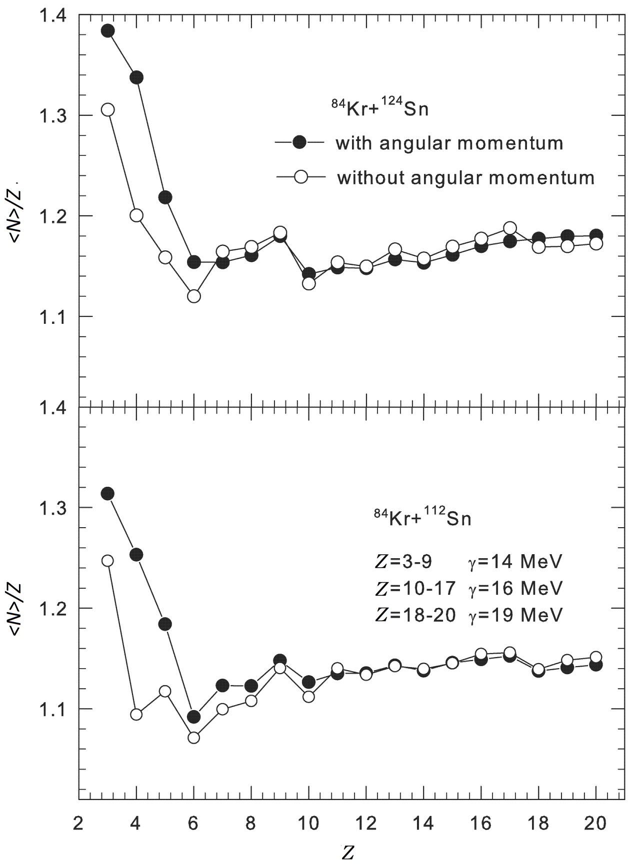

Fig. 2. The neutron-to-proton ratio $\langle N\rangle/Z$ of fragments produced at the freeze-out density $\rho = \rho_0/6$.

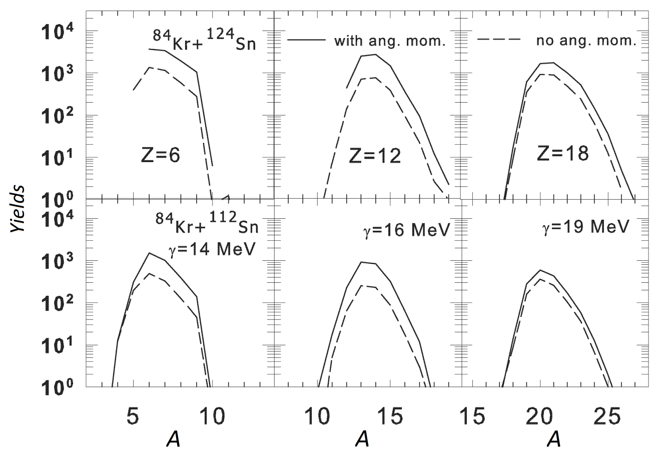

Fig. 3. Predicted isotope distributions for $Z = 6, 12$ and 18 fragments for ^{84}Kr+^{112}Sn (top panel) ^{84}Kr+^{124}Sn (bottom panel) collisions. The solid lines correspond to the present results with angular momentum, the dashed lines show results without angular momentum. For our predictions $\gamma = 14$, 16 and 19 MeV values are used for Z=6, 12 and 18 isotopes, respectively. These γ values are in agreement with our previous predictions in [12, 13, 26, 37].

compare it with experimental data in the future, we apply the secondary de-excitation of the hot fragments which can lead to important consequences especially for the isospin composition of final fragments.

For our calculations we made following assumptions: We take the sources obtained from the ^{84}Kr projectile at different excitation energies, 2, 3, 4, 5, 6 and 7 MeV/n, as shown in Table 1. Liquid-gas phase transition theory is applied in this energy interval to explain nuclear multifragmentation on the basis of SMM. At $E_x < 2$ MeV/nucleon the compound nucleus and fission channels are found to be dominant. We have taken two sources with the same charge and the same excitation energy, but with two different $\langle N\rangle/Z$ ratios corresponding to those of ^{84}Kr+^{112}Sn and ^{84}Kr+^{124}Sn, as in experiment [30]. Then, firstly, we made SMM calculations for each source and found the charge and isotope distributions and $\langle N\rangle/Z$ ratios of fragments in the presence of second source (^{112,124}Sn) without and with angular momentum. Angular momentum values are randomly selected with an increasing order (see Table 1). Afterwards, we have taken mixture of all sources with weights, as shown in Table 1, corresponding to their excitation energies, which are related to the impact parameters. After this mixture is determined, we propose that we can obtain similar conditions to compare with experiments.

In Fig. 1, we show the charge yields of cold fragments with and without angular momentum conservation. Angular momentum values are selected as shown in Table 1. As seen in Fig. 1, an angular momentum favors emission of large nearly symmetric fragments (like a nuclear fission) since the system in the freeze-out needs to have a large moment of inertia in order to minimize the rotational energy and to maximize the entropy. It is in a competition with the second source through the Coulomb interaction which prevents to emit an IMF with a large charge number.

The initial value of neutron-to-proton ratio of the projectile source ^{84}Kr is 1.33 while 1.28 and 1.42 are corresponding to initial $\langle N\rangle/Z$ ratios of ^{84}Kr+^{112}Sn and ^{84}Kr+^{124}Sn. In Fig. 2, we see that angular momentum leads to increasing $\langle N\rangle/Z$ values of light IMFs in the case of strongly asymmetric decay. By the increasing moment of inertia of the system, it favors a bigger phase space of the reaction [3]. This trend may be responsible for many isospin observables.

We show in Fig. 3 the variation of isotopic distribution for Z=6, 12 and 18 for ^{84}Kr+^{124}Sn and ^{84}Kr+^{112}Sn reactions. We have demonstrated that isotopic distributions are very sensitive to Coulomb and angular momentum effects for peripheral reactions at Fermi energies. On the basis of our findings, we belive that it should be taken into account these new effects for the realistic description of experimental data, e.g., FAZIA [30]. Possible modifications for the symmetry energy term can also be investigated by means of the isotopic distributions of projectile fragments. In previous works, it is seen that the calculations for $Z = 6$ ($Z < 10$ small fragments) agree well with the data at $\gamma = 14$ (as in MSU and ALADIN analysis [24, 26]), for $Z = 12$ at $\gamma = 16$ while the calculations for $Z = 18$ with $\gamma \approx 19$ [13]. In a forthcoming paper, we will introduce the results of detailed analyses and interpretation of FAZIA [30] experimental data, on the basis of present calculations.

To verify our new-found trends we also performed the similar calculations for lighter and heavier systems, e.g., ^{84}Kr+^{84}Kr and ^{197}Au+^{197}Au collisions. In all cases, we have got the similar qualitative modifications of the standard multifragmentation picture related to the effects of angular momentum and the Coulomb field of sources.

IV. CONCLUSION

As a result, we have theoretically investigated the charge and isotope distributions and $\langle N\rangle/Z$ values of fragments after the multifragmention of the Kr-like projectiles in peripheral ^{84}Kr+^{112,124}Sn collisions around the Fermi energy within the microcanonical Markov chain approach on the basis of the statistical multifragmentation model. Coulomb and angular momentum effects originated after the collision dynamics are taken into account for the first time in this study. We demonstrated that conservation of angular momentum and complicated Coulomb interactions caused by the proximity of target and projectile-like sources in the freeze-out stage produce significant changes in the multifragmentation picture. There appears to be new fragment formation trends, such as an asymmetry of IMF emission and increasing the neutron content of light IMFs. These features are demonstrated after the secondary excitation of hot fragments for the formation of cold fragments, similar to the previously analyzed reactions leading to the production and decay of the single isolated sources. We have presently introduced our preliminary results, and investigations about velocity distributions of fragments in this new approach to analyze the experimental data are ongoing. Particular isotopic effects, such as the odd-even staggering of the yield of final fragments studied by the FAZIA collaboration [38], can also be analyzed within similar statistical approaches. Some preliminary encouraging results obtained with the help of the ensemble of residual sources were already reported [37, 39]. These investigations are important since they show a new connection between dynamical and statistical phenomena in nuclear reactions. We believe that it may also provide us with inputs to understand the nuclear equation of state and nuclear composition, which are important to determine the properties of nuclear and stellar matter at extreme conditions and their connections to the thermodynamics of stellar matter in astrophysical events [33]. Our theoretical results may be enlightening for further analysis of the experiments.

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