Investigation of Isotope Composition of Nuclear Fragments with Angular Momentum and Coulomb Effects in Peripheral 84Kr+112,124Sn Collisions at 35AMeV Postprint

Authors: Nihal Buyukcizmeci, Ergun Aysegul, Imal Hamide, Ogul Riza, S Botvina Alexander

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Abstract

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Full Text

Preamble

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

Nihal Buyukcizmeci,[1],† Aysegul Ergun,[1] Hamide Imal,[1] Riza Ogul,[1] and Alexander S Botvina[2],[3]

[1]Department of Physics, University of Selçuk, Konya 42079, Turkey
[2]Institute for Nuclear Research, Russian Academy of Sciences, Moscow 117312, Russia
[3]Frankfurt Institute for Advanced Studies, J.W. Goethe University, Frankfurt am Main D-60438, Germany

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New theoretical calculations are performed to investigate the Coulomb proximity and angular momentum effects on the multifragmentation picture for 84Kr+112,124Sn 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 the Statistical Multifragmentation Model. It is shown that the Coulomb interactions and angular momentum effects are very important for reproducing the 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 the dense environment of other species.

Keywords: Multifragmentation, Angular momentum, Coulomb effect
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INTRODUCTION

During peripheral heavy-ion collisions at Fermi energies (20–50 MeV per nucleon), a considerable amount of angular momentum can be transferred from the interaction region to the excited projectile and target residual nuclei, leading to significant changes in their multifragmentation behavior [1-6]. Additional long-range forces caused by the complicated Coulomb interaction between the target and projectile-like sources are also essentially involved in the process [3, 7]. Multifragmentation in the presence of an external Coulomb field offers a possibility to study experimentally the effects of this long-range force, which are very important for the disintegration of matter [2]. This is also necessary for constructing a reliable equation of state (EoS) of nuclear matter at subnuclear densities. Another motivation for these studies is that similar conditions for nuclear matter occur during the collapse and explosion of massive stars and in the crust of neutron stars [8, 9], where the Coulomb interactions of the dense electron environment change the fragmentation picture. It is generally assumed that statistical equilibrium regarding the fragment composition at subnuclear densities should be established in these astrophysical cases. Therefore, analyzing 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], making them suitable tools for studying the EoS of hot nuclear matter and 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 a statistical ensemble approach within the 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 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 N /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 a single thermalized source and the averaged Coulomb interaction of fragments (the Wigner-Seitz approximation), since direct positioning of fragments in the freeze-out volume has minor influence on their charge and isotope distributions. We have justified the assumption of formation and decay of single thermalized sources for relativistic peripheral collisions and central collisions of heavy nuclei around the Fermi energy through 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. 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 of large angular momentum transfer to the multifragmenting sources. We believe that the long-range Coulomb interaction of the target- and projectile-like sources changes the fragmentation pattern and leads to 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 have been no systematic theoretical investigations of the Coulomb and angular momentum effects on the multifragmentation picture in these reactions, especially on the isotope yields which are crucial for astrophysical applications. Angular momentum may lead to more neutron-rich IMF production and anisotropic emission with respect to the projectile and target sources, as reported in Refs. [3, 7]. In this paper, we theoretically investigate the influence of angular momentum and Coulomb interactions on the charge yields and neutron-to-proton ratios of particles for peripheral 84Kr+112,124Sn collisions at 35 MeV per nucleon. This is quite a typical reaction, and our selection is partly motivated by recent FAZIA experiments [30]. Our investigation of the interpretation of FAZIA experiments is underway. For the simulation of the reactions, we consider the break-up of a single source 84Kr in the proximity of a secondary source 112,124Sn. The calculations are carried out within the Markov chain version of the statistical multifragmentation model (SMM), which is designed for microcanonical simulation of the decay modes of nuclear sources [3, 31]. This method is based on producing the Markov chain of partitions that 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, allowing us to account for 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, statistical equilibrium in a 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 Ex, momentum, angular momentum, mass number A, and charge number Z are considered. The breakup channels and compound-nucleus channels are also included, and competition between all channels is permitted. The SMM includes conventional evaporation and fission processes occurring at low excitation energy as well as the transition region between 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], allowing connections to 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. Fragments with mass number A $>$ 4 are treated as heated nuclear liquid drops, making it possible to study nuclear liquid-gas coexistence in the freeze-out volume. Free energies FA,Z of each fragment are parameterized as a sum of bulk, surface, Coulomb, and symmetry energy contributions:

$$F_{A,Z} = F_B + E_S + E_C + E_{sym}$$

The bulk contribution is given by $F_B = (-W_0 - T^2/\varepsilon_0)A$, where T is the temperature, the parameter ε_0 is related to the level density, and $W_0 = 16$ MeV is the binding energy of infinite nuclear matter. The surface energy contribution is $E_S = B_0 A^{2/3}[(T_c^2 - T^2)/(T_c^2)]^{5/4}$, where $B_0 = 18$ MeV is the surface energy term and $T_c = 18$ MeV is the critical temperature of infinite nuclear matter. In the standard SMM version, the Coulomb energy contribution is $E_C = cZ^2/A^{1/3}$, where c denotes the Coulomb parameter obtained in the Wigner-Seitz approximation, $c = (3/5)(e^2/r_0)(1 - (\rho/\rho_0)^{1/3})$, 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 $E_{sym} = \gamma(A - 2Z)^2/A$, where $\gamma = 25$ MeV is the symmetry energy parameter. All 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 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 $\gamma = 14$ MeV for $Z \leq 9$, $\gamma = 16$ MeV for $Z = 10 - 17$, and $\gamma = 18 - 19$ MeV for $Z \geq 18$. In this work, we use $\rho = \rho_0/6$ for freeze-out density to better evaluate Coulomb and angular momentum effects. Typically, 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, 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 excitation energy of projectile and target residues, causing the relative velocity between the residues to decrease. These excited target and projectile-like sources decay afterward.

The projectile and target-like sources will not be far from each other before disintegration since nuclear multifragmentation is a fast process with a characteristic time around 100 fm/c. We believe that at these short distances, the long-range Coulomb field of one source affects the breakup of the other. This allows us to treat multifragmentation in a double nuclear system, representing a new physical situation compared to standard multifragmentation of a single isolated source. According to our estimates from 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 sources 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 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.

In particular, an additional Coulomb barrier will prevent disintegration of the sources into many small pieces. It should be noted that during evolution of a double system we must account for 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 that can be transferred after the collision, which also influences the positions and sizes of fragments at freeze-out [1, 3, 7].

We present results for multifragmentation of the projectile-like source (the first source 84Kr) by assuming the Coulomb field originates from the center of the target source (the second source 112,124Sn). We have assumed that the first source flies along the Y-axis and the second one flies in the opposite direction (relative 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 the Z-axis are determined by the sizes of colliding nuclei as well as their possible repulsion after collision. The angular momentum axis is assumed to be the X-axis. We believe this relative space configuration of the sources is suitable for investigating Coulomb and angular momentum effects. Pre-equilibrium emission of a few nucleons during the dynamical stage may decrease the excitation energy and relative velocity of the residues. These effects can be accounted for in the statistical approach by changing the corresponding input parameters, such as the mass number, charge, excitation energy, angular momentum, and relative velocity of the sources. In Table 1 , we present the parameters of the sources used in our calculations. The excitation energies of the sources are taken in the interval 2–7 MeV/nucleon. The angular momentum values are selected randomly in increasing order (see Table 1). The weights of the sources are estimated using the impact parameter dependence of the excitation energy and angular momentum transferred to the residues. The weights are normalized to unity.

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

We have investigated the influences of angular momentum and Coulomb field 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 interpreting many experiments on heavy-ion collisions at Fermi energies. After breakup of the sources, we calculate the Coulomb propagation of produced hot fragments by accounting for the Coulomb interactions of particles in the double system. To clarify the modification of the multifragmentation picture caused by these new effects and to compare it with experimental data in the future, we apply 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 the following assumptions: We consider sources obtained from the 84Kr projectile at different excitation energies—2, 3, 4, 5, 6, and 7 MeV/nucleon—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, 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 N /Z ratios corresponding to those of 84Kr+112Sn and 84Kr+124Sn, as in the experiment [30]. First, we performed SMM calculations for each source and determined the charge and isotope distributions and N /Z ratios of fragments in the presence of the second source (112,124Sn) both without and with angular momentum. Angular momentum values are randomly selected in increasing order (see Table 1). Subsequently, we took a 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 can obtain conditions suitable for comparison with experiments.

In Fig. 1 [Figure 1: see original paper], 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, angular momentum favors emission of large nearly symmetric fragments (similar to nuclear fission) since the system in freeze-out needs to have a large moment of inertia to minimize rotational energy and maximize entropy. This competes with the second source through Coulomb interaction, which prevents emission of IMFs with large charge numbers.

The initial neutron-to-proton ratio of the projectile source 84Kr is 1.33, while 1.28 and 1.42 correspond to the initial N /Z ratios of 84Kr+112Sn and 84Kr+124Sn, respectively. In Fig. 2 [Figure 2: see original paper], we see that angular momentum leads to increasing N /Z values of light IMFs in the case of strongly asymmetric decay. By increasing the moment of inertia of the system, it favors a larger phase space for the reaction [3]. This trend may be responsible for many isospin observables.

We show in Fig. 3 [Figure 3: see original paper] the variation of isotopic distribution for Z = 6, 12, and 18 for 84Kr+124Sn and 84Kr+112Sn 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 believe these new effects should be taken into account for realistic description of experimental data, e.g., FAZIA [30]. Possible modifications of the symmetry energy term can also be investigated through the isotopic distributions of projectile fragments. In previous works, calculations for Z = 6 (Z < 10 small fragments) agree well with data at $\gamma = 14$ (as in MSU and ALADIN analysis [24, 26]), for Z = 12 at $\gamma = 16$, and for Z = 18 with γ 19 [13]. In a forthcoming paper, we will present results of detailed analyses and interpretation of FAZIA [30] experimental data on the basis of the present calculations.

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

IV. CONCLUSION

In summary, we have theoretically investigated the charge and isotope distributions and N /Z values of fragments after multifragmentation of Kr-like projectiles in peripheral 84Kr+112,124Sn collisions around the Fermi energy within the microcanonical Markov chain approach based on the statistical multifragmentation model. Coulomb and angular momentum effects originating after 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. New fragment formation trends appear, such as asymmetry of IMF emission and increasing neutron content of light IMFs. These features are demonstrated after secondary de-excitation of hot fragments for formation of cold fragments, similar to previously analyzed reactions leading to production and decay of single isolated sources. We have presently introduced our preliminary results, and investigations of velocity distributions of fragments in this new approach to analyze 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 reveal a new connection between dynamical and statistical phenomena in nuclear reactions. We believe this may also provide inputs to understand the nuclear equation of state and nuclear composition, which are important for determining 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 experiments.

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Note: Figure translations are in progress. See original paper for figures.