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Theoretical analyses of FAZIA data with a statistical approach

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Summary. — We have performed systematical calculations on multifragmentation picture for peripheral ^{84}Kr+^{112,124}Sn collisions at an incident beam energy of 35 MeV/nucleon. In order to investigate the Coulomb and angular momentum effects for these reactions, the calculations are performed to reproduce the data for charge distributions of the fragments, on the basis of the microcanonical Markov chain approach within the statistical multifragmentation model.

1. – Introduction

In this short communication, we shall discuss the influence of angular momentum and Coulomb interactions between projectile and target like nuclei on the charge yields of fragments for peripheral ^{84}Kr+^{112,124}Sn collisions at 35 MeV/nucleon for FAZIA experiment [1]. To simulate the peripheral ^{84}Kr+^{112,124}Sn reactions, we consider the break-up of a single source ^{84}Kr in the neighborhood of a secondary source ^{112,124}Sn. The calculations were 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 [2-4]. This model version contains also ingredients taken from the standard SMM version developed in refs. [5]. We use the Markov chain of partitions to characterize the whole statistical ensemble. The individual fragment partitions and coordinate positions of fragments in the freeze-out volume are generated within this method. Partitions are selected according to the Metropolis algorithm. The decay channels are generated by the Monte Carlo method according to their statistical weights over 10^5 events. Thus, we take into account the influences of angular momentum and Coulomb interactions for each spatial configuration of primary fragments in the freeze-out volume in the same way used in refs. [3, 4, 6, 7]. In this work we have used the value of the freeze-out density as $\rho = \rho_0/6$ (here ρ_0 is the normal nuclear matter density) for better evaluation of Coulomb and angular momentum effects. These kinds of investigations are also important for construction of a reliable EoS of nuclear matter at subnuclear densities. One may expect that similar conditions occur during the collapse and explosion of massive stars and in the crust of neutron stars [8,9], where the Coulomb

TABLE I. – *Values for the sources assumed to be formed according to the peripheral collisions for* ^{84}Kr + ^{112,124}Sn *reactions.*

E_x (MeV/n)	Z_s	A_s (^{112}Sn)	A_s (^{124}Sn)	Weight	Ang. Mom. $\hbar$
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	40
6	29	66	70	0.08	40
7	28	64	68	0.03	40

interactions of the dense electron environment make the fragmentation picture fluctuate. In our previous studies, isospin composition of the produced fragments [10], charge and isotope yields, and correlations of various fragment properties were successfully described and compared with ALADIN data by the statistical ensemble approach [11-14] within SMM [5]. The results of our analysis of the experimental data of the MSU experiments at 50 MeV/nucleon [15] were given in refs. [16, 17]. In the following section, we will show the results of our new calculations together with angular momentum and Coulomb interaction effects between the projectile- and target-like sources.

2. – The angular momentum and Coulomb interaction effects for projectile fragmentation in peripheral collisions at Fermi energies

We study peripheral nucleus-nucleus collisions at 35 MeV/nucleon with the corresponding relative velocities between the projectile and target around 45–70 mm/ns. The projectile nucleons can interact with target nucleons at the initial dynamical stage of collision, as a result, pre-equilibrium particles can be observed due to this interaction of energetic products. The excitation energy of projectile and target residues may change and the relative velocity between the residues decreases as well. Later on, these excited target- and projectile-like sources decay. Since a characteristic time is around 100 fm/c for nuclear multifragmentation, projectile- and target-like sources will not be far (≈ 15 fm) from each other before disintegration. At these short distances the long-range Coulomb field of one of the sources influences the break-up of the other one. In this situation, we suppose that the multifragmentation of a double nuclear system is a new physical situation with respect to the standard multifragmentation of a single isolated source. Two excited sources in such a double system are determined by the short-range nuclear forces. The presence of an external Coulomb field may affect the composition of the produced fragments and their relative positions. An additional Coulomb barrier will prevent disintegration of the sources into many small pieces. In addition, 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 [2, 6]. In our approximation, we consider the sources obtained from ^{84}Kr projectile at different excitation energies: 2, 3, 4, 5, 6 and 7 MeV/n as shown in table I. Such a selection of the adequate ensemble of the sources is a quite effective way to describe the experimental data and make important physical conclusions within the statistical approach (see, *e.g.*, [11, 12]). We have taken two sources with the same charge and the same excitation energy, but with two different N/Z ratios corresponding to N/Z ratios of ^{84}Kr+^{112}Sn and ^{84}Kr+^{124}Sn, as in experiments [1]. Then, firstly, we made SMM calculations for

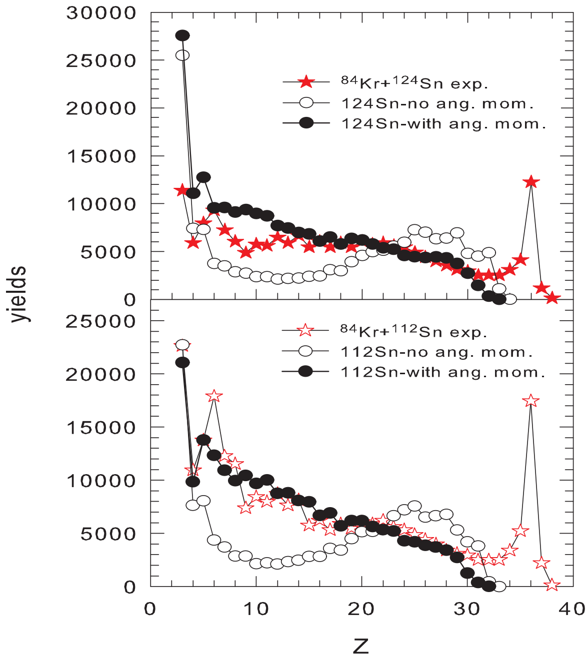

Fig. 1. – Comparison of the charge yield of fragments, in the case without (open circles) and with angular momentum (full circles). Red stars show FAZIA experimental data [1] for ^{84}Kr+^{124}Sn (top panel) and ^{84}Kr+^{112}Sn (bottom panel). These projectile-like sources are assumed to be formed in the peripheral collisions at 35 MeV/nucleon, and their disintegration are affected by the Coulomb field of the target source as shown in table I. The distributions are normalized in the region $Z = 18$–28 as in ref. [1].

each source and found charge and isotope distributions, N/Z ratio of fragments in the presence of second source (^{112,124}Sn) without and with angular momentum. In our previous theoretical study, we selected angular momentum values with a randomly increasing order (see table 1 in ref. [3]). In this study we have selected angular momentum values as average values (see table I). Afterwards, we have taken a mixture of all sources with weights (as shown in table I) corresponding to their excitation energies, which are related to the impact parameters. After this mixture was done, we directly compared with experimental data as shown in fig. 1. We show the total charge yields of cold fragments in the case with and without angular momentum conservation in fig. 1. Angular momentum values are selected as shown in table I. It is seen that the angular momentum favors the emission of large nearly symmetric fragments (like a nuclear fission) since the system in the freeze-out stage 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 from emitting an IMF with a large charge number. We have found very good agreement of experimental data with our predictions including Coulomb and angular momentum effects for ^{112,124}Sn. We do not consider small excitation energies ($E_x < 2\,\mathrm{MeV/n}$) since the detection of big projectile-like fragments is affected by a narrow acceptance angle of the apparatus. The grazing angle should be simulated within a dynamical approach, that is beyond the present work. Therefore, there are no peaks for $Z > 34$ in our calculations. Moreover, we think that this acceptance angle is also the reason of a strongly disturbed U-shape distribution of detected charges (in comparison with the typical smooth U-shapes observed in other experiments), and this cause us to decrease the weights of low excitations in our ensemble of the sources to reproduce the data.

3. – Conclusions

As a result, we have found 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. We also observed 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 cold fragments, similar to the previously analyzed reactions leading to the production and decay of the single isolated sources. Up to now, we have reported some preliminary encouraging results obtained with the help of the ensemble of residual sources in refs. [3, 4]. The present study is still in progress for velocity distributions of fragments and for the possibility to apply this new approach for the analyses of the experimental data at intermediate peripheral collisions such as the FAZIA data [1]. These investigations are important since they point out a new connection between dynamical and statistical phenomena in nuclear reactions. In the light of our theoretical results, we plan to construct a connection between the results of dynamical processes and statistical approach and we are willing to analyze the future experiments as well.

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