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Mass Distributions and Neutron-Proton Ratios of Fragments in Peripheral Heavy-Ion Collisions

Hamide AVCI*[1]

Abstract

The mass and average neutron-proton ratio (N/Z) distributions of fragments from multifragmentation of excited projectile nuclei formed in heavy-ion collisions were reproduced theoretically. The experimental measurements in peripheral heavy-ion collisions of ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn at 1 GeV/nucleon were carried out with the Fragment Separator (FRS) of GSI. The mass distribution and N/Z ratios of the produced nuclear fragments are calculated in the frame of a statistical approach. Comparisons with the experimental data show that the statistical models are successfully reproduce the mass yields and N/Z measured in the both reaction systems. The calculations in the present paper were carried out for the first time and were not published anywhere else.

Keywords: Mass yield, nuclear multifragmentation, neutron-proton ratio (N/Z)

1. INTRODUCTION

One of the most important aims of current research in the field of nuclear physics is to describe the behavior of nuclear matter at extreme conditions at high temperature and pressure at various densities (to determine the equation of state related to the symmetry energy). For this reason, the properties of nuclear matter at extreme conditions have been under investigations by various groups both experimentally and theoretically. The results of these studies can be used in a wide range of research areas such as radiotherpy (treatment planning), space research, isotope production etc. The results are also used as a tool to investigate the stellar matter at extreme conditions as a fundamental research subject in astrophysical studies. The supernova explosion mechanism and neutron stars modelling may be examples of this kind of studies.

In order to simulate nuclear multifragmentation reactions the liquid-gas phase transition theory is widely used. In this theory, it is assumed that the hot and dense nuclear matter is formed when two heavy-ion collide at high energies. Then this matter expands as a result of strong repulsive forces at short distances and enters subsaturation densities. In this case the density fluctuations of the matter leads the system to thermodynamical equilibrium. At the end of this process the matter disintegrates into nuclear hot fragments. When there are at least 3 intermediate mass fragments satisfying the condition Z ≥ 3. At saturation density $\rho_0 = 0.15 fm^{-3}$, and freeze-out density $\rho \approx \frac{\rho_0}{3}$. The low temperature region is defined as $T \approx 3 - 8\, MeV$. The properties of large and

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small hot particles can be studies with statistical models relying on the phase transition theory.

Beside statistical models, dynamical models such as Time Dependent Hartree Fock, Molecular Dynamics and Quantum Molecular Dynamics are also widely used in modeling the nuclear reactions and astrophysical events. Nucleation theory of nuclear matter can also be studied on the basis of macroscopic models which rely on Fisher nucleation model, and kinetic theory of Boltzmann and Boltzmann-Uehling-Uhlenbeck (BUU) equation. Presently, we consider statistical multifragmentation model in this calculations. So far the results based on the statistical multifragmentation model show that this model is found to be very successful for reproducing the experimental data of nuclear reactions at low and high energies [1- 7].

For the additional important references we can cite for mid-peripheral heavy ion collision experiments as [8]. We also refer to the experiments performed at relativistic projectile energies around 1 GeV/nucleon in the high-resolution magnetic spectrometer, the Fragment Separator (FRS) at GSI laboratories for the ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn reactions, and the experimental results [9]. In the present paper, FRS (FRagment Separator) experiments were theoretically analysed in the framework of statistical multifragmentation model.

2. MATERIALS AND METHODS

We know that in the statistical approach to analyse the nuclear reactions, there is a concept of equilibrium as described: a) There are few stages of reactions leading to multifragmentation. b) There is a short time around 100fm/c for primary fragment production. c) We assume that freeze-out low density should be around 0.1 -0.6 ρ_0 (here ρ_0 is the normal nuclear matter density) d) There is a high degree of equilibration at the freeze-out volume.

Various models can be used for the definition of peripheral heavy-ion collisions. In this study, we have used the statistical multifragmentation model (SMM) [4]. According to the SMM, when two heavy-ion collide, a compressed and hot blob of nuclear matter is formed. This dense and hot substance will expand due to repulsive nucleon-nucleon forces. It will then enter a low-density freezing zone and the system reaches a statistical equilibrium. According to this model all fragmentation channels are composed of nucleons. It assumes that the laws of conservation of energy, momentum, angular momentum, mass number A and charge number Z are taken into account. It also includes compound nucleus channels and the competition between all channels is permitted. The statistical weight of fragmentation channels is defined in the Microcanonical approach as follows:

$$W_j = \frac{1}{\xi}\exp\left(S_j\left(E^*, A, Z\right)\right) \tag{2.1}$$

where Sj is the entropy of the system in channel j and ξ is the normalization constant.

Accessible states of decay channels are created by the Monte Carlo method considering the statistical weight of these channels. In this approach the particles with A ≤ 4 are considered as elementary particles or gase particles. The fragments with A>4 are considered as hot liquid droplets. In this case, the coexistence of the phases in the freezing volume can be studied on the liquid-gas phase transition theory. To express the free energy one may utilize the Weizecker's semi-empirical formula. In this formula, the F_{AZ} of each fragment is the sum of the bulk, surface, Coulomb and symmetry energy contributions as shown below:

$$F_{AZ} = F_{A,Z}^{B} + F_{A,Z}^{S} + E_{A,Z}^{C} + E_{A,Z}^{sym} \tag{2.2}$$

The terms are defined as follows:

$$F_{A,Z}^{B} = -\left(W_0 + \frac{T^2}{\varepsilon_0}\right)A \tag{2.3}$$

where, T is the temperature, ε_0 is related to the level density (approx. 16 MeV at normal nuclear matter density), and W_0 is the binding energy of infinite nuclear matter ($16MeV$),

$$F_{A,Z}^{S} = B_0 A^{2/3}\left(\frac{T_c^2 - T^2}{T_c^2 + T^2}\right)^{5/4} \tag{2.4}$$

where B_0 is the surface energy coefficient (18MeV), and *Tc* is the critical temperature of infinite nuclear matter (18 MeV);

$$E_{A,Z}^{C} = c\frac{Z^2}{A^{1/3}} \tag{2.5}$$

where

$$c = \left(\frac{3}{5}\right)\left(\frac{e^2}{r_0}\right)\left(1-\left(\frac{\rho}{\rho_0}\right)^{1/3}\right) \tag{2.6}$$

is the Coulomb parameter get from the Wigner-Seitz approach with the charge unit e and r_0 = 1.17 fm;

$$E_{A,Z}^{sym} = \frac{\gamma(A-2Z)^2}{A} \tag{2.7}$$

where γ is the standard effective symmetry energy parameter (25 MeV). The parameters here are those in the Bethe-Weizsäcker formula and correspond to the conjecture of isolated fragments with normal density in the freeze-out configuration. These liquid drop paramaters including symmetry and surface terms should be reduced at low densities (for excited hot fragments) to reproduce the experimental data measured in the yields of fragments emitted from the heavy-ion collisions [5- 7].

3. RESULTS AND DISCUSSION

In the literature, important properties of nuclear multifragmentation have been studied in various studies. For examples; fragment multiplicity, charge distribution, mass distribution, isotopic distribution and isoscaling observables. In this study, we reproduced the fragment mass and neutron to proton ratio distributions in the ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn reactions performed at 1 GeV/nucleon at GSI laboratory. The initial neutron-to-proton ratios of these symmetrical systems are 1.24 and 1.48 for ^{112}Sn and ^{124}Sn, respectively. Now, we compare our results and experimental data [9]. In the calculations, the projectile and target nuclei were chosen to have the same N/Z so that isospin diffusions can be excluded. A statistical ensemble version of the SMM was used to define the properties of this isospin symmetric reaction systems. In our previous publication [10] we investigated the isotope and charge yields in the same reaction system of FRS experiments. Now, we have presently investigated mass yield and mean N/Z ratios of the fragmentation products of the same reactions. As for the comparison of our theoretical calculations and the experimental data, we normalized the data and predicted results with respect to the measured cross sections in the interval $20 \leq Z \leq 25$ as shown in Ref.[10]. The obtained factor was 0.00334 mb and 0.00344 mb per theoretical event for fragmentation of ^{124}Sn and for ^{112}Sn projectiles, respectively.

Figure 1 shows the present results that we obtained from the statistical ensemble calculations for the mass distribution of the final cold fragments in 500 000 reaction events. Here, red stars represent the experimental data and blue circles the theoretical predictions. Upper panel shows the mass distribution of the particles emitted from a neutron-rich projectile ^{124}Sn and lower panel the results for a neutron-poor projectile source ^{112}Sn.

The results were in agreement with the literature, that the U-shape of nuclear mass distributions were seen in Figure 1, both in upper and lower panels. Theoretical calculations for Z<10 are not shown in Figure 1. Because there is no experimental data that we can compare in this region. From these figures, one can see an agreement between theoretical and experimental values of the yields. Since the isotopes cannot be fully addressed in the experiments, such differences are, generally, observed in the distribution curves. See Refs [9, 11] for a comprehensive analysis of these differences.

Recently, we have carried out the calculations for weakly excited nuclear matter to reproduce the compound nuclei contribution at low excitation energies for Ex<1 MeV/nucleon [12]. In order to calculate the contribution of compound nuclei, the excitation energy interval was chosen, within weighting calculations, from 0 to 4 MeV per nucleon with the corresponding masses and charges of the excited source nuclei. Thus we demonstrated a connection of the compound nucleus regime with the multifragmentation regime.

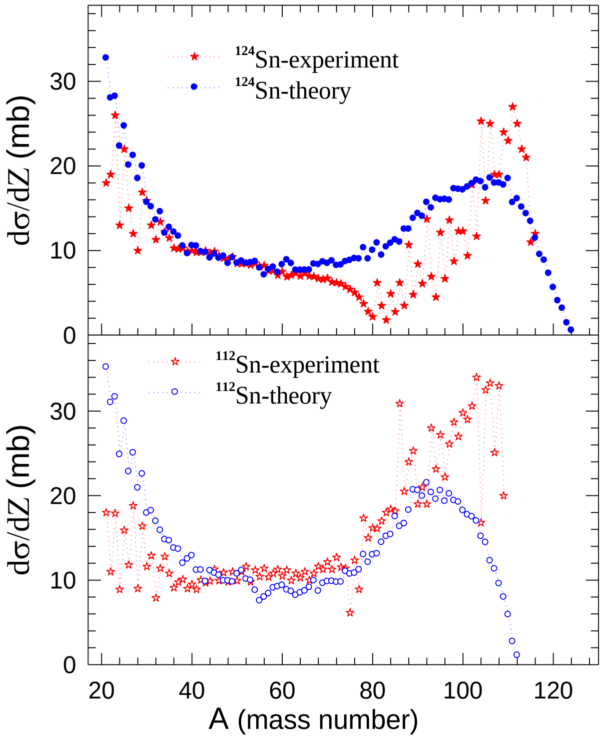

Figure 1 Production cross-sections of fragments emitted from two reaction systems as a function of mass number of the fragments

The final stage in the evolution of a highly excited nuclear system is the de-excitation stage of hot primary particles. Primary hot fragments are emitted from excited semi-projectile sources. This state in which all particles are considered hot can be described as "hot" fragmentation. When the system expands and the excitation of the hot primary particles is removed, cold fragmentation occurs. In the case of "cold" fragmentation the fragments preserve the Z/A ratio of initial nucleus. In contrast to that the "hot" fragmentation products, after the de-excitation stage, fall into the vicinity of the β-stability line, the so called exotic nuclei [4].

Figure 2 shows the present results that the average <N>/Z ratios of primary fragments (hot) and secondary fragments (cold) as a function of fragment charge number Z, in the interval $10 \leq Z \leq 25$. Upper panel shows the results for a neutron-rich projectile ^{124}Sn (full circles) and lower panel shows the results for a neutron-poor projectile source ^{112}Sn (empty circles). In this figure, red stars show the experimental result. Blue symbols show the theoretical calculations for cold fragments and red symbols show theoretical calculations of the hot fragments formed before de-excitation process. These systems have a large difference in neutron-to-proton ratios of the fragments emitted from their quasiprojectile sources. The differences between the N/Z values of the hot fragments in the upper and lower panels of Figure 2, are also higher than the differences between the N/Z values of the cold fragments. This stems from the large difference in the initial isospin asymmetry of the reaction systems and de-excitation processes.

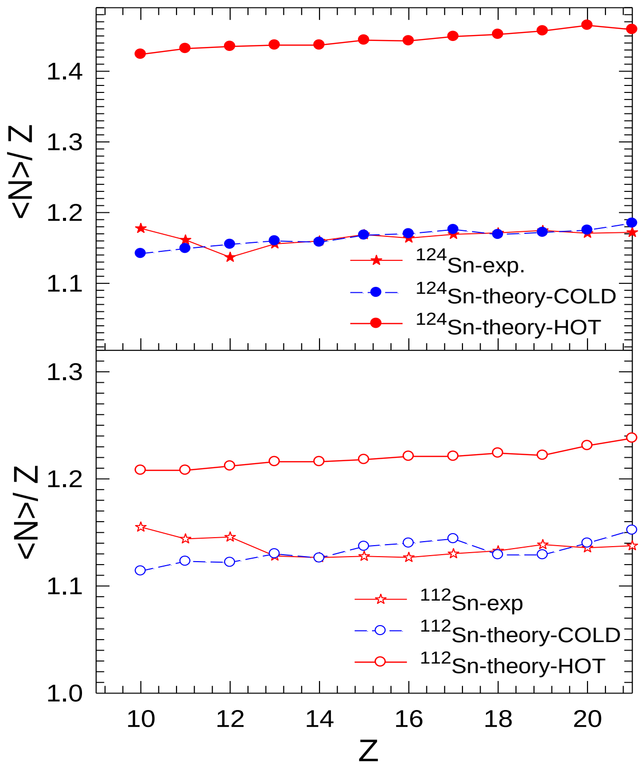

Figure 2 Mean N/Z values of the fragments emitted from two reaction systems

In the calculations of N/Z values we have used the reduced symmetry energy values for the optimization process in Ref. [10]. For a detailed discussion of the modifications of these model parameters in optimization calculations, we will refer the reader to Refs. [5, 13]. One can see in Figure 2 that, the most neutron-rich systems preferably populate the most neutron-rich isotopes, additionally the most proton-rich systems populate the most proton-rich isotopes. This result may be observed in Figure 2 that both in experimental and predicted theoretical calculation data. This is consistent with other findings in the literature (see e.g. Ref. [14]).

4. CONCLUSIONS

As a result, we have shown that statistical models successfully reproduce the experimental data for fragment production and mean N/Z values. It is remarkable that in the present calculations the isospin term (symmetry energy) is not subdivided into surface and volume parts, simply we have taken the effective values of the symmetry energy parameter into account as 25 MeV. One can see from the figures that there is a good agreement between theoretical and experimental results. We can argue that our results are in consistent with the existing studies in the literature [5-7, 10, 15]. It is shown in our calculations that the symmetry energy parameter should be reduced at low densities to be able to reproduce the experimental data. The effect of other liquid-drop parameters of nuclear matter are widely investigated in Ref. [5].

Consequently, our analysis of FRS experiments show that neutron-rich sources preferentially, produce neutron rich fragments when enough excitation energy is deposited in projectile nuclei. Thus, we have shown that the nuclear multifragmentation reactions become superior to produce neutron-rich and proton-rich isotopes, in relativistic energies (1 GeV/nucleon) [5, 9, 11], as well, as a continuation of the Fermi energy regime [16-18].

To investigate the properties of nuclear matter at extreme conditions in more details, further experiments are needed e.g., to extract information for the properties of neutron-rich exotic nuclei towards the neutron dripline in nuclear chart [19].

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