PROJECTILE FRAGMENTATION IN NUCLEAR REACTIONS AT FERMI ENERGIES*

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In this short communication, we have interpreted TAMU data for peripheral collisions of ^{40}Ca + ^{112,124}Sn and ^{48}Ca + ^{112,124}Sn at E/A = 32 MeV with different isospin degrees of freedom which were studied at the Cyclotron Institute of Texas A&M University (TAMU) using the K500 Superconducting Cyclotron. Isotopic yields of light intermediate mass fragments $Z \leq 8$, (here, we only consider carbon isotopes) were studied on the basis of the statistical multifragmentation model. It is seen from the fractional yields that the neutron-rich systems preferentially populate the most neutron-rich isotopes. It is confirmed that symmetry energy is the main parameter governing the isotopic composition of the fraction yields.

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1. Introduction

The isospin composition of the produced fragments in nuclear reactions has a particular importance because it can be used for determining the strength of the symmetry energy during fragment formation in the hot and diluted environment [1–4]. The nuclear symmetry energy and its density dependence were extensively studied by many groups through the heavy ion collisions in the Fermi energy regime to investigate the connection with the isospin part of the equation of state [5, 6]. Our theoretical analyses to date suggest that we can extract information about modification of fragment properties from the fragment yields [7].

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In this work, our theoretical analysis is based on the isotope production in TAMU data given in Ref. [5], which were measured in a number of nuclear reactions at various projectile and target N/Z, in the Fermi energy regime. In Ref. [5], the peripheral collisions of asymmetric systems ^{40,48}Ca + ^{112,124}Sn were analyzed to determine the degree of isospin N/Z equilibration in the Fermi energy regime. They compared the experimental results with model calculations within phenomenological DIT (deep inelastic transfer) and the statistical multifragmentation model (SMM), where the standard value $\gamma = 25$ MeV was used for symmetry energy parameter. However, in the present calculations, we used various values of γ according to the fact that γ tends to decrease for hot fragments at low density freeze-out. In this work, a microcanonical Markov-chain approach [8] based on the statistical multifragmentation model (SMM) [9] was used to perform the calculations for simulation of the decay of single projectile sources formed during the same reaction systems. In this model, it is assumed that a statistical equilibrium is reached at a low-density freeze-out stage. It includes all breakup channels composed of nucleons and excited fragments, and during each partitions, the laws of conservation of energy E^*, momentum, angular momentum, mass number A and charge number Z are considered. One can study the nuclear liquid–gas coexistence in the freeze-out volume. Free energies of each fragment are parameterized as a sum of the bulk, surface, Coulomb and symmetry energy contributions [9]. The symmetry energy for fragments is defined in the SMM as $E^{\rm sym}_{A,Z} = \gamma(A-2Z)^2/A$, where the symmetry energy parameter γ is a phenomenological coefficient and expected to reduce at low density freeze-out. In the microcanonical treatment, the statistical weight of a breakup channel is calculated as an exponential of the entropy of the system and the decay channels (partitions) are generated uniformly in the phase space by Monte Carlo method according to their statistical weights Refs. [9–11]. Actually, the present work may be considered as an extension of this analysis [12] for higher masses with more neutron-rich quasi-projectile sources produced from ^{40}Ca and ^{48}Ca projectiles at 32 MeV/nucleon.

2. Results of calculations and comparison with data

The peripheral collisions of four asymmetric reaction systems with different isospin components will be simulated according to the experimental analysis given in Ref. [5]. During the interaction between projectile and target nuclei, a projectile-like (quasi-projectile) and a target-like (quasi-target) single sources are assumed to be formed as a result of the exchange of nucleons. In order to determine the mass and atomic numbers ($A_{\rm s}$ and $Z_{\rm s}$) of the quasi-projectile single sources for each reactions studied in Ref. [5], we follow the fragment yield ratio and fitting procedure approach defined in this reference. In this way, we determine the values of Z_s, N_s and A_s for the single sources as (Z_s, N_s) = (16, 18), (16,19), (16,21) and (16,23) for the reactions ^{40}Ca+^{112}Sn, ^{40}Ca+^{124}Sn, ^{48}Ca+^{112}Sn and ^{48}Ca+^{124}Sn, respectively.

In this section, our theoretical predictions for isotope yields were compared to the data given in Ref. [5]. Since the cold fragments are the detected ones in experiments, we consider cold fragment distributions in the present calculations to make a comparison to the data. We discussed the properties of isotopic yields for hot fragments in details somewhere else [7]. These secondary decays include evaporation, fission, and Fermi-break-up processes. The modification of fragment properties under freeze-out conditions are taken into account in the description of low energy reactions [9,13]. In particular, the modification of symmetry energy is crucial in the first deexcitation steps.

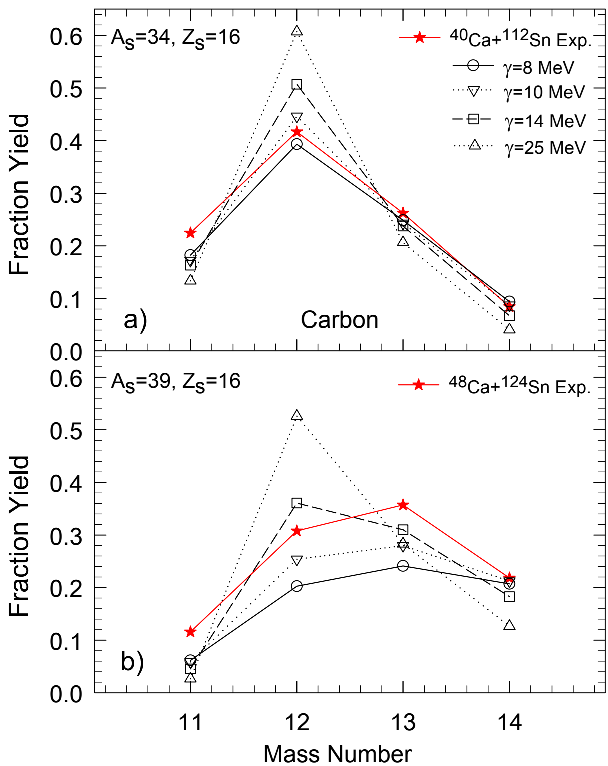

Fig. 1. Variation of fractional yield (for carbon) with mass number of the fragments at various values of symmetry energy parameter γ at $E_x = 5$ MeV/nucleon: (a) neutron poor, (b) neutron-rich systems.

For the quantitative comparison of theory and TAMU data, the microcanonical Markov-chain calculations of fragment yields were normalized to one (relative fractions) as was done for experimental results in Ref. [5]. In Fig. 1, we show the variation of fractional yield (for carbon) with mass number of the fragments at various values of symmetry energy parameter γ at $E_x = 5$ MeV/nucleon. First, we compare our results obtained within the microcanonical Markov-chain SMM version [8] to the experimental data in Fig. 2. In this figure, we show the experimental fractional yields for carbon fragments emitted from the four reaction systems in the Fermi energy regime Ref. [5], and predicted yields of the fragments from the multifragmentation of the sources presumably formed during the reactions. It is seen from Fig. 2 that the neutron-rich sources (with higher N/Z) populate the most neutron-rich isotopes in the neutron-rich side of the isotopic curves.

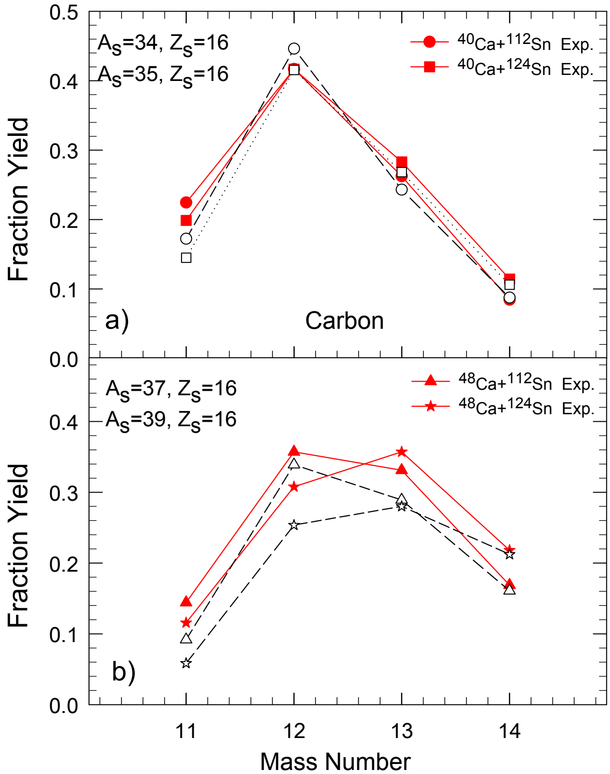

Fig. 2. Experimental fractional yields for carbon fragments, and predicted yields of the fragments (empty symbols) from the multifragmentation of the sources assumed to be formed during the reactions at $\gamma = 10$ MeV and $E_x = 5$ MeV/nucleon: (a) neutron poor, (b) neutron-rich systems.

This is in agreement with the experimental data of Refs. [5,14]. Both panels show that our secondary cold fragment distributions produced at a reduced gamma value less than $\gamma = 14$ MeV are in a close agreement with the experimental data. This was already obtained in previous analyses through the isoscaling, N/Z, and isotopic yield [2,3]. In Fig. 3, we also show the experimental and predicted values of isobaric fragment yield ratios for the isobaric pairs with $A_{\mathrm{f}} = 6$, 7, 14, and 16 obtained from the fragmentation of four reaction systems. In particular, one may see that ^{7}Li/^{7}Be is very high since ^{7}Li is much more neutron-rich than ^{7}Be. This new approach was used in Ref. [5] for determining the N/Z of the quasi-projectiles.

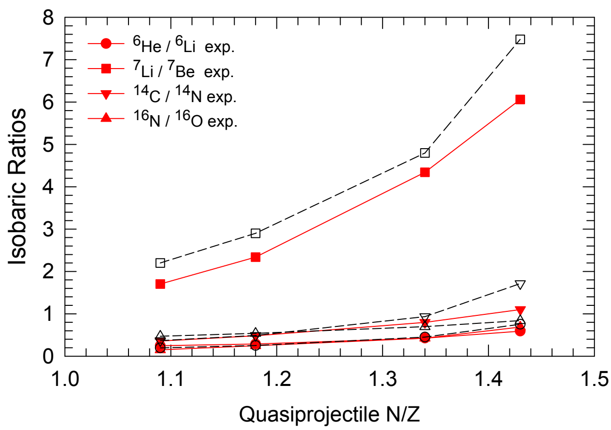

Fig. 3. Experimental isobaric yield ratios (full squares, circles and triangles) plotted as a function of the quasi-projectile system N/Z, and theoretical results (empty symbols) based on the Markov-chain calculations as described in the text, at $E_x = 5$ MeV/nucleon and $\gamma = 10$ MeV.

As a result, symmetry energy is seen to be the main model parameter governing the mean N/Z values and the isotopic composition of the fragment yields in order to reproduce experimental data. Extracted information from the analyses of experiments of this kind will be particularly useful for the studies of exotic nuclei far from stability and for understanding the nuclear composition in astrophysical objects. These studies may also be important for probing the isospin part of the nuclear effective interactions in microscopic calculations to obtain macroscopic properties of the collisions in the Fermi energy regime.

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REFERENCES

[1] A. Ono *et al.*, *Phys. Rev. C* **68**, 051601(R) (2003).

[2] A. Le Fèvre *et al.*, *Phys. Rev. Lett.* **94**, 162701 (2005).

[3] R. Ogul *et al.*, *Phys. Rev. C* **83**, 024608 (2011).

[4] H. Imal, A. Ergun *et al.*, *Phys. Rev. C* **91**, 034605 (2015).

[5] A.L. Keksis *et al.*, *Phys. Rev. C* **81**, 054602 (2010).

[6] D.V. Shetty, S.J. Yennello, G.A. Souliotis, *Phys. Rev. C* **76**, 024606 (2007).

[7] N. Buyukcizmeci *et al.*, *J. Phys. G: Nucl. Part. Phys.* **39**, 115102 (2012).

[8] A.S. Botvina, I.N. Mishustin, *Phys. Rev. C* **63**, 061601(R) (2001).

[9] J.P. Bondorf, *et al.*, *Phys. Rep.* **257**, 133 (1995).

[10] A.S. Botvina, A.S. Iljinov, I.N. Mishustin, *Sov. J. Nucl. Phys.* **42**, 712 (1985).

[11] A. Ergun *et al.*, *Phys. Rev. C* **92**, 014610 (2015).

[12] S.N. Soisson, *et al.*, *J. Phys. G: Nucl. Part. Phys.* **39**, 115104 (2012).

[13] N. Eren *et al.*, *Eur. Phys. J. A* **49**, 48 (2013).

[14] D.V. Shetty *et al.*, *Phys. Rev. C* **68**, 054605 (2003).