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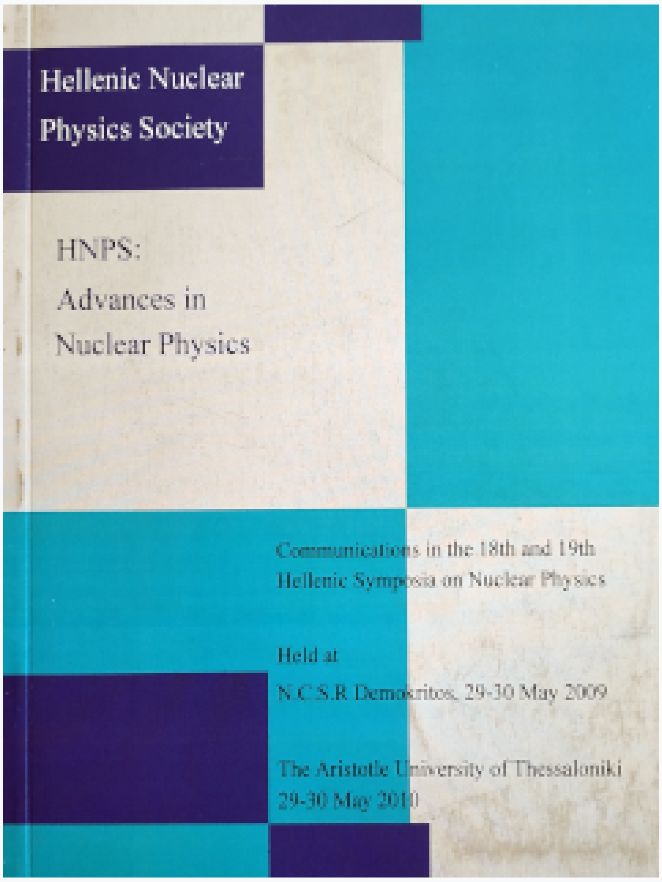

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Isoscaling of mass $A \simeq 40$ reconstructed quasiprojectiles from collisions in the Fermi energy regime

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Abstract

Isoscaling studies of fragments with Z=1-8 from reconstructed quasiprojectiles of mass $A \simeq$40 from the ^{40}Ca + ^{112,124}Sn and ^{40}Ar + ^{112,124}Sn reactions at beam energy of 45 MeV/nucleon were performed. After initial efforts to obtain isoscaling using pairs of systems differing in their neutron-to-proton ratio N/Z, "intra-system" isoscaling for each of these four systems was obtained using fragment sources restricted in two narrow N/Z zones, one neutron rich and one neutron poor. The observed isoscaling behaviour was excellent and the isoscaling parameter α was found to decrease as the excitation energy increases. Corrections due to undetected neutrons were also taken into account in the source N/Z determination by using the theoretical models DIT (Deep Inelastic Transfer) and SMM (Statistical Multifragmentation Model) along with a software replica of the experimental setup. The reduced isoscaling parameter α/Δ was found to decrease as the excitation energy of the quasiprojectile source increases, in good agreement with recent work on reconstructed mass $A \simeq 80$ quasiprojectiles. This decrease of α/Δ may point to a decrease of the symmetry energy coefficient with increasing excitation energy.

Keywords: Heavy-ion reactions; Isoscaling; reconstructed quasi-projectiles;

1. Inroduction

The nuclear equation of state (EOS) determines the relationship between energy, temperature, density and isospin asymmetry for a nuclear system and is divided into an isospin symmetric contribution ($N \approx Z$) and a symmetry energy part, quadratically dependent on isospin asymmetry [1]. The symmetry energy expressing the energy difference between symmetric nuclear matter and pure neutron matter is not adequately constrained away from the normal nuclear density. The symmetry energy is important in a number of astrophysical topics like the structure and cooling of neutron stars and the dynamics of supernova explosions, as well as in nuclear physics issues like the structure of nuclei away from the the valley of stability. Information on the symmetry energy has been

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extracted from the neutron skin, elastic scattering of neutron rich nuclei and from heavy ion collisions [2]. One observable sensitive to the symmetry energy is fragment isotopic compotition investigated in the isoscaling approach [2, 3]. In the isoscaling, which refers to an exponential relation between the yields of a given fragment from two similar reactions which differ only in their isospin asymmetry (N/Z), the effects of the nuclear symmetry energy are isolated in the fragment yield ratios, allowing access of the symmetry energy coefficient during the formation of hot fragments [3].

2. Experiment, analysis and results

The experimental work was performed at the Cyclotron Institute of Texas A&M University. Beams of ^{40}Ar and ^{40}Ca ions of 45 MeV/nucleon were delivered by the K500 superconducting cyclotron and interacted with isotopically enriched ^{112}Sn and ^{124}Sn targets. Fragments produced in peripheral and semi-peripheral collisions were detected by the FAUST multi-detector array. Details on the experimental setup can be found in Ref. [4].

The event-by-event particles detection providing the opportunity to isotopically and kinematically reconstruct the primary fragments. Since FAUST is a charged particle detector, neutrons cannot be detected. As a result, the reconstructed events may have the right atomic number but smaller than the actual mass number, due to the inability of neutron loss. To ensure selection of fragments coming from the decay of quasiprojectiles, the parallel velocity component (with respect to the beam direction) of each individual fragment was required to be greater than the velocity of the c.m. of the projectile-target system. The main criterion for QPs selection was that the total Z of the reconstructed event be close to the Z of the projectile. For the ^{40}Ar+^{124,112}Sn systems the Z range chosen was Z_{QP}=12-21, whereas for the ^{40}Ca+^{124,112}Sn, the corresponding range was Z_{QP}=14-23. Due to limitations in the number of pages of this article, only the ^{40}Ar+^{124}Sn and ^{40}Ca+^{124}Sn systems will be presented. In the upper parts of each panel in Fig. 1, the velocity vs Z_{event} distributions for the reconstructed events are presented, along with the boxes which indicate the Z ranges of the QPs. The lower parts of each panel show the Z_{event} distributions. The intense peaks appear at Z_{event}=5-7 are due to incomplete reconstruction of the selected QPs. The yield ratio $R_{21}(N, Z)$ of a given fragment produced in two similar reactions that differ in the isospin content can exhibit isoscaling which has been observed experimentally [2] and obtained in theoretical studies [3]. Isoscaling occurring when the two reactions take place at the same temperature and differ only in their in the isospin asymmetry according to the relation

$$R_{21}(N, Z) \equiv \frac{Y_2(N, Z)}{Y_1(N, Z)} = C \exp(\alpha N + \beta Z) \ , \qquad (1)$$

where $Y_2(N,Z)$, $Y_1(N,Z)$ are the fragment yields from the neutron rich and the neutron deficient source respectively, α and β are the scaling parameters and C is an overall normalization factor. It is common to consider reaction 2 as the

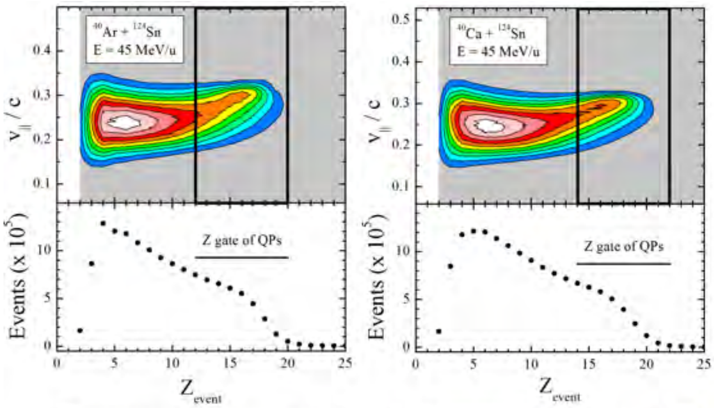

Figure 1: (Color online). Distributions of $v_{||}/c$ versus Z_{event} in the upper part of each panel and Z_{event} distributions in the lower part of each panel, (see text).

neutron rich source, while reaction 1 as the neutron deficient one. The isoscaling parameter α is related to the symmetry energy coefficient C_{sym} of the nuclear binding energy through the relation [5],

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right] \equiv \frac{4C_{sym}}{T}\,\Delta\ , \qquad (2)$$

where, (Z_1,A_1) and (Z_2,A_2) are the charge and mass numbers from the two systems respectively and T their common temperature. This relation provides the link between the measurable quantities and the nuclear symmetry energy coefficient. It should be pointed out that the parameter α refers to the hot primary fragments which undergo sequential decay into cold secondary fragments, while the parameter Δ represents the difference in the neutron-to-proton composition of the two sources considered in the isoscaling approach.

In this work, we investigated the isoscaling behavior of fragments with Z=1-8. The isoscaling approach of using pairs of systems differing in their N/Z ratio was not good (for details see [6]). In order to improve the isoscaling behavior, our approach was to perform the isoscaling for each system separately using as sources a neutron-rich and a neutron-poor N/Z zone with sufficient statistics. The $(N/Z)_{QP}$ zones for the ^{40}Ar+^{124}Sn reaction were 1.05-1.09 (neutron-rich) and 0.91-0.95 (neutron-poor), while for the ^{40}Ca+^{124}Sn were 1.04-1.08 and 0.92-0.96 respectively, as can be seen in Fig. 2 From the mean N/Z values of the two N/Z zones for each system, the values of the Z/A of the sources were calculated, along with the difference Δ in equation (2). Employing the yields of the fragments from the two QPs sources for each system, the “intra-system” isoscaling behavior was studied in detail. At first, the yield ratios of the fragments from the above mentioned neutron rich and neutron poor QPs sources were investigated for all systems under study. It was found that the yield ratios of the fragments of of the same element as a function of the neutron number can

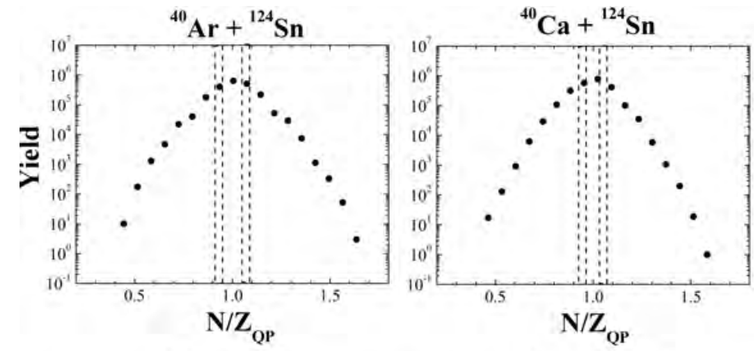

Figure 2: (Color online). Distributions of N/Z of the reconstructed QPs for $^{40}Ar+^{124}Sn$ and $^{40}Ca+^{124}Sn$ reaction systems. In each panel, the dashed lines indicate the two narrow $(N/Z)_{QP})$ zones employed in the isoscaling procedure (see text).

be fit by a straight line the slope of which gives the isoscaling parameter α, see Eq. (1). As a next step, the isoscaling for each reaction system was performed at eight excitation energy bins from 1.5 to 8.5 MeV/nucleon with a step of 1 MeV. At each excitation energy bin, the yield ratios of the fragments of the same element were fitted by straight lines whose slopes provide the isoscaling parameter α. As can be seen in Fig. 3, the fit lines are parallel and equidistant in the semilogarithmic plots, indicating an excellent isoscaling behavior. In the upper panel of Fig. 3, the isoscaling of the corresponding reactions is presented without excitation energy cuts.

The isoscaling parameter α is related to the symmetry energy coefficient C_{sym} through (2), which is now written in the form $\alpha/\Delta = 4C_{sym}/T$, where α/Δ is the reduced isoscaling parameter. The α/Δ parameter was determined for each reaction under study. However, the neutrons produced in the reactions could not be detected by the experimental setup. For this reason, Δ has to be corrected for neutron loss. The correction in Δ was performed employing the theoretical models DIT (Deep Inelastic Transfer) and SMM (Statistical Multifragmentation Model), along with the Faust filter software which takes into account the geometry of the setup and the energy thresholds of the detectors used in the experiment.

Using the corrected Δ values along with the isoscaling parameters α, the corrected reduced isoscaling parameter α/Δ was determined at each excitation energy bin. The values of α/Δ as a function of the quasiprojectile excitation energy for each system are shown in Fig. 4 As we see in the left panel of Fig.4, the values of the corrected α/Δ decrease as the excitation energy of the QPs increases for all reaction systems studied in this work. Also, the values of α/Δ obtained in our recent work on mass $A \simeq 80$ show the same trend in good agreement with the results of the present work. We note that the N/Z correction procedure followed was based on measured neutron multiplicities, whereras in this work was performed via the DIT/SMM/filter simulation procedure.

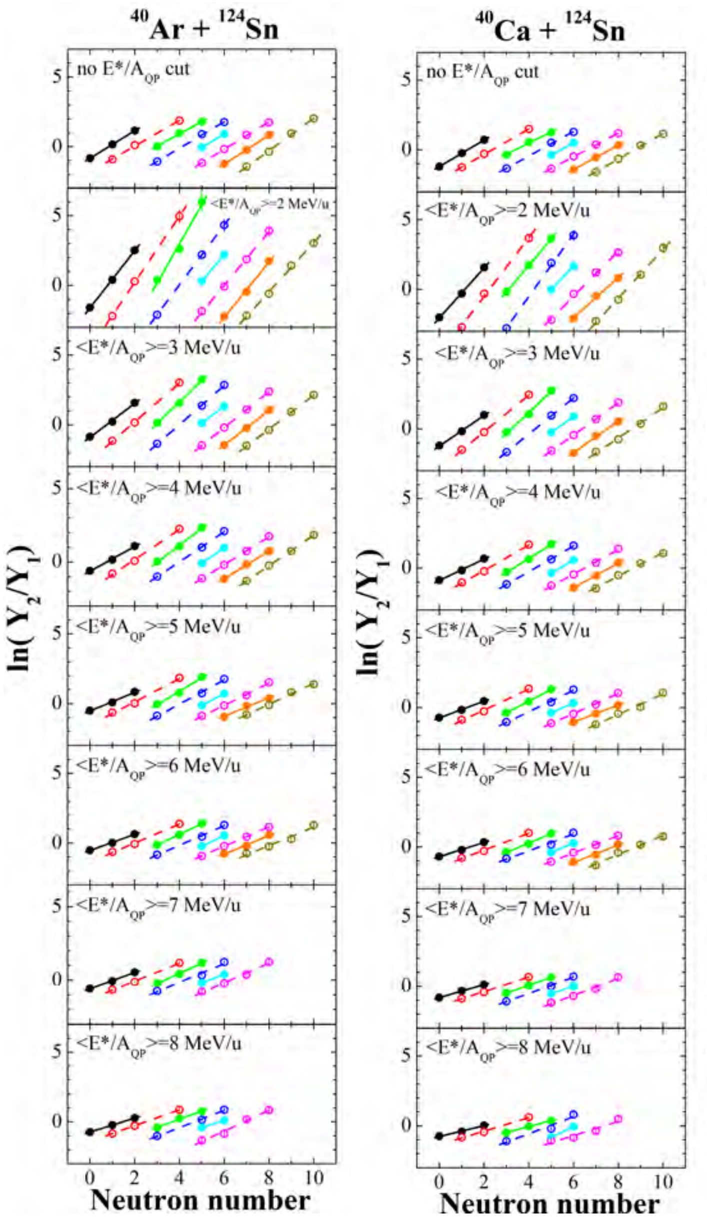

Figure 3: (Color online). Iosotopic yield ratios of fragments from reconstructed sources (quasiprojectiles) for the ^{40}Ar+^{124}Sn and ^{40}Ca+^{124}Sn reactions at 45 MeV/nucleon. The isoscaling was performed using fragments from the neutron-rich and neutron-deficient N/Z bins for 8 excitation energy bins (see text). In the upper panels, the isoscaling without the excitation energy cuts is presented for comparison.

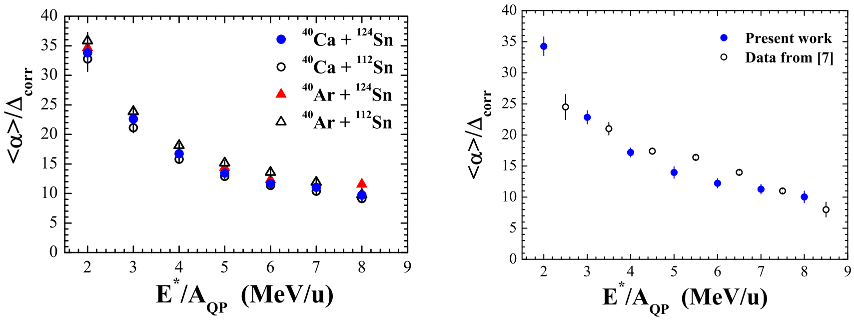

Figure 4: (Color online). Left panel: Reduced isoscaling parameter α/Δ as a function of the excitation energy of the fragmenting sources for the four systems studied in this work. Right panel: Comparison of the averaged value of α/Δ parameter obtained from data of this work with corresponding data from [7].

3. Summary

In this work, a systematic study of fragment isoscaling in reconstructed QPs of mass $A \simeq 40$ obtained in peripheral collisions of ^{40}Ca + ^{124,112}Sn and ^{40}Ar + ^{124,112}Sn reactions at 45 MeV/nucleon. Intra-system isoscaling for each reaction system was performed using as QPs sources two narrow N/Z regions (one neutron-rich and one neutron-poor). The isoscaling behavior was excellent and the isoscaling parameter α was found to decrease with increasing excitation energy. Correction for neutron loss of the N/Z of the sources was performed and was applied to the determination of the parameter Δ. The reduced isoscaling parameter α/Δ was found to decrease with increasing the excitation energy of the QPs source, in good agreement with the recent work on reconstructed mass $A \simeq 80$ QPs [7]. This consistent decrease of α/Δ may indicate a possible decrease of the symmetry energy coefficient with increasing excitation energy.

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