Isoscaling and nuclear temperature studies of reconstructed quasiprojectiles from peripheral and semiperipheral collisions in the Fermi energy regime

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One of the important observables in heavy – ion collisions is the isotopic composition of the detected fragments investigated in the isoscaling approach [1]. In this approach, the nuclear symmetry energy effects are isolated in the fragment yields allowing us to study the symmetry energy in the formation of hot fragments [2,3]. The isoscaling effect refers to an exponential relation between the yields of a given fragment (N,Z) from two reactions which differ in the isospin asymmetry N/Z [4] of the primary hot fragments and is expressed by 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, Y_1 are the fragment yields from a neutron rich and a neutron deficient system respectively, α and β are the scaling parameters and C is an overall normalization factor. In the present work, the isoscaling effect is investigated for the case of fragments emitted during the de-excitation of quasi-projectiles (QPs), in different $(N/Z)_{QP}$ zones of the same reaction. In this way, the isoscaling parameter α is determined as a function of the excitation energy. The systems studied in this work are $^{40}Ca+^{112,124}Sn$ and $^{48}Ca+^{112,124}Sn$ at the beam energy of 45 MeV/u. The measurements were performed at the K500 Cyclotron accelerator of Texas A&M University and the projectile fragments were detected using a forward array for particle detection (FAUST) [5] and A.L. Keksis *et al.*, during his PhD dissertation [6].

The experimental determination of the QPs for each reaction can be obtained from the plots of the atomic number Z of the reconstructed events as a function of the parallel component of their velocities

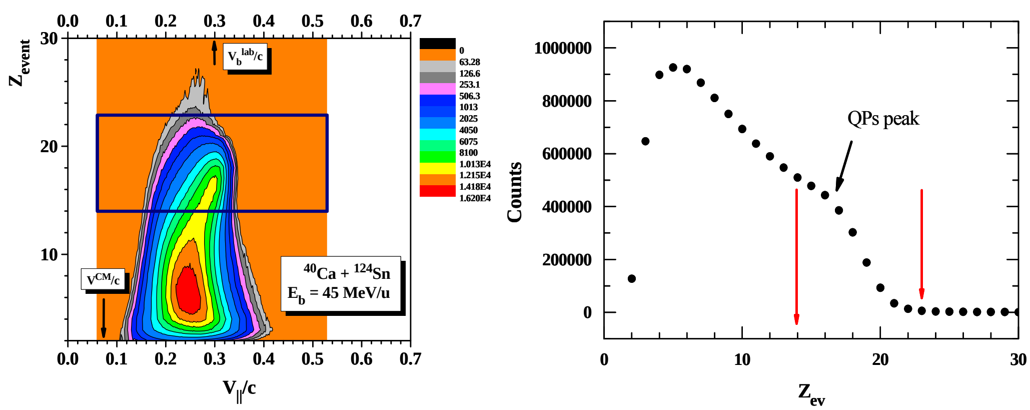

Figure 1. (Color online) Left panel: Selection of the reconstructed QPs from Z-V_z/c contour plot for the reaction $^{40}Ca+^{124}Sn$ at 45 MeV/u. Right panel: Charge distribution of the reconstructed events. The quasiprojectiles are characterized by Z_{QP}=14-23 (red arrows).

with respect to the beam axis at the beam energy of 45 MeV/u. QPs are also characterized by velocities greater than the velocity of the center of mass system, $V_{QP}>V_{cm}$. The charge of the reconstructed events of the reaction $^{40}Ca+^{124}Sn$ is plotted as a function of the parallel component of their velocity with respect to the beam axis in Fig. 1 (left panel). To display better the reconstructed QPs peak, the same plot is presented in three dimensions (right figure). From plots like this in Fig. 1, one defines the Z gate for the QPs. Similar behaviour was noted for the other reactions under study.

Since the charge numbers of the QPs are known, it is possible to get the region of the N/Z ratios for the QPs as a function of the excitation energy. A typical plot of the $(N/Z)_{QP}$ ratios versus the excitation energy is shown in Fig. 2, where characteristic zones of different N/Z_{QP} ratios are observed.

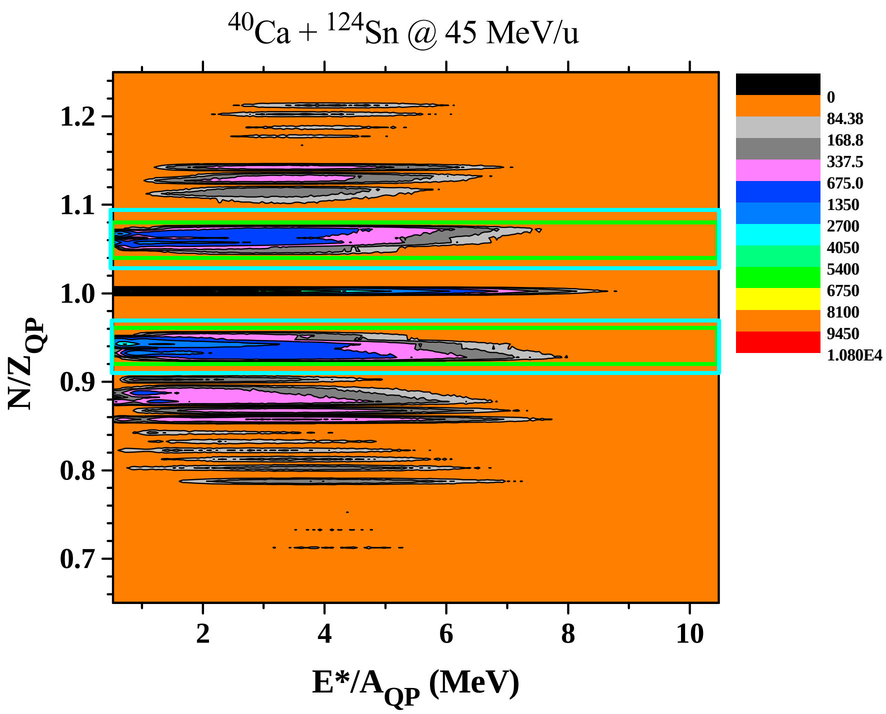

Figure 2. (Color online) N/Z ratio of the quasiprojectiles as a function of the excitation energy. The two green rectangulars represent the N/Z regions (0.92 – 0.96 and 1.04 – 1.08) used in the isoscaling. The same procedure was repeated for a wider $(N/Z)_{QP}$ range 0.91 – 0.97 and 1.03 – 1.09 light (blue rectangles)

To get the isoscaling parameter α for each excitation energy and for each element, two different N/Z_{QP} zones were selected and the yields ratio R_{21} for the isotopes obey, in logarithmic form, the expression

$$R_{21}(N) \propto \exp(\alpha N) \tag{2}$$

Applying eq. (2) for the detected isotopes of each element up to Oxygen (which was the heaviest element could be isotopically identified) and for each excitation energy region up to 8 MeV/u, we were able to extract the parameter α values as a function of the excitation energy, as implied by eq. (2), performing a linear fit to the experimental yield ratios for each element. Typical yield ratios of projectile fragments along with the straight line fits to the data points at the excitation energy window 3.5 – 4.5 MeV/u is shown in Fig. 3.

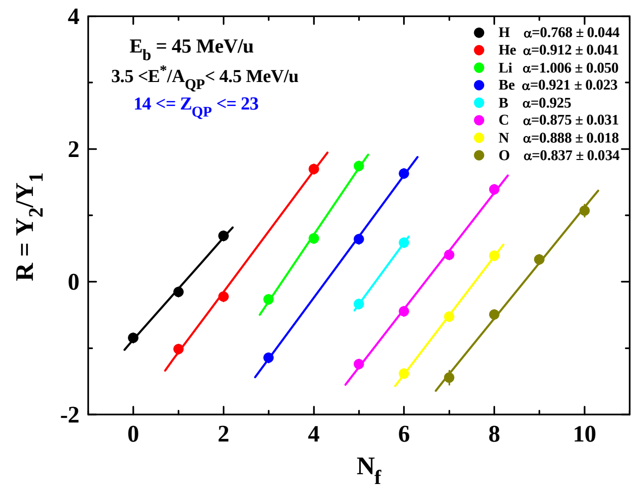

Figure 3. (Color online) Yield ratios $R=Y_2(N,Z)/Y_1(N,Z)$ of projectile fragments from primary fragments (QPs) with N/Z ratios $(N/Z)_2=1.04 - 1.08$ and $(N/Z)_1=0.92 - 0.96$ taken from the reaction $^{40}Ca+^{124}Sn$ at the energy of 45 MeV/u.

To further examine the sensitivity of the isoscaling parameters to the selection of two different $(N/Z)_{QP}$ regions, the observable $\xi = \langle\alpha\rangle/\Delta$ used, where $\Delta = (Z/A)_1^2 - (Z/A)_2^2$ was determined from the experimental data. In Fig. 4, it is shown that the ratio $\langle\alpha\rangle/\Delta$ is independent on choice of $(N/Z)_{QP}$ region and its value decreases as the excitation energy increases.

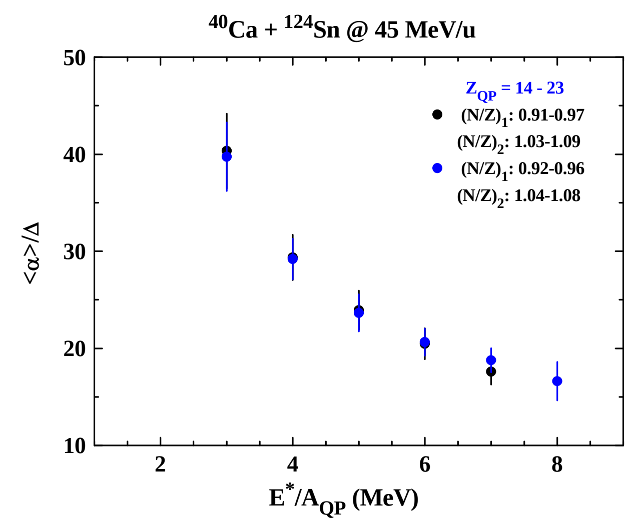

Figure 4. $\langle\alpha\rangle/\Delta$ measurements for different $(N/Z)_{QP}$ regions (blue and black dots) as a function of the excitation energy for the reaction system $^{40}Ca+^{124}Sn$ at the beam energy of 45 MeV/u (see text).

The isoscaling parameter α, the nuclear temperature T and the difference in proton fraction squared of the sources Δ as a function of the excitation energy are related with the symmetry energy coefficient C_{sym} [4] via the expression $\alpha T = 4C_{sym}\Delta$. It is thus important to investigate the excitation energy dependence of the nuclear temperature. The experimental determination of the nuclear temperatures was carried out using the double isotope ratios method. The isotope yield ratio thermometer requires the yields of four isotopes and is obtained from [7]

$$T = \frac{B}{\ln(\alpha \cdot R)} \qquad (3)$$

where, B is a binding energy parameter, α is the statistical factor that depends on the statistical weights of the spins of nuclei involved in the calculation and R is the isotope yield ratio given by the expression

$$R = \frac{Y(A_1, Z_1)/Y(A_1+1, Z_1)}{Y(A_2, Z_2)/Y(A_2+1, Z_2)} \qquad (4)$$

Using the eqs. (3) and (4) and different isotope pairs in the denumerator of eq. (3), namely d, t and ^{12}C, ^{13}C, the nuclear temperature was determined as a function of the excitation energy. It is important to note

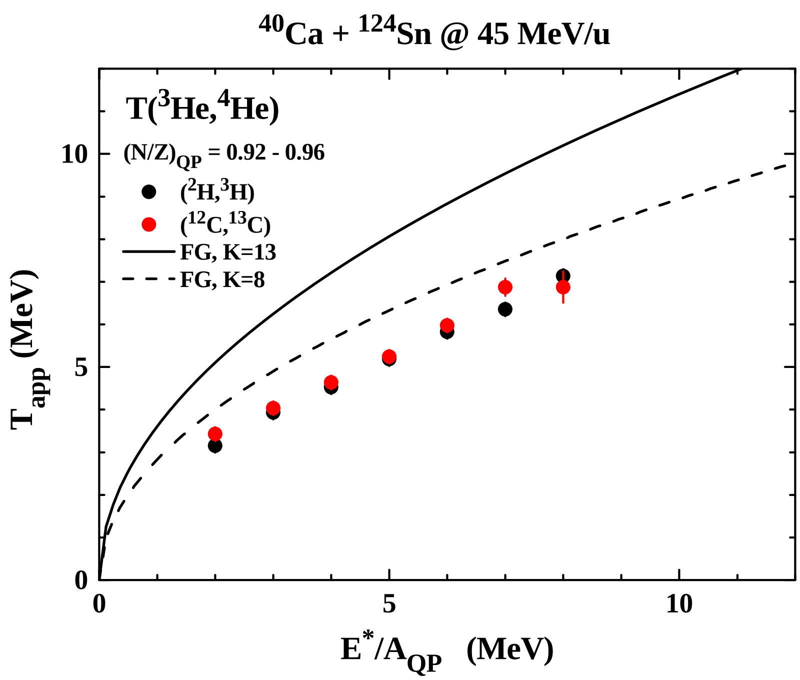

Figure 5. (Color online) Apparent isotope temperatures T(^{3}He,^{4}He) derived from (^{2}H,^{3}H) and (^{3}He,^{4}He) isotope pairs as a function of the excitation energy for the $(N/Z)_{QP}$ region 0.92 – 0.96. The agreement between the two thermometers (black and red dots) is obvious. The solid and dashed lines are the predictions of the Fermi-gas model with inverse level density parameter K=13 and 8 respectively. Similar behaviour is observed for the other reactions under study.

at this point that the measured temperatures in Fig. 5 are not corresponding to the temperature of the source (quasi-projectiles), since corrections for sequential decay of the quasi-projectiles have not taken into account yet.

We plan to investigate the relation among the isoscaling parameter α, nuclear temperatures T and the symmetry free energy F_{sym}. Moreover, statistical and dynamical codes will be used and comparisons with the data will be made.

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