Isoscaling from quasiprojectiles in $^{48}\text{Ca} + ^{112,124}\text{Sn}$ reactions at 45 MeV/A

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Abstract

The yield of intermediate mass fragments (IMFs) $Z=3\text{-}7$, emitted in damped $^{48}\text{Ca} + {}^{112,124}\text{Sn}$ reactions at 45 MeV/A, is used to study the isoscaling. The measured yield ratios of these fragments are found to obey the exponential law of isoscaling. Inclusive yield of IMFs was subjected to a cut on the out of plane data ($\cos(\theta) \leq 0.4$), which is assumed to contain, primarily statistical component of fragment yields. The observed isoscaling behaviour do not show any significant sensitivity to the angle cut in the present study. Another constraint on the relative velocity between IMFs and projectile remnants ($1.0 \leq v_{rel}/v_c \leq 2.0$), which ensures the origin of two fragments to be fast moving quasiprojectile (QP) only, also do not show any significant change in the isoscaling parameters. Finally, assuming similar temperatures ($T$) in the two reactions, ratios were scaled with saddle point energies using the expression $\exp(\Delta B/T)$, which gives an estimation of the size and temperature of the decaying system in the two cases.
I. INTRODUCTION

Study of intermediate mass fragments (IMFs) in multifragmentation reactions has been widely used as a tool to understand the nuclear reaction mechanisms [1–3]. In the last one decade, such studies have been extended to explore the isoscaling phenomenon in those reactions [4–7]. Isoscaling is considered as a vital tool to calculate the symmetry energy term in the nuclear equation of state, which along with exploring the reaction dynamics has relevance in astrophysical applications.

In general, isoscaling is observed by comparing the isotopic yield of fragments from reactions having isotopically different projectiles and/or targets at similar temperature. The ratio $R_{21}(N, Z)$, of yields of a given fragment has an exponential dependence on neutron ($N$) and proton ($Z$) numbers of the fragment and the relation is described as,

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

where, three parameters, $C$, $\alpha$ & $\beta$ describes the overall isoscaling behaviour. The index 2 corresponds to neutron rich source and 1 to neutron poor.

Isoscaling has been observed in a variety of nuclear reactions, multifragmentation, evaporation and damped collisions [4, 8–10], where fragment (IMFs or heavy fragments) yield ratios are compared either from the projectile fragmentation or target fragmentation or the fragments arising from a central collision. Isoscaling parameters $\alpha$ or $\beta$, are then used to calculate the symmetry energy coefficient, $C_{sym}$ using the following expressions,

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

$$\beta T = \frac{4C_{sym}}{A} \left[ \left( \frac{N}{A} \right)_1^2 - \left( \frac{N}{A} \right)_2^2 \right],$$

where $Z$, $N$ and $A$ are the protons, neutrons and mass numbers of the decaying systems in two reactions.

Even though experimental investigations of isoscaling phenomenon have progressed to calculate the symmetry energy coefficient and its implications on the equation-of-state of nuclear matter but there are many assumptions in reaching that goal. For example, non-statistical emission of particles in such studies is assumed to be negligible or it cancels out in the ratios. However, it is possible to check the validity of such assumptions by looking at the
isoscaling for out of plane reaction events, as these events are expected to have negligible non-statistical component. Out of plane is defined by the normal to reaction plane and the break-up axis of the QP while reaction plane is defined by the beam axis and the direction of QP [11]. Also without complete reconstruction, it is practically impossible to know the exact source of IMF emission.

The common signature of isoscaling studies is to use two different reactions, one having neutron rich projectile and target as compared to the other of a given element. However, Souliotis et al., had measured the isoscaling from projectile residues Z=10-36 from $^{86}$Kr arising from different reactions at 25 MeV/A. The observation of isoscaling in intermediate energy region, using the yields of IMFs from the decay of similar & excited quasiprojectiles, originating after the interaction of same incident heavy ion beam with different targets having different N/Z ratios, is not yet established.

To the best of our knowledge, this is the first such study, where, we have measured the isoscaling from the QP splitting in the two reactions, $^{48}$Ca + $^{124}$Sn & $^{48}$Ca + $^{112}$Sn at 45 MeV/A of lab energy. Based on the above discussion, we have studied isoscaling subjected to various cuts on inclusive data, which would help us verifying some of the above assumptions. The scaling of yield ratios with the expression exp($\Delta B/T$), shows that isoscaling is followed from the ground state mass differences of the decaying systems. Such measurements offer a new dimension to study the isoscaling phenomenon.

II. EXPERIMENTAL DETAILS

Experiment was carried out using the K800 cyclotron at Laboratori Nazionali del Sud (LNS), Catania, Italy. Isotopically enriched, self supporting targets of $^{124}$Sn & $^{112}$Sn having thicknesses of 689 $\mu$g/cm$^2$ & 627 $\mu$g/cm$^2$ respectively, placed inside the Charged Heavy Ion Mass and Energy Resolving Array (CHIMERA), were bombarded with $^{48}$Ca beam of 45 AMeV energy. The pulsed beam had a repetition rate of 120 ns. The CHIMERA array, arranged in 4$\pi$ geometry, consists of 1192 $\Delta$E-E (Si-CsI(Tl)) telescopes, which covers $\simeq$94% of the total solid angle. Each telescope consists of 300 $\mu$m thick silicon detector while CsI(Tl) detectors have different thicknesses as a function of polar angle. More details about the array can be found in Refs. [12–14].

Energy calibration for silicon detectors was carried out using various beams like $^{12}$C, $^{16}$O from MP Tandem accelerator at different energies. Data acquisition was set to trigger on
minimum bias condition of $\geq 2$. This hardware condition combined with various other cuts in offline analysis, ensures the origin of events to be QP only.

FIG. 1. Correlation contours for different elements taken from $^{48}$Ca + $^{124}$Sn reaction

Reaction products were characterized in charge (Z), mass (A) and energy using the energy, timing and light output information obtained from $\Delta E$-$E$ telescopes. Data collected in the forward region ($6.0 \leq \theta \leq 20.0$) were used in the present study. A 2-dimensional correlation plot of the raw data, showing a very good isotopic separation for different elements from $Z = 1$-$8$ is shown in Fig. 1.

III. RESULTS AND DISCUSSION

In order to get the yield of different isotopes from the two reactions, the two dimensional $\Delta E$-$E$ distributions were linearized using a calculation of the distance between the data point
and the two closest chosen lines [7]. Fig. 2 shows one such plot for the Li-isotopes obtained from $^{48}\text{Ca} + ^{124}\text{Sn}$ reaction.

![Li isotope plot](image)

**FIG. 2.** Li-isotopes taken from $^{48}\text{Ca} + ^{124}\text{Sn}$ reaction

Red line is the Gaussian fit to various isotopes. Within the defined angle cut ($6.0 \leq \theta \leq 20.0$), yield of isotopes of different elements ($Z=3-7$) was integrated over the entire set of data from the two reactions. Shown in Fig. 3 is the normalised yield of Li isotopes from the two reactions. The difference in yields for different isotopes is clearly visible in this figure.

Isoscaling was observed after fitting the experimentally obtained yields of various IMFs with Eq. (1). Fig. 4 shows the isoscaling lines for different isotopes. The value of isoscaling parameter $\alpha$ was found to be independent of fragment $Z$, which if found otherwise, could be considered as a signature of strong surface dependence of the symmetry energy [15]. The $\alpha$ values for different fragments are shown in Fig. 5. A straight line trend of global scaling of
FIG. 3. Normalized yield of Li-isotopes. Lines are drawn to guide the eye. Except for $^9$Li isotopes in the two reactions, error bars are smaller than the symbol size.

yield ratios, which is defined as,

$$S(N) = R_{21}(N, Z) \exp(-Z\beta) = C\exp(\alpha N),$$

is considered as a test of goodness of the isoscaling behaviour. Such trend for the present data is shown in Fig. 6. Clearly, all isotopes of different IMFs follow a straight line trend.

Global scaling of yield ratios shows a good agreement with a single value of $\alpha$ (0.240) and $\beta$ (-0.122). It is clear from eq. (2) that beside excitation energy, magnitude of $\alpha$ also depends on difference in composition (N/Z) of the two decaying systems. As discussed before, isoscaling in the present study is observed from the decay of similar QP, after the interaction of projectile beam of $^{48}$Ca with different targets, which may be the reason behind the smaller value of $\alpha$ as compared to existing works [4, 5, 7].

As a next step, a cut on the relative velocity between the IMF and projectile remnant
(1.0 ≤ \(v_{rel}/v_c\) ≤ 2.0) was applied to study the isoscaling. Importance of such cut lies in eliminating the contamination from target, if any, as those events are expected to have a large relative velocity. However, no appreciable change in isoscaling parameters, \(\alpha\) (0.256) & \(\beta\) (-0.127) was observed using such a cut.

Isoscaling was also studied for out of plane events. An out of plane angle cut (\(\cos(\theta) \leq 0.4\)), was used to study the isoscaling. As discussed already, importance of such gating lies in eliminating the any possible contamination of the data by non-statistical component. Such tests are useful in verifying one of the main assumption of isoscaling analysis that dynamical effects cancels out in ratios & isoscaling is the result of events arising from the statistical split only. Again the parameters were found immune to the angle cut and values extracted from the fits are \(\alpha\) (0.254) & \(\beta\) (-0.136).

Assuming the Weisskopf formalism [16] of particle emission probability (\(\Gamma\)) to be valid
FIG. 5. Variation of \( \alpha \) with fragment \( Z \). Global value used is shown by straight line.

for IMFs,

\[
\Gamma \propto e^{\Delta S},
\]

(5)

where \( \Delta S \), change in entropy is calculated as,

\[
\Delta S = S_{saddle} - S_{eq} \simeq -Q/T.
\]

(6)

\( S_{saddle} \) represents entropy at saddle point and \( S_{eq} \) is the entropy at equilibrium configuration of touching spheres. Using the above values of entropy in Eq.(5) gives

\[
\Gamma \propto e^{exp(-Q/T)} = exp(B/T),
\]

(7)

because, binding energy (B) is equal to negative of Q-value of a reaction.
Assuming similar temperature for the two quasiprojectiles from $^{48}$Ca + $^{124}$Sn & $^{48}$Ca + $^{112}$Sn systems, yield ratios would become a function of binding energy differences as,

$$R_{21} = \frac{\Gamma_2}{\Gamma_1} \simeq \exp\left(\frac{(B_2 - B_1)}{T}\right) = \exp\left(\frac{\Delta B}{T}\right). \quad (8)$$

$B_2$ & $B_1$ represents binding energies of IMFs from neutron rich and neutron poor system, respectively. After incorporating the Coulomb correction to above expression, a search was made for the Z & A of the two possible nuclei, whose decay would follow the experimental yield ratios. The possible candidates found are $Z_1 = 25.9$, $A_1 = 69.7$, $Z_2 = 23.0$ & $A_2 = 59.9$. Values of fit parameters, $a_1$ (0.874), $a_2$ (0.376), where $a_1$ is a constant and $a_2$ is the inverse of temperature. Using the sizes and temperature calculated from the fit, $C_{sym}$ was found to be 18.5 MeV. A semi-log plot of scaling of experimental ratios with eq.(8) for these two nuclei is shown in Fig. 7.
IV. SUMMARY AND CONCLUSION

We have measured the isoscaling from the projectile fragmentation of $^{48}$Ca arising out of $^{48}$Ca + $^{124}$Sn & $^{48}$Ca + $^{112}$Sn reactions at 45 AMeV. Yield ratios of various isotopes ($3 \leq Z \leq 7$) were found to obey the exponential law of isoscaling. Data were subjected to the relative velocity cut, so as to ensure the origin of the events to be projectile only. The parameters of the fit $\alpha$ & $\beta$ do not show any significant dependence on the velocity cut. No appreciable change in the parameters was observed for the fit to out of plane data, which either proves the validity of the assumption of cancellation of dynamical effects in ratios or it may also lead to an interpretation that isoscaling is not so sensitive to such effects at all. The method of scaling of yield ratios with binding energy difference was tried assuming same temperature for both the systems. The extracted values of $Z$ & $A$ of two nuclei shows a sizeable exchange/transfer of nucleons/cluster between the projectile and target. Even
though in no way these numbers are absolute, but they still offer a unique opportunity to look at reaction dynamics in a new perspective. Clearly, before moving to correlate the isoscaling parameters to symmetry energy term and equation of state (EOS), we need to answer the basic question of the exact source and temperature of the decaying system and present study is first step toward those answers.