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Symmetry energy and isoscaling property of fragments emitted in ^{14}N, ^{20}Ne + ^{112,116,124}Sn at 18-30MeV/nucleon

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The study of the symmetry energy term in nuclear equation of state (EOS), has been one of the most prominent research topics in nuclear astrophysics, both in the theoretical and experimental domains in the last decade. The importance of the symmetry energy lies on its dependence on nucleon density which finally determines the reaction rates involving electrons and neutrinos, particle abundances, and other factors in astrophysical scenarios like supernova dynamics, proto-neutron star evolution, the r-process, the long-term cooling of neutron stars, and the structure of cold-catalyzed neutron stars. The coefficient of symmetry energy, C_{sym}, can be measured from the isotopic compositions of the emitted fragments, through isoscaling property. It is basically a property of identical fragments emitted in reactions with different isospin asymmetry by which the ratio of the isotopes show an exponential dependence on N and Z of the isotope. Two reactions, 1 and 2, having the same temperature T, will exhibit isoscaling behavior if the ratio R_{21} of the yields of a particular isotope having neutron and proton number N and Z respectively, emitted from the two reactions have an exponential relationship of the form,
\begin{equation}
\tag{1}
R_{21}=\dfrac{Y_2(N,Z)}{Y_1(N,Z)}= C exp{(\alpha N+\beta Z)}
\end{equation}
where, $Y_2(N,Z)$ and $Y_1(N,Z)$, are the yields of the isotope from the neutron rich system and neutron deficient system, respectively, C is the normalization constant, α and β are the isoscaling parameters. The parameter α and β have a relationship with C_{sym}, which is derived on the basis of statistical models, where the emitted fragments are considered to be at saturation density,
\begin{equation}
\tag{2}
\alpha =\dfrac{4C_{sym}}{T} \left[{\left(\dfrac{Z_{1}}{A_{1}}\right)}^2 -{\left(\dfrac{Z_{2}}{A_{2}}\right)}^2\right]
\end{equation}
where T is the common temperature for both systems; Z_1, A_1 and Z_2, A_2 are the atomic and mass numbers of the two multifragmenting systems.

In this paper, we shall show the dependence of symmetry energy on excitation energy (E^*) from the study of isoscaling property of intermediate mass fragments (IMF). The availability of the first beam at the K500 superconducting cyclotron has enabled such investigations over a range of excitation energies at VECC, Kolkata. The experiment was conducted using neon ion beams with energies 18 and 22 MeV/ nucleon, as well as nitrogen ion beams with energies of 19 and 30 MeV/ nucleon. Enriched ^{112}Sn ($\sim$ 2.6 mg/ cm^2), ^{116}Sn ($\sim$ 2.23 mg/ cm^2) and ^{124}Sn ($\sim$ 2.81 mg/ cm^2), were used as targets. Fragments produced in the reactions ^{20}Ne + ^{112,116,124}Sn and ^{14}N + ^{112,124}Sn, were detected isotopically using silicon strip ΔE - E detector telescopes. Experimentally obtained yields of different fragments have been normalized with the incident number of particles and number of target nuclei per unit area. The isotopic yield ratios of each element emitted from the reacting systems were plotted with neutron number N and fitted individually using Cexp(αN), while the isotonic yield ratios were plotted with atomic number Z and fitted with C$'$exp(βZ). It was observed that isoscaling is well respected by the IMFs emitted in all reactions across the excitation energy range studied. The fitted parameters for both plots were found to be nearly identical.

Accurate determination of C_{sym} from the isoscaling parameters requires precise measurements of the nuclear temperature of the composite systems formed during the nuclear reaction. In this study, two independent methods were employed to calculate the nuclear temperatures: the double isotope ratio method and the Fermi gas model. The values of C_{sym} at a particular excitation energy were extracted using the average values of α and β at that energy. The values obtained are approximately $\sim$ 26–20 MeV using the temperature from the Fermi gas model and $\sim$ 24–17 MeV using the double isotope ratio method, for E/*A = 2.1 - 2.8 MeV. A decreasing trend of* C_{sym} *with excitation energy is observed for E*/A $>$ 2 MeV, consistent with previous studies. However, an anomaly is observed at E/*A = 1.8 MeV, which may be attributed to the reduction or absence of multifragmentation below* E/A = 2 MeV.

The experimental results were compared with the isospin-dependent hybrid model of nuclear multifragmentation [S. Mallik and G. Chaudhuri, Nucl. Phys. A 1002, 121948 (2020)]. In this model, the initial stages of the reaction, where the projectile and target fuse, is taken care of by dynamical approaches. The fragmentation of the excited system is described by a statistical model. The model calculation involves three distinct stages: The initial stage of the reaction is studied using the Boltzmann-Uehling-Uhlenbeck equation in an isospin-dependent transport model (BUU@VECC-McGill). Pre-equilibrium emission in the early stages can influence the yields of the emitted fragments. Therefore, excitation and isospin asymmetry of the compound nuclear system, formed after the dynamical stage are determined by considering 98\% of the total mass, with the remaining part attributed to pre-equilibrium emission. The Canonical Thermodynamical Model (CTM) is then applied to analyze the fragmentation of the compound nuclear system, using the excitation energy (E*) and isospin asymmetry obtained from stage (i). (iii) Finally, the secondary decay of the excited fragments produced in stage (ii) is studied using the evaporation model based on Weisskopf's formalism. The freeze-out volume in the calculation is assumed to be three times the normal volume of the compound nuclear system. The model satisfactorily reproduces the experimental results,* C_{sym}*, at E*/A = 2.1, 2.6 and 2.8 MeV, but fails for 1.8 MeV. The experimental value of C_{sym}, E/*A =1.8 MeV, much less that the theoretical value, which may be due to reduction or vanishing of multifragmentation below E* = 2 MeV/nucleon.

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