Symmetry Energy and the Isoscaling in Reactions on Enriched Tin Isotopes*

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Abstract—The coefficients of symmetry energy term for fragments with \( Z = 4, 11, 12 \) measured in multifragmentation reactions initiated by proton and deuteron with energy of 3.65 \( A \) GeV on enriched tin isotopes \( ^{112,118,120,124}\text{Sn} \) are determined. The dependence of isoscaling parameter on the excitation energy, the temperature of fragmenting systems and the density ratio for heavy mass products are analyzed.

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1. INTRODUCTION

In the last few years investigations of isoscaling phenomenon in nuclear reactions in liquid-gas phase transition region have been of large interest. This is accounted for by the use of isoscaling parameter in obtaining information about symmetry energy in nuclear equation of state (EOS) in regions away from normal density conditions [1–7]. Besides the nuclear point of view such investigations are also of great importance for understanding some processes in astrophysics, in particular, in supernovae explosions and neutron stars [8–11].

The isotopic effect was observed by Bogatin et al. [12–14] for reactions induced by protons, deuterons, and \( \alpha \) particles of incident energies between 660 MeV and 15.3 GeV on \( ^{112,124}\text{Sn} \) targets. The dependence of yields of photonuclear reactions and nucleon–nuclear reactions on values of third projection of isospin of target and product nuclei was investigated in our previous works [15–18].

In a series of recent papers the scaling properties of cross sections for fragment production with respect to the isotopic composition of the emitting systems were investigated [19–21]. It has been shown, that the yield ratio of a given isotope produced in two reactions with different isospin asymmetry exhibits an exponential dependence on proton and neutron number. This observation known as isoscaling has been identified in a variety of reaction mechanisms, including multifragmentation process:

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

where \( Y(N, Z) \) is the yield of a fragment with \( Z \) protons and \( N \) neutrons; indices “1” and “2” correspond to different targets with different isotopic compositions, with “2” corresponding to neutron-rich target; \( C \) is a normalization coefficient. The parameters \( \alpha \) and \( \beta \) were expressed using the difference of chemical potentials of the two systems as follows: \( \alpha = \Delta \mu_n/T \) and \( \beta = \Delta \mu_p/T \) [20], where \( T \) is the temperature of the excited nucleus.

Based on the statistical interpretation of isoscaling, the coefficient of the symmetry term in the nuclear mass can be extracted using isoscaling parameter [7, 22].

The aim of this paper is to obtain the coefficient of symmetry energy term in multifragmentation reactions by using the values of isoscaling parameters for fragments in \( Z = 4, 11, 12 \) charge region in proton- and deuteron-induced reactions with energy of beams 3.65 \( A \) GeV on enriched tin targets \( (^{112,118,120,124}\text{Sn}) \).

2. EXPERIMENTAL DETAILS AND DISCUSSION

The targets of tin isotopes \( ^{112,118,120,124}\text{Sn} \) (enrichments—92.6, 98.7, 99.6, 95.9%, respectively) were irradiated at the Nuclotron and Synchrotron of the JINR (Joint Institute for Nuclear Research at Dubna) by proton and deuteron beams with the energy of 3.65 \( A \) GeV. The description of the experiment is given in [23].

Isoscaling. In our previous studies of the nuclear reactions induced by protons with energies of 0.66, 3.65, and 8.1 GeV, deuterons \((E = 3.65 \text{ A GeV})\), and \( ^{12}\text{C} \) ions \((E = 2.2 \text{ A GeV})\) on targets of tin...
isotopes the isoscaling behavior was shown using the induced-activity method [17, 18] and it was described in terms of the third component of the fragment isospin $t_3 = (N - Z)/2$. The isotopic ratio of the product formation cross sections has been considered in the following form:

$$R_{21} = Y_2(N, Z)/Y_1(N, Z) = \exp(C + Bt_3), \quad (2)$$

where $C$ and $B$ are fitting parameters. The parameter $B$ is related to the difference of the chemical potentials of neutrons of the two fragmenting systems ($B = 2\alpha$, where $\alpha$ is a coefficient in Eq. (1)). A similar form of description of isotopic dependency of the yields of products in the reactions initiated by protons and light ions with energies of 0.66 to 15.3 GeV on the separated tin isotopes was used in [7].

In this paper we discuss multifragmentation products with $A = 7–28$ to find the symmetry coefficient $\gamma$. The discussions of experimental values of cross-section ratios of fragments produced in reactions induced by protons and deuterons with the 3.65 A GeV incident energy on enriched tin isotopes was used in [7].

Figure shows the isoscaling exhibited by fragments $^7$Be, $^{22}$Na, $^{24}$Na, $^{28}$Mg measured in the reactions of $p$ and $d$ on $^{112,118,120,124}$Sn.

The values of fitting parameter $B$ obtained from experimental data (for target pairs $^{124}$Sn/$^{112}$Sn) are $0.57 \pm 0.02$ and $0.55 \pm 0.07$ for proton- and deuteron-induced reactions, respectively, which is in agreement with the values extracted from other multifragmentation reactions [19–21].

3. EXCITATION ENERGY, TEMPERATURE, SYMMETRY ENERGY

In the recent years the interest in isoscaling of the reaction products has considerably increased, motivated by the possibility to extract information on the symmetry energy of hot nuclei and nuclear matter during the liquid-gas phase transition.

Investigation of isoscaling allows us to obtain the symmetry energy coefficient $\gamma$ in the symmetry term in the equation of state. It has been shown [7, 20] that the symmetry energy in the statistical model calculations is related to the isoscaling parameter $\alpha$ ($B = 2\alpha$) through the relation

$$\alpha T = 4\gamma(Z_1^2/A_1^2 - Z_2^2/A_2^2), \quad (3)$$

where $\alpha$ is the isoscaling parameter for the hot primary fragments, i.e., before their sequential decay into cold secondary fragments; $Z_1$, $A_1$ and $Z_2$, $A_2$ are the charges and mass numbers of the two fragmenting systems; $T$ is the temperature of the systems; $\gamma$ is the symmetry energy coefficient.

Usually the temperature $T$ is obtained from the double ratios of cross sections of two light isotopes formed in multifragmentation process, such as $^3$He/$^6$Li, $^{4.6}$He/$^{6.8}$Li, $^{6.8}$He/$^{6.8}$Li [7].

In the present work the temperature of the fragmenting system has been determined by unconventional methods. We use the expanding Fermi gas model predictions according to which dependence of temperature $T$ on the excitation energy $E^*$ of emitting source is the following (see [1] and references therein):

$$T = [K_0(\rho/\rho_0)^{0.69}E^*]^{0.5}, \quad (4)$$

where $K_0 = 10$ is the inverse level density parameter. The value of degree for density ratio is taken from [1, 2] ($\rho$ and $\rho_0$ are the densities of the hot and normal nuclear systems, respectively, $\rho_0 \sim 0.15$ fm$^{-3}$).

The excitation energy of the source for each beam was determined using the standard two-step vector model. We determine the recoil properties of nuclei with “thick-target thick-catcher” experiment using the induced activity method [24]. The quantities measured were the fractions $F$ and $B$ of product nuclei that recoil out of the target ($^{118}$Sn) foil in forward and backward directions related to the beam. The value of the forward velocity $v_{\|}$ was determined, which can be used to obtain the average cascade deposition energy (excitation energy $E^*$). The relation between the excitation energy $E^*$ and value of the forward velocity $v_{\|}$ can be estimated as

$$E^* = 3.253 \times 10^{-2} \cdot k' A_v (T_p/(T_p + 2))^{0.5}, \quad (5)$$

where excitation energy $E^*$ and bombarding energy $T_p$ are expressed in terms of $m_p c^2$; $A_v$ is the target mass in u, and $v_{\|}$ is in units of (MeV/u)$^{1/2}$. The constant $k'$ has been evaluated by Scheidemann and Poril [25] on the basis of Monte-Carlo cascade calculations as $k' = 0.8$.

Mean excitation energy for light isotopes $^{24}$Na and $^{28}$Mg is 591.5 and 535.4 MeV for proton- and deuteron-induced reactions, respectively [24]. According to INC calculations the residual mass number of the system after cascade process $A_{res} \approx 106$ for the $^{118}$Sn target, since mean number of the emitted particles at energy $E_p = 3.65$ GeV is equal to 13 ($\Delta A = n_p + n_n = 13$), and $A_{res} = A_t + 1(2) - \Delta A$ [26]. Mean excitation energy per nucleon is $E^*/A_{res} \approx 5.58$ MeV.

For deduced density ratio $\rho/\rho_0$ we used excitation energy $E^*$ dependence of the density $\rho/\rho_0$ obtained for reactions with fragmenting system mass $A \approx 100$ in [1]. In that work on Fig. 10 experimental points obtained for $^{58}$Fe + $^{58}$Fe, $^{58}$Fe + $^{58}$Ni, and $^{58}$Ni + $^{58}$Ni reactions at beam energies of 30, 40, and 47 A MeV are shown. For comparison, there are also shown the