ISOSCALING IN NECK FRAGMENTATION*

E. De Filippo[a], F. Amorini[b], A. Anzalone[b], L. Auditore[c], V. Baran[d], I. Berceanu[d]
J. Blicharska[e], J. Brzychczyk[f], B. Borderie[g], R. Bougault[h], M. Bruno[i]
G. Cardella[a], S. Cavallaro[b], M.B. Chatterjee[j], A. Chbihi[k], M. Colonna[b]
M. D'Agostino[i], R. Dayras[l], M. Di Toro[b], J. Frankland[k], E. Galichet[g,b]
W. Gawlikowicz[f], E. Geraci[i], F. Giustolisi[b], A. Grzeszczuk[e], P. Guazzoni[m]
D. Guinet[n], M. Iacono-Manno[b], S. Kowalski[e], E. La Guidara[b], G. Lanzalone[b]
G. Lanzanò[a], C. Maiolino[b], Z. Majka[f], N. Le Neindre[g], A. Pagano[a], M. Papa[a]
M. Petrovici[d], E. Piasecki[p], S. Pirrone[a], R. Płaneta[f], G. Politi[a], A. Pop[d]
F. Porto[a], M.F. Rivet[g], E. Rosato[q], F. Rizzo[b], S. Russo[m], P. Russotto[b], M. Sassi[m]
K. Schmidt[e], K. Siwek-Wilczyńska[p], I. Skwira[p], M.L. Sperduto[a], A. Sochocka[f]
L. Świderski[p], A. Trifirò[c], M. Trimarchi[c], G. Vannini[i], G. Verde[a], M. Vigilante[q]
J.P. Wieleczko[k], J. Wilczyński[r], L. Zetta[m], W. Zipper[e]

[a]INFN Sez. di Catania and Dipartimento di Fisica, Università di Catania, Italy
[b]INFN Lab. Naz. del Sud and Dip. di Fisica, Università di Catania, Italy
[c]INFN, Gr. coll. di Messina and Dip. di Fisica, Università di Messina, Italy
[d]Institute for Physics and Nuclear Engineering, Bucharest, Romania
[e]Institute of Physics, University of Silesia, Katowice, Poland
[f]M. Smoluchowski Institute of Physics, Jagellonian University, Cracow, Poland
[g]Institut de Phisique Nucléaire, IN2P3-CNRS, Orsay, France
[h]LPC, ENSI Caen and Universitè de Caen, France
[i]INFN Sez. di Bologna and Dipartimento di Fisica, Università di Bologna, Italy
[j]Saha Institute of Nuclear Physics, Kolkata, India
[k]GANIL, CEA, IN2P3-CNRS, Caen, France
[l]DAPNIA/SPhN, CEA-Saclay, France
[m]INFN Sez. di Milano and Dipartimento di Fisica, Università di Milano, Italy
[n]IPN, IN2P3-CNRS and Université Claude Bernard, Lyon, France
[p]Institute for Experimental Physics, Warsaw University, Warsaw, Poland
[q]INFN Sez. di Napoli and Dipartimento di Fisica, Università di Napoli, Italy
[r]A. Sołtan Institute for Nuclear Studies, Swierk/Warsaw, Poland

(Received December 13, 2005)

Production of intermediate mass fragments (IMF) has been studied in semi-peripheral ^{124}Sn (35 A MeV) + ^{64}Ni and ^{112}Sn (35 A MeV) + ^{58}Ni reactions. Our recently proposed new method of an analysis of the neck-like fragmentation processes that provides information on the IMFs time sequence and time scale is reviewed. Isotopic analysis of so characterized IMFs gives evidence for neutron enrichment of mid-velocity fragments. A clear isoscaling behavior is found despite the short emission time scale. Evolution of the isoscaling parameters from semi-peripheral to central collisions is discussed.

PACS numbers: 25.70.Mn, 25.70.Pq

* Presented at the XXIX Mazurian Lakes Conference on Physics August 30–September 6, 2005, Piaski, Poland.

1. Introduction

The density dependence of the symmetry energy term in the nuclear equation of state (EOS) is a fundamental question in studying properties of nuclear matter. Theoretical studies (for a review see Ref. [1] and references therein) predict different behaviour beyond the nuclear matter saturation point: from linear or parabolic rise of the symmetry energy with the increasing density (for asy-stiff and asy-superstiff EOS, respectively) to a form slightly decreasing at higher densities (asy-soft EOS). It is still debated in which way the dynamics of heavy ion reactions at intermediate energies (allowing to access densities below the saturation point) can be sensitive to the density dependence of the symmetry energy. Some experimental works [2–4] refer to this question. The phenomenon analyzed in these papers is the so called isotopic scaling (isoscaling) [5, 6] resulting from comparisons of isotopic yields (from a well defined emission source) for pairs of reactions of nuclear systems having different isotopic composition. Parametrization of the symmetry energy term of the EOS can be evaluated through the comparison of this experimental observable with predictions of those models which are sensitive to the isoscaling parameters, for example the AMD (antisymmetrized molecular dynamics) model [7], stochastic BNV (Boltzmann–Nordheim–Vlasov) transport model [8] or the statistical multifragmentation (SMM) model [9].

In recent papers [10,11] semi-peripheral collisions in the ^{124}Sn + ^{64}Ni reaction at 35 A MeV have been studied for selected class of well reconstructed ternary events involving the detection of a projectile fragment (PLF), a target fragment (TLF) and one IMF emitted at mid-velocity (between PLF and TLF velocities) in the same event. A method based on the relative velocity analysis permits to "calibrate" the IMFs emission time scale and to establish the emission chronology: light IMFs (*e.g.* Be or C) are produced earlier (within 100 fm/c) than heavier fragments (*e.g.* Mg or Ar). The IMF emission has been interpreted as fragmentation of the "neck" formed between the two interacting nuclei. Because the neck fragments are formed in the dilute region in proximity to the PLF and TLF (having the saturation density), various isospin effects are expected showing dependence on the initial neutron-to-proton ratio N/Z of the system. Fragments originating from the neck fragmentation are more neutron-rich than fragments statistically emitted from the PLF source [12–14]. Simulations of the reaction dynamics [8] show that this effect could be linked to the isospin term in EOS that drives neutrons towards the diluted neck region, while protons in the opposite direction.

In the present paper, we are going to characterize isotopic properties of the mid-velocity IMFs (selected with our mentioned above new method) produced in a short time scale in two reactions of the neutron rich system ^{124}Sn (35 A MeV) + ^{64}Ni and neutron poor system ^{112}Sn (35 A MeV) + ^{58}Ni.

We will show that despite the short emission time scale, an isoscaling signal is present for light IMFs originating from the neck region. The isotopic ratios and isoscaling parameters are compatible with the neutron enrichment of the mid-velocity fragments. The BNV simulations of the neck fragmentation processes confirm these effects.

2. Experiment

The experiment was performed at the LNS in Catania using the Superconducting Cyclotron and the CHIMERA detector [15]. The CHIMERA detector (of 4π geometry) consists of 1192 telescopes built of two-layer 300 μm-thick planar silicon detectors followed by CsI (Tl) scintillators. In the experiment only the forward part of the detector (688 telescopes) composed of 18 rings centered around the beam axis was used. It covered the angular range from 1° to 30°. Data for two reactions: ^{124}Sn (35 A MeV) + ^{64}Ni and ^{112}Sn (35 A MeV) + ^{58}Ni were collected. Using the $\Delta E - E$ method, charge identification with one charge unit resolution was achieved up to $Z = 50$. The time-of-flight method was used to extract the mass of fragments stopped in silicon detectors. Light charged particles ($Z \leq 3$) were identified using the pulse-shape technique in the CsI (Tl) detectors [16]. Isotopic identification for particles punching through the silicon detector was achieved for atomic numbers $3 \leq Z \leq 8$ in the angular range $13.5^\circ \leq \theta \leq 30^\circ$ [17].

3. Event selection and relative velocity correlations

Basic procedures for event selection and time scale determination of the IMF emission from the neck region in the ^{124}Sn + ^{64}Ni reaction have been extensively described in Ref. [11]. Very briefly, we have selected the class of well reconstructed ternary events, where along with PLF and TLF a third fragment (IMF) with the velocity distribution centered at the mid-velocity (between PLF and TLF) is produced. The time scale of the IMF production has been extracted using a method based on the correlations between the relative velocities $V_{\rm rel}/V_{\rm Viola}$ (IMF-PLF) and $V_{\rm rel}/V_{\rm Viola}$ (IMF-TLF), where $V_{\rm Viola}$ is the velocity corresponding to the Coulomb repulsion energy for a given sub-system. Most of the light mid-velocity IMFs are produced in a short time (less than 100 fm/c) after the reseparation of the two main partners of the reaction (PLF and TLF). The obtained estimates of the emission times have been found consistent with theoretical calculations [8] describing the IMF emission as the neck fragmentation in stochastic BNV transport model. Our evaluation is also in agreement with previous simulations based on the Coulomb trajectory calculations [18]. In the following we present new results on the isotopic characteristics of the production of fragments in the ^{112}Sn (35 A MeV) + ^{58}Ni and ^{124}Sn (35 A MeV) + ^{64}Ni reactions.

4. Isotopic analysis and isoscaling

Data on the neutron poor ^{112}Sn + ^{58}Ni system have been analyzed with the same method as in case of the neutron rich system ^{124}Sn + ^{64}Ni. The emission pattern of light IMFs of $Z \leq 8$, observed for mid-velocities (*e.g.* the charge and angular distributions, $V_{\rm rel}/V_{\rm Viola}$ correlations, the degree of the PLF-IMF-TLF alignment *etc.*) is essentially the same for the two reactions. Fig. 1 shows the heavy-to-light isotope ratio for charges $3 \leq Z \leq 6$, plotted as a function of the IMF parallel velocity, for the neutron rich (open squares) and neutron poor (solid circles) systems. Two features are clearly seen: *(i)* the tendency to maintain memory of the entrance channel N/Z ratio, so that the ratios for the neutron rich system are always significantly higher than those for the neutron poor system; *(ii)* the systematically observed fact that the isotopic ratio reaches its maximum at the mid-velocity region and then decreases with the increasing parallel velocity. The latter effect is evident for

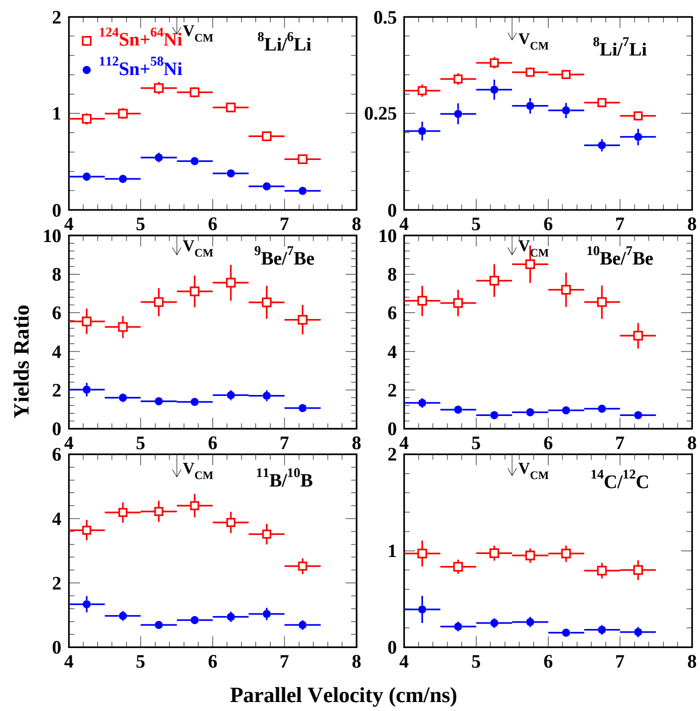

Fig. 1. The heavy-to-light isotope ratio for IMFs of $3 \leq Z \leq 6$ as a function of their parallel velocity for the neutron rich (open squares) and neutron poor (solid circles) systems. The velocity integration bins are indicated by the horizontal error bars.

the neutron rich system, while for the neutron poor system the distributions are flatter. IMFs having the parallel velocity greater than 6 cm/ns originate mainly from the PLF source and are poorer in neutrons than those observed at mid-velocities. Similar observations have been reported in Ref. [19]. At least for Li isotopes, the neutron enrichment at mid-velocities is present also for the neutron poor system ($N/Z = 1.18$); this effect was reported earlier [13] for a system with the initial N/Z ratio close to unity.

It has been shown (see *e.g.* Refs. [2, 5, 6]) that the ratio of the isotopic yields $R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z)$ in two reactions differing in their initial N/Z composition (conventionally N/Z of the system 2 is greater than N/Z of the system 1) follows exponential dependence $R_{21}(N,Z) = C\exp(\alpha N + \beta Z)$, where C is the normalization constant and α and β are two free parameters (isoscaling parameters). In models of multifragmentation attempting to demonstrate the liquid–gas phase transition using concepts of the grand-canonical approximation (equilibrium multifragmentation models), the isoscaling parameters α and β have been related to the relative free neutron and free-proton densities of the emitting source. In Ref. [20] our data for the most central collisions were analyzed using the isoscaling observable and the observed signals were found consistent with possible observation of the liquid–gas phase transition manifested by the neutron enrichment of the gas phase (isospin distillation). It is interesting that the isoscaling behavior has also been observed in theoretical simulations of the dynamical models such as the stochastic BNV or molecular dynamics AMD model [7], both in central [21, 22] and semi-peripheral collisions [8]. In these calculations the isoscaling parameters show sensitivity to the symmetry term of EOS.

In the present analysis we tested at first whether or not the isoscaling signal is observed in our neck fragmentation data. For this analysis a window in the IMF parallel velocity between 4.0 and 6.0 cm/ns was set. As described in Ref. [11], this window in the $V_{\rm rel}/V_{\rm Viola}$ (IMF-PLF) *versus* $V_{\rm rel}/V_{\rm Viola}$ (IMF-TLF) correlation plot (see Fig. 3) selects the prompt component of the ternary neck fragmentation. Figs. 2(a) and 2(b) show the measured isotopic ratios R_{21} (2 is for the neutron rich system, 1 for neutron poor system) as a function of the neutron number and proton number, respectively. The isotopic ratios have been normalized to the R_{21} ratio for ^{6}Li. A clear isoscaling behavior is observed. The best fit gives values of $\alpha = 0.63 \pm 0.02$ and $\beta = -0.55 \pm 0.02$. In Fig. 2(c) a combined visualization of the isoscaling phenomenon is presented in form of the function $S(N) = R_{21}\exp(-\beta Z)$ for all the isotopic ratios. For comparison, the isoscaling data representing central collisions [20] have been rescaled and shown in the same plot (for central collisions $\alpha = 0.44 \pm 0.01$). Our selection of mid-velocity fragments rather excludes equilibrium emission. Therefore, the isoscaling observed for these presumably dynamically produced fragments (within a short time scale),

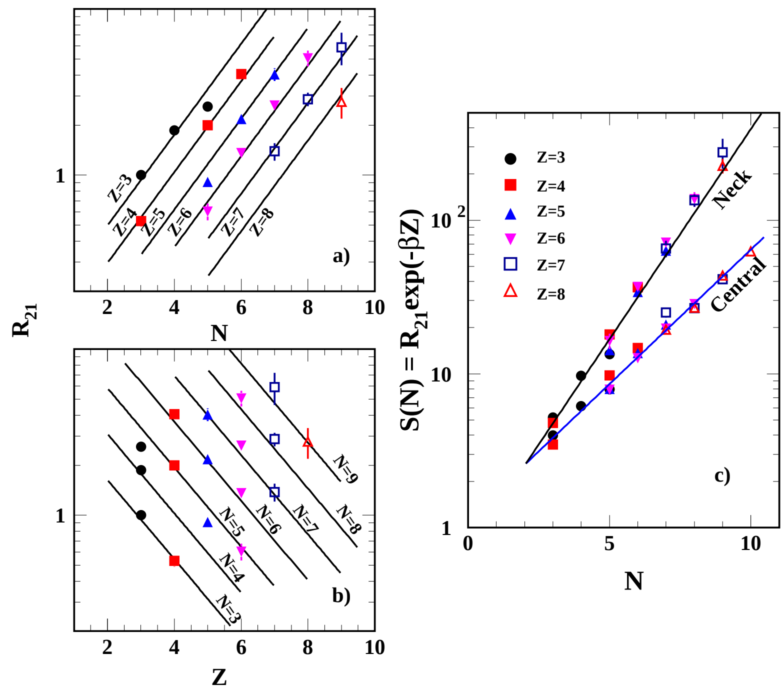

Fig. 2. (a) Isotopic ratios R_{21} as a function of the neutron number of selected IMFs (see text); (b) Isotopic ratios R_{21} as a function of the proton number of selected IMFs; (c) Combined presentation of the isoscaling, plotted as a function of the neutron number. Data labelled "central" are taken from Ref. [20]

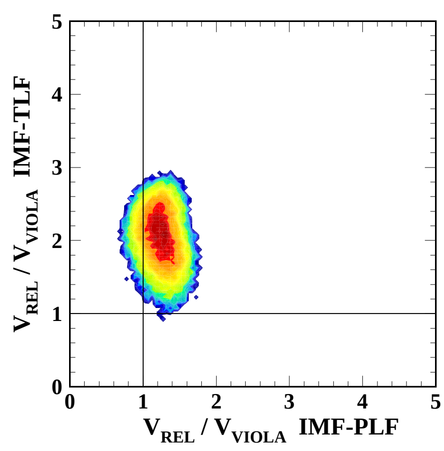

Fig. 3. Correlations between relative velocities $V_{\rm rel}/V_{\rm Viola}$ (IMF-PLF) and $V_{\rm rel}/V_{\rm Viola}$ (IMF-TLF) for fragments of charge $3 \leq Z \leq 8$ and parallel velocity between 4.0 and 6.0 cm/ns in the ^{124}Sn + ^{64}Ni reaction.

should be sensitive to the symmetry energy term of EOS. A steeper dependence of the α parameter for the neck emission can suggest the neutron enrichment of the neck in case of the neutron rich system as compared with the neutron poor system, the effect similar as it was shown in Fig. 1. In the BNV model calculations this is connected with migration of neutrons towards the dilute neck region. This effect is predicted to be enhanced for the stiff form of the symmetry energy term of the EOS.

Our data are qualitatively in agreement with the BNV transport model predictions showing the isoscaling signal for neck fragmentation processes [8] and the increase of the isoscaling parameters with the increasing stiffness of the symmetry energy. However, more detailed comparisons between data and theoretical predictions are needed for better understanding of the role of the preequilibrium neutron emission and the influence of the sequential decay of primary excited fragments on the deduced values of the isoscaling parameters.

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