Isoscaling, isobaric yield ratio and the symmetry energy: interpretation of the results with SMM

P. Marini, A. Botvina, A. Bonasera, Z. Kohley, L. W. May, R. Tripathi,
S. Wuenschel, and S. J. Yennello

Significant theoretical and experimental works [1-3] have been devoted to the study of the nuclear symmetry energy (E_{sym}), which is essential for understanding not only the structure of radioactive nuclei [4], but also many important issues in astrophysics [5]. The value of the symmetry energy has been well constrained only at normal nuclear density and zero temperature. Heavy ion collisions remain the most powerful way to study the nuclear matter behavior in extreme conditions of temperature and density that can otherwise be encountered only in astrophysical environments, like supernova explosions and neutrons stars.

Several observables in heavy ion collisions are known to be affected by the symmetry energy (E_{sym}), but quantitative information is difficult to extract, due to secondary decay of excited primary fragments, which can distort signatures contained in primary fragment observables. When experimentally determining the symmetry energy two important considerations are the degree of confidence which can be accorded to the estimation and the way in which the secondary decay processes impact the currently used observables. Indeed most of the primary fragments produced in Fermi-energy heavy-ion reactions are expected to be in an excited state when they are formed, while the majority of the experimentally detected fragments are in their ground states. Previous works [6, 7] have evaluated the excitation energies of the primary fragments and demonstrated that secondary decay is important.

In this respect we are investigating the effect of the secondary decay as predicted by the Statistical Multifragmentation Model (SMM) [8] on the symmetry energy coefficient extracted by the isoscaling and isobaric yield methods. Isoscaling [9] has been observed for a variety of reaction mechanisms that are dominated by phase space, including evaporation, multifragmentation, and deep inelastic scattering under the condition of statistical emission. Its statistical interpretation links the isoscaling parameter α to the symmetry energy coefficient C_{sym} [9-12].

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right] \qquad (1)$$

where T is the temperature and the Z/A values correspond to the proton fraction of the most probable primary isotope produced in two similar sources with different proton-to-neutron ratios.

Recently a different method based on the Modified Fisher Model [13] has been suggested [14-16], which allows one to extract C_{sym} from the yield ratio between two pairs of isobars differing by 2 units in $I=N-Z$ and produced by the same source. The two methods have been applied to secondary fragments from ^{78,86}Kr+ ^{58,64}Ni at 35AMeV reactions, taken on the NIMROD-ISiS array. The details of the experiment and of the analysis can be found in Ref. [17] and [18], respectively. A comparison to models is now needed to constrain E_{sym}.

The Statistical Multifragmentation Model (SMM) [8] has been widely used for interpreting experimental data on multiple fragment production in different nuclear reactions and to extract information on the symmetry energy starting from secondary fragments. Isotopic yields of fragments (N,Z) emitted in the multifragmentation of the quasi-projectile simulated by SMM have been determined for both the quasi-projectile sources (^{78}Kr and ^{86}Kr). C_{sym}/T has been extracted from the isoscaling parameter α using as Z/A the values corresponding to the neutron richness of the neutron-rich and neutron-poor sources, respectively. The isobaric yield ratio method instead provides a direct estimation of C_{sym}/T for each source.

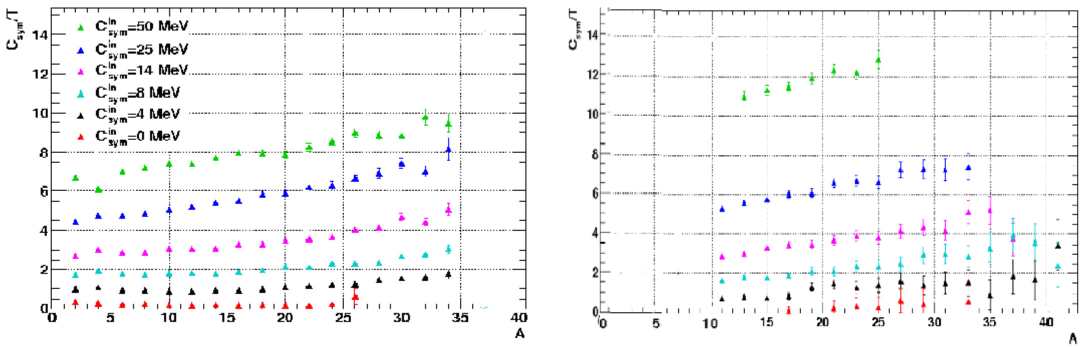

FIG. 1. C_{sym}/T values as a function of the fragment mass number ($A=2Z$ for the isoscaling method) extracted from the isoscaling (left) and isobaric yield ratio (right) methods for hot fragments.

For hot fragments (i.e. before the secondary de-excitation) the behaviour of C_{sym}/T as a function of the fragment mass A for a chosen source excitation energy (5 AMeV) and input symmetry energy coefficient (25 MeV) is shown in fig.1. C_{sym}/T shows the same behavior as function of A, even for other values of source excitation energy (3, 4 and 7 AMeV) and input symmetry energy values C_{sym} (4, 8 and 14 MeV). The increasing trend is observed independently on the method used to determine C_{sym}/T. Attempts to physically interpret this trend have been done by varying the source size, to eventually figure out finite size effects, by isolating the Coulomb contribution (C_{sym} =0) and by selecting a narrow hot fragment excitation energy window.

Ideally, primary fragments should be detected to extract information on C_{sym} as will be shown later, but experimentally only cold fragments can be detected and, unless we rely on models to reconstruct primary quantities, information has to be extracted from secondary fragments (i.e. after de-excitation). The behavior of C_{sym}/T extracted with isoscaling and isobaric yield ratio methods as a function of the fragment mass for secondary fragments is plotted in fig.2. The same trend has been observed varying the source excitation energy and the symmetry energy input parameter. In the figure results obtained applying GEMINI to hot fragments generated by SMM are also plotted. It turns out that the de-excitation processes in SMM and GEMINI favour the production of different isobars. Indeed for C_{sym}/T to be estimated for a given isobars A, fragments with N-Z=3, 1, -1 have to be produced by the code. For 15<A<25 the prduction of all the three isobars is damped in SMM code, while fragments produced by GEMINI have A < 28. C_{sym}/T obtained with the isoscaling method applied to SMM cold

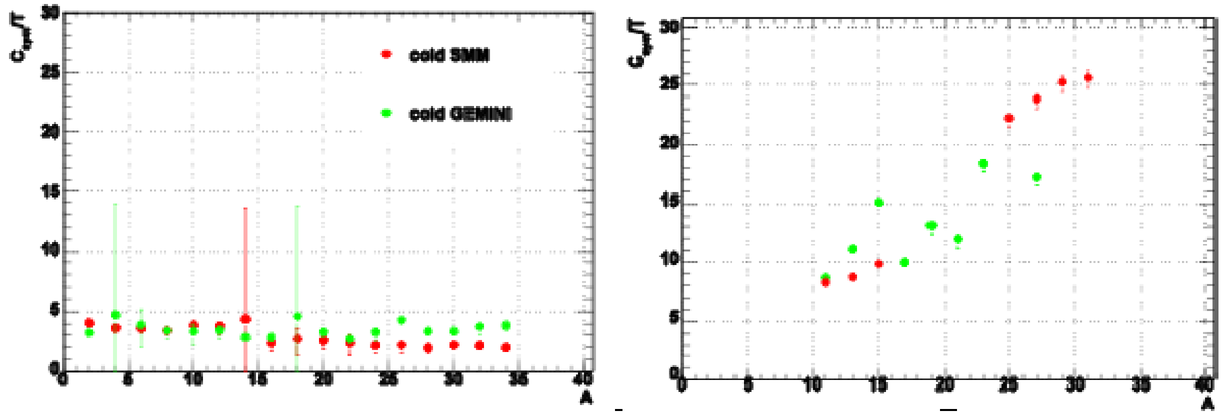

FIG. 2. C_{sym}/T values as a function of the fragment mass number ($A=2Z$ for the isoscaling method) extracted from the isoscaling (left) and isobaric yield ratio (right) methods for cold fragments. In green the values obtained applying the two methods to fragments produced by SMM and de-excited by GEMINI are plotted.

fragments shows a gap between Z=7 and Z=8, which is due to the change in de-excitation mechanism implemented in SMM for A=16. We observe a flat behavior of C_{sym}/T as a function of 2Z (=A) for isoscaling-extracted results, while C_{sym}/T increases as a function of A for isobaric yield method-extracted values. A possible interpretation of the two different trends may be that the secondary decay effects are minimized (or cancels out) when taking the ratio of the same isotope produced in similar sources, as done in the isoscaling method. On the contrary the effects do not cancel out when considering the ratio of two isobars produced by the same source. The opposite is true when considering the effect of the particle identification thresholds on the computation of the yield ratios. Moreover we would like to stress that C_{sym}/T can be directly extracted from the isobaric yield ratio method only if the second order approximation of the Lanadau free energy per particle as a function of the relative isospin asymmetry $m=(N-Z)/A$ is valid [18]. If higher order terms are significant, they have to be taken into account in the estimation of C_{sym}/T. We are currently working to estimate their contribution.

The correlation of the extracted C_{sym} ($C_{sym}out$) with the input C_{sym} ($C_{sym}in$) are plotted in fig.3 and fig. 4 for both hot and cold fragments, respectively. As a measure of the temperature we have used the microcanonical temperature estimated by the SMM code. Other estimations of the temperature could be performed, using for example the particle kinetic energy spectra or the momentum fluctuations. In both cases we should disentangle the Coulomb contribution to the kinetic energy and momentum fluctuations, respectively, from the temperature contribution, but the Coulomb interaction can not be turned off without affecting also the partition configuration in SMM.

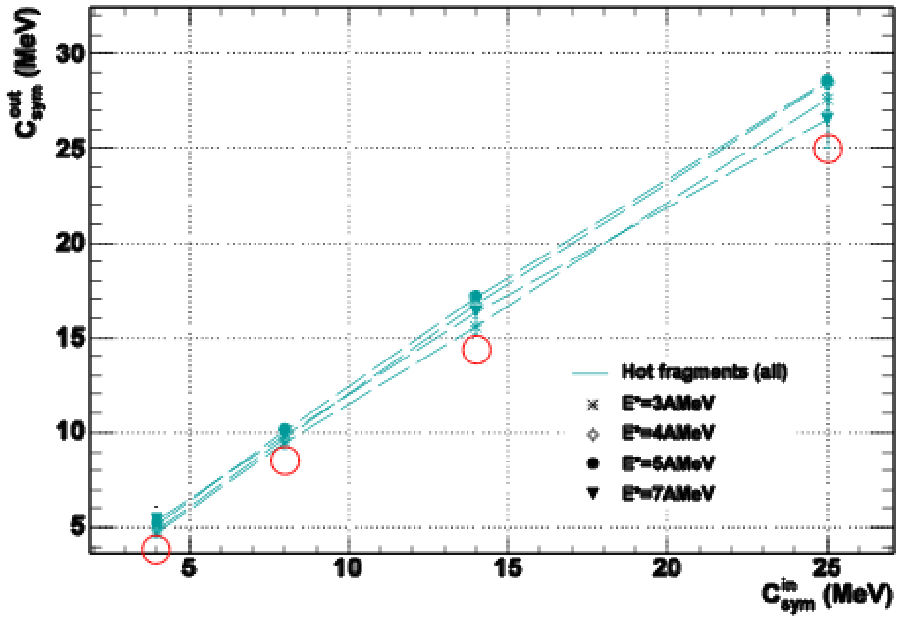

FIG. 3. Correlation between the SMM input symmetry energy coefficient value ($C_{sym}in$) and the symmetry energy coefficient value determined by the analysis of hot fragments.

The $C_{sym}out$ values extracted from hot fragments are in good agreement with the input values $C_{sym}in$, suggesting that information on C_{sym} can be extracted from primary fragments. The correlation for values extracted from isoscaling analysis is significantly damped for excitation energy above 3 MeV/nucleon by the secondary de-excitation. The correlation for values extracted with the isobaric yield ratio method is present but the output values are in disagreement with the input values of a factor of 2-3. A possible reason could be the estimation of the temperature used to determine C_{sym}, but work is still in progress on this issue.

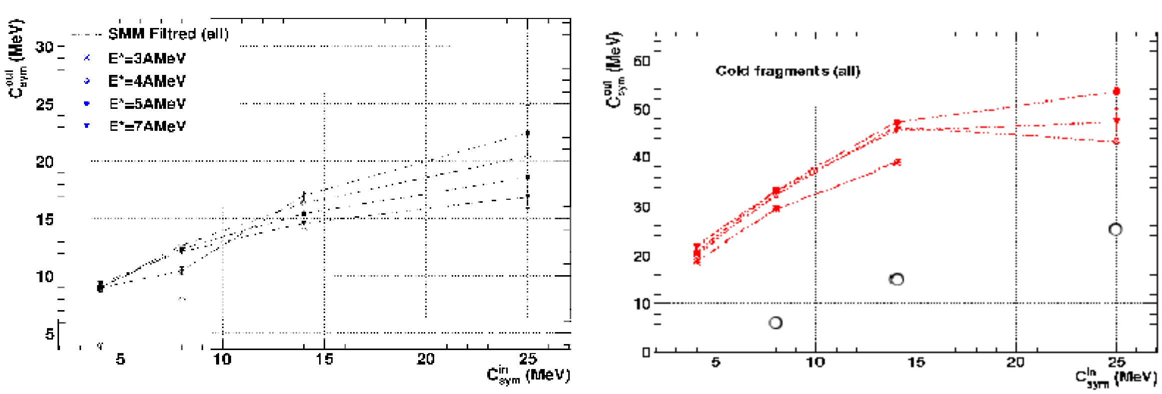

FIG. 4. Correlation between the SMM input symmetry energy coefficient value ($C_{sym}in$) and the symmetry energy coefficient value determined by the isoscaling (left) and the isobaric yield ratio (right) methods for cold fragments.

[1] D.V. Shetty *et al.*, Phys. Rev. C **76**, 024606 (2007).

[2] B.A. Li *et al.*, Phys. Rep. **464**, 113 (2008).
[3] V. Baran *et al.*, Phys. Rep. **410**, 335 (20050; and references therein.
[4] B.A. Brown *et al.*, Phys. Rev. Lett. **85**, 5296 (2000).
[5] J.M. Lattimer *et al.*, Astrophys. J. **550**, 426 (2001).
[6] S. Hudan *et al.*, Phys. Rev. C **67**, 064613 (2003).
[7] N. Marie *et al.*, Phys. Rev. C **58**, 256 (1998).
[8] J.P. Bondorf *et al.*, Phys. Rep. **257**, 133 (1995).
[9] M.B. Tseng *et al.*, Phys. Rev. Lett. **86**, 5023 (2001).
[10] G. Chauduri *et al.*, Nucl. Phys. **A813**, 293 (2008); and references therein.
[11] A.S. Botvina *et al.*, Phys. Rev. C **65**, 044610 (2002).
[12] A. Ono *et al.*, Phys. Rev. C **68**, 051601(R) (2003).
[13] R.W. Minich *et al.*, Phys. Lett. B **118**, 458 (1982).
[14] M. Huang *et al.*, Phys. Rev. C **81**, 044618 (2010).
[15] M. Huang *et al.*, Nucl. Phys. **A847**, 233 (2010).
[16] M. Huang *et al.*, Phys. Rev. C **81**, 044620 (2010).
[17] S. Wuenschel *et al.*, Phys. Rev. C **79**, 061602 (R) (2009).
[18] P. Marini *et al.*, Phys. Rev. C (submitted).