Isotopic yields as a probe of the symmetry energy: dealing with the secondary decay effects

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Abstract. The impact of the secondary de-excitation on isotopic distributions commonly used as observable to extract information on the symmetry energy is pointed out. A comparison of three methods differently affected by secondary decay shows a good agreement of the results up to $A = 20$, suggesting a lack of secondary decay effects in our data within our resolution. Data from the $4\pi$ detector INDRA and the VAMOS spectrometer could extend this work to higher $A$. The same data allow us to perform a primary fragment reconstruction, which opens up the possibility of planning a program on charged particle spectroscopy of exotic nuclei.

1. Introduction
In the last decade a growing interest in isospin effects in nuclear reactions was stimulated by the increasing understanding of the importance of the symmetry energy term in the nuclear equation of state. Indeed, understanding the properties of asymmetric nuclear matter both at normal densities and at densities away from the saturation density has an important impact on both the study of the nuclear structure close to the drip lines [1] and of astrophysical processes [2].

A variety of observables have been proposed to access the symmetry energy in heavy-ion collisions [3]. Recent measurements of the giant dipole [4], Pygmy dipole [5] and giant monopole [6] resonances in neutron-rich nuclei, neutron/proton emission [7], isospin diffusion [8] and fragment isotopic ratio [9, 10] have provided initial constraints on the density dependence of the symmetry energy at sub-saturation densities. New experimental constraints on the symmetry energy at supra-saturation densities are expected from a recent neutron-proton flow measurement performed at GSI [11]. Further stringent constraints will be available in the near future from refinement of these measurements with both stable and rare isotope beams at SPIRAL2, FAIR, RIKEN and MSU.
In this work, among the experimental observables commonly used to explore the symmetry energy at sub-saturation densities, we concentrate on the isotopic distributions of complex fragments produced in multifragmentation processes at Fermi energies. Indeed theoretical predictions [12] suggest that information can be extracted from the isotopic distributions of primary fragments. However, quantitative information is difficult to extract as most fragments, produced in excited states [13, 14], decay to lighter stable isotopes on a typical time scale of $\sim 10^{-20}$ s [15], before being detected. Model calculations [16, 17] suggest that isotopic distributions of secondary fragments (after secondary decay) are narrower [18, 19, 20, 16] than those of primary fragments (before de-excitation) and shifted toward less n-rich nuclei [17].

Observables built on isotopic distributions can be divided in two groups: those calculated from the isotopic distribution of fragments produced in a single source, such as the shape of the distribution and the isobaric yield ratio [21], and those calculated taking the ratio of the yields of fragments produced in two different sources, such as isoscaling [9, 22, 23, 24] and m-scaling [25] methods. The first group of observables has been shown to be significantly distorted by secondary de-excitation [12, 17]. On the other hand some work shows that the effect of the sequential decay on the second group of observables, in particular on the isoscaling parameters, is negligible [16] whereas other authors show that the secondary decay indeed affects such observables, distorting the values of the symmetry energy that can be extracted [26, 27, 28].

To overcome this issue observables unaffected by secondary decay should be identified and used or primary fragments should be traced back from measured quantities. In this work we report on the experimental comparison of results obtained with three different methods, the isoscaling [9, 22, 23, 24], the m-scaling [25] and the isobaric yield ratio [21] methods, on quasi-projectile fragmentation data, exploiting the 4π charged particle and neutron array NIMROD-ISIS [29, 30]. Moreover we present a preliminary analysis aimed at the reconstruction of primary fragments produced in semiperipheral collisions, measured coupling the 4π charged particle detector INDRA [31] and the VAMOS spectrometer [32].

2. A comparison of three methods
The experiment was performed at Texas A&M University K500 superconducting Cyclotron. Beams of $^{64}$Zn, $^{70}$Zn and $^{64}$Ni at 35 AMeV beam energy were impinged on $^{64}$Zn, $^{70}$Zn and $^{64}$Ni targets. The 4π NIMROD-ISIS array [29, 30] was used for the detection of charged particles, obtaining isotopic resolution for $Z \leq 17$. The charged-particle array was housed inside the TAMU Neutron Ball [30], which measured the free neutron multiplicity. Details on the experiment can be found in [33, 34].

Particle and event selections were performed to select quasi-projectile fragmentation events. Thanks to the high isotopic resolution of NIMROD and the free neutron information the quasi-projectile was identified, event-by-event, in charge, mass and excitation energy [34] and the data sorted according to the quasi-projectile isospin asymmetry $m_s = \frac{N-Z}{A}$ and its excitation energy. Details on the analysis can be found in [34].

The isoscaling [9, 22, 23, 24], m-scaling [25] and isobaric yield ratio [21] methods were applied to the experimental data, to extract the symmetry energy coefficient to the temperature ratio, $C_{sym}/T$. Without entering in the details of the methods, which can be found in [34], we would like to point out that the main difference between the first two methods of extracting $C_{sym}/T$ and the third is that in the first two cases we are computing the yield ratios of the same fragment produced by two different sources, while in the third case we consider different isobars produced by a common source. Therefore, the isobaric yield ratio method is dependent on the selected isobars and vulnerable to secondary decay effects, whereas isoscaling and m-scaling are less affected by secondary de-excitation effects, since they are removed, to first order, when taking the ratio of the yields of the same fragment type produced by two sources. Details on the used formalism can be found in [34] and references therein.
In figure 1, we present a comparison of the results obtained with the three methods. A good agreement of the three values for each $A$ is observed up to mass $A = 21$: this is the region with the best mass resolution. Moreover the extracted symmetry term shows a generally flat trend as a function of $A$ for the same mass region, independent of the method used. This may be consistent with the lack of secondary de-excitation effects in our data, within our isotopic resolution, as well as with the assumption of a freeze-out volume where the disassembly occurs. However, it would be interesting to extend such analysis to higher mass fragments, for $A > 20$, with the isobaric yield ratio method. Indeed a recent work [35] predicts, within a statistical model, finite size effects to be rather significant for heavy fragments. Data collected in the experiment presented in the next section will be suitable for such analysis.

3. Toward a primary fragment reconstruction

The experiment was performed at GANIL CIME Cyclotron. $^{40}$Ca and $^{48}$Ca ion beams with energies of 35 AMeV were impinged on isotopically enriched $^{40,48}$Ca targets, to measure isotope production cross sections over a wide range of Z and N. The 4π INDRA multidetector array [31] was used for the detection of charged particles emitted in the $7^\circ - 176^\circ$ polar angular range. Telescope detectors, constituted by an ionization chamber, a high resolution silicon detector and a CsI(Tl), provided the detection and the identification of all reaction products. A high granularity, low energy thresholds, good energy resolution and a large dynamic range in energy and identification capability are the main INDRA characteristics, which allow a complete, event-by-event, reconstruction of kinematics.

INDRA was coupled with the large acceptance mass spectrometer VAMOS [32], placed at forward angles. The VAMOS spectrometer was designed to select and identify heavy reaction-products in charge, mass and kinetic energy. Indeed the VAMOS focal plane detection system consisted of two position sensitive detectors coupled with an ionization chamber, a silicon and a CsI detector walls, which provided $\Delta E$, $E$, $Z$, position and time-of-flight measurements. The scattering angle at the target, $B\rho$ parameters and the mass $A$ of each particle were obtained by software trajectory reconstruction.

The coupling of these two detectors allows to have an event by event complete information on
the projectile-like fragment (PLF), with a high isotopic resolution (VAMOS), on the associated light charged particles (INDRA), and last, but not least, on the neutron multiplicity by means of mass conservation.

Further details on the experimental set-up can be found in ref. [36], while details on the trajectory reconstruction procedures can be found in [37, 38].

A distribution of charge $Z_{PLF}$ vs. mass $A_{PLF}$ of projectile-like fragments detected in VAMOS is presented in Fig. 2. Residues from $Z = 5$ to $Z = 21$ are detected and identified. Up to 10 different isotopes are unambiguously identified for $Z = 10$, from $^{17}\text{Ne}$ to $^{26}\text{Ne}$, while up to 14 isotopes are identified for $Z = 18$. Further refinements to the trajectory reconstruction procedure, that are currently under way, will further improve the mass identification, removing not well reconstructed fragments. Indeed fragments hitting the edges of the drift chambers,
crucial for the position determination, introduce a spread in the observed mass distributions toward unacceptable values of $A$ for a given $Z$.

An example of the achieved isotopic resolution for $Z = 18$ is shown in Fig. 3 for the $^{40}\text{Ca} + ^{48}\text{Ca}$, $^{48}\text{Ca} + ^{40}\text{Ca}$ and $^{48}\text{Ca} + ^{48}\text{Ca}$ reactions. A very good mass resolution is observed for all the reactions: isotopes from $^{32}\text{Ar}$ to $^{46}\text{Ar}$ are clearly identified. As expected, the Ar mass distribution is shifted toward less neutron-rich isotopes, for projectile-like Ar fragments emitted in the less neutron-rich $^{40}\text{Ca} + ^{48}\text{Ca}$ reaction.

In the following we will present the procedure we are setting up to obtain a primary fragment reconstruction, exploiting the VAMOS identification capability and the INDRA granularity. The primary fragment reconstruction procedure consists in the selection of a PLF and the analysis of the particles emitted in coincidence. The results that we present here are preliminary results, aimed to verify the feasibility of the procedure. As a first step, we focused on the $^{40}\text{Ca} + ^{48}\text{Ca}$ peripheral collisions and we investigated the excited states of $^{38}\text{Ar}$ and $^{35}\text{Cl}$ above the particle emission threshold.

Particle and event selections were performed to select events of $^{40}\text{Ca}^* \text{ quasi-projectile decay}$ with S emission. Therefore only events where a S projectile-like fragment was detected in VAMOS were selected. No constraints on the S mass were placed at this point. In each event light charged particles detected in coincidence in INDRA were accepted requiring their longitudinal velocity relative to the beam velocity to be greater than 50%. This selection is intended to remove fragments from non-quasi-projectile sources, i.e. fragments produced from pre-equilibrium or quasi-target sources. An example of the longitudinal to the beam velocity ratio for each particle $Z$ is shown in Fig. 4. A projection of the velocity ratio for each $Z$ shows the presence of two (or three) components, each one corresponding to the quasi-projectile and quasi-target emission, with a minimum around 0.5. The third component corresponds to pre-equilibrium emission and it is present in the lightest charge spectra ($Z = 1, 2$). The particle selection will be improved by a more accurate INDRA energy calibration, currently in progress. Later on, we will refer to velocity-accepted charged particles detected in INDRA in coincidence with a sulphur PLF, detected in VAMOS, simply as particles emitted in coincidence or particles in coincidence.

Fully detected $^{40}\text{Ca}^*$ quasi-projectile decay events were selected requiring the sum of the
fragment charge detected in VAMOS ($Z_{PLF \ VAMOS} = 16$ for sulphur S) and the charge of the particles in coincidence ($Z_{tot \ INDRA}$) detected in INDRA to be $Z_{tot} = 20$, i.e.

$$Z_{tot} = Z_{PLF \ VAMOS} + Z_{tot \ INDRA} = Z_{PLF \ VAMOS} + \sum_{iCP \ INDRA}^{M_{CP \ INDRA}} Z_i.$$  \hspace{1cm} (1)

In Fig. 5 the PLF charge detected in VAMOS is plotted versus the sum of the accepted-fragment charge detected in INDRA. The full line indicates Ca quasi-projectile decay events fully reconstructed, i.e. $Z_{tot} = 20$. We observe that, thanks to the $4\pi$ INDRA coverage and its granularity, the majority of the events are fully detected in charge.

The multiplicity of charged particles emitted in coincidence with the S projectile-like fragment for a fully detected QP event is presented in Fig.6. The distribution is peaked at 2, indicating

**Figure 5.** Total charge detected in INDRA vs charge of the PLF fragment. The line indicate the events with a total detected charge of 20.

**Figure 6.** Multiplicity of particles emitted in coincidence with a S fragment detected in VAMOS.
that more likely two $Z = 2$ fragments or a $Z = 3$ and a $Z = 1$ fragments are emitted in coincidence with the sulphur PLF. The distribution extends above multiplicity 4, even if with a lower statistics. This could be due to a not correct particle identification in INDRA. Events with multiplicity 3 were chosen in the present analysis as a test-case. The selection of fully detected Ca decay events ($Z_{\text{tot}} = 20$) with S emission ($Z_{\text{PLF VAMOS}}$) imply a total charge detected in INDRA $Z_{\text{tot INDRA}} = 4$.

A $Z_{\text{tot INDRA}} = 4$ with a particle multiplicity $M_{\text{CP INDRA}} = 3$ is obtained when two $Z = 1$ fragments and one $Z = 2$ fragment are emitted in coincidence with the PLF. This was verified by plotting the average multiplicity of each fragment ($Z$) per event, as shown in Fig. 7. We observe that the average $Z = 1, 2$ multiplicities per event are about 1.6 and 0.8, respectively. Multiplicity 3 events with particles with $Z > 2$ are due to not well identified fragments.

The PLF fragment mass $A_{\text{PLF}} = 34$ was selected in order to obtain the highest available statistics for our analysis and, at the same time, to investigate known cases to test our procedure. A plot of the mass of $Z = 1$ and $Z = 2$ particles emitted in coincidence with a $^{34}$S showed that those particles are mainly protons and alphas. Therefore in the $^{40}$Ca* reconstruction we considered one $^{34}$S, one $^4$He and two $^1$H fragments. There are four paths through which the primary $^{40}$Ca* quasi-projectile may decay producing one $^{34}$S, one $^4$He and two $^1$H: a simultaneous break-up in 4 fragments:

$$^{40}\text{Ca}^* \rightarrow ^{34}\text{S} + ^4\text{He} + ^1\text{H} + ^1\text{H}$$  \hspace{1cm} (2)

or a break-up through the formation of an intermediate excited nucleus ($^{39}$Kr, $^{38}$Ar and $^{35}$Cl):

$$^{40}\text{Ca}^* \rightarrow ^{39}\text{Kr}^* + ^1\text{H} \rightarrow ^{34}\text{S} + ^4\text{He} + ^1\text{H}$$  \hspace{1cm} (3)

$$^{40}\text{Ca}^* \rightarrow ^{38}\text{Ar}^* + ^1\text{H} + ^1\text{H} \rightarrow ^{34}\text{S} + ^4\text{He}$$  \hspace{1cm} (4)

$$^{40}\text{Ca}^* \rightarrow ^{35}\text{Cl}^* + ^4\text{He} + ^1\text{H} \rightarrow ^{34}\text{S} + ^1\text{H}$$  \hspace{1cm} (5)

As an example, we analysed the last two cases, in which the primary $^{40}$Ca* fragment decays through the formation of the excited $^{38}$Ar* and $^{35}$Cl* nuclei.

Figure 7. Average multiplicity of each fragment ($Z$) per event.
The reconstructed excitation energy of the intermediate fragments was calculated through calorimetry as:

$$E^* = \sum_i^{M_{CP}} K^{CP}(i) - Q.$$  \hspace{1cm} (6)

The first term is the sum of the kinetic energies in the intermediate fragment center-of-mass of the particles ($M_{CP}$) produced in the decay of such fragment, i.e. of $^{34}$S and $^4$He for $^{38}$Ar and of $^{34}$S and $^1$H for $^{35}$Cl. The second term in the equation is the reaction $Q$ value. The mass of the intermediate fragment was calculated as the sum of the masses of the charged particles belonging to the considered excited fragment.

In Fig. 8, the excitation energy of the $^{38}$Ar and $^{35}$Cl intermediate fragments is shown. The $^{38}$Ar nucleus presents an excited state decaying in $^{34}$S+$^4$He at 7.21 MeV excitation energy [39]. The second and the third levels are at 9.88 and 14.6 MeV, respectively. Similarly, excited states of $^{35}$Cl decaying in $^{34}$S+$^1$H have been observed for excitation energies of 6.37, 7.09 and 10.0 MeV [39]. Structures are present in the $^{38}$Ar (Fig. 8-left) excitation energy spectrum. Two peaks can be observed at the excitation energy of 7.2 $\pm$ 0.7 MeV and 9.4 $\pm$ 0.4 MeV, which are consistent with the expected position of the first two states of $^{38}$Ar decaying in $^{34}$S+$^4$He. We do not observe the expected peak at 14.6 MeV, probably due to the need of background correction. Similarly in Fig. 8(right) two peaks at an excitation energy of 6.4 $\pm$ 0.6 and 7.1 $\pm$ 0.9 MeV can be identified, which correspond to the two first excited states of $^{35}$Cl decaying in $^{34}$S+$^1$H. The observation of these peaks gives us confidence that, with a proper treatment of the background, the spectra can be cleaned up and the peaks unambiguously identified. We should notice that, while neutrons are taken into account in the first presented experiment, they are not included.
in the present analysis. A full calibration of INDRA is required to improve the present analysis, which seems, however, very promising. This kind of analysis allows one to trace back primary fragments produced in the collisions, removing the impact of the secondary decay, for instance, on isoscaling and isobaric yield ratio analysis. Moreover excited states of exotic nuclei decaying by particle emission could be investigated, giving hints for the planning of more dedicated charged particle spectroscopy experiments to be performed with exotic nuclei.

4. Conclusions

In this work we pointed out the importance of a proper treatment of the secondary decay when extracting information on the symmetry energy term of the equation of state.

Three methods, differently affected by secondary de-excitation, showed a good agreement of the results up to $A = 21$, indicating a possible lack of de-excitation effects in our data, within our isotopic resolution. The INDRA-VAMOS data could be used to extend such analysis to heavier fragments.

A procedure to trace back primary fragments exploiting the VAMOS high isotopic resolution and the INDRA granularity and energy resolution was presented. The preliminary results are promising and open up the possibility for a new program on charged particle spectroscopy on exotic nuclei.

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