Isospin effects in multifragmentation - Review of experiments and interpretations

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Abstract

The majority of isospin effects observed in multifragmentation reactions can be understood within a grand-canonical description of the excited intermediate ensembles formed in the reaction process. This property has been successfully used to follow equilibration processes and to identify emitting sources. Challenging motivations for isospin studies in multifragmentation are derived from the importance of the density dependence of the symmetry term of the equation of state for astrophysical processes and for effects linked to the manifestation of the liquid-gas phase transition in reactions of finite nuclei.

1 Introduction

The interest in isospin effects in nuclear reactions has been growing very rapidly in recent years. It is motivated by the prospects of new experimental possibilities offered by existing or planned radioactive-beam facilities as well as by an increasing awareness of the importance of the symmetry term in the nuclear equation of state, not only for nuclear structure but, in particular, also for astrophysical applications. Supernova simulations or neutron star models require inputs for the nuclear equation of state at extreme values of density and asymmetry [1, 2, 3].

The term isospin effects is a shorthand notation for reaction phenomena that are explicitly related to the isotopic degree of freedom of the studied nuclei or nuclear systems, and thus to the two-component nature of nuclear matter. The neutron-to-proton ratio N/Z or the isospin asymmetry $I = (N-Z)/A$, i.e. the relative neutron excess of a system with mass number A, describe its isotopic composition. For extended nuclear matter, the corresponding quantity is the asymmetry parameter $\delta = (\rho_{\rm n} - \rho_{\rm p})/\rho$, given in terms of the neutron, proton and total densities $\rho_{\rm n}$, $\rho_{\rm p}$ and ρ. The asymmetry parameter enters quadratically in the equation of state of asymmetric nuclear matter at low temperatures,

$$e(\rho, \delta) = e(\rho, 0) + e_{\rm sym}(\rho) \cdot \delta^2. \tag{1}$$

The validity of the quadratic approximation is expected from the charge symmetry of the nuclear forces and has been confirmed numerically for a wide range of densities. The quantity of interest is thus the symmetry energy $e_{\rm sym}(\rho)$ and its dependence on density which is still not sufficiently well known.

Theoretical predictions for the symmetry energy are rather consistent at densities near the saturation point but differ widely as one moves away from it. It has become customary to distinguish so-called asy-stiff and asy-soft type equations of state, characterized by a monotonic increase of the symmetry term with density and by a parabolic dependence, respectively. Predictions derived from relativistic-mean-field theory, e.g., belong to the former class while variational many-body theories tend to predict a change from attraction to repulsion in the potential part of $e_{\rm sym}(\rho)$, thus causing symmetric nuclear matter to eventually become unstable as the density increases. Examples of the latter kind are shown in Fig. 1. Three-body forces, in particular, have a large effect at high density.

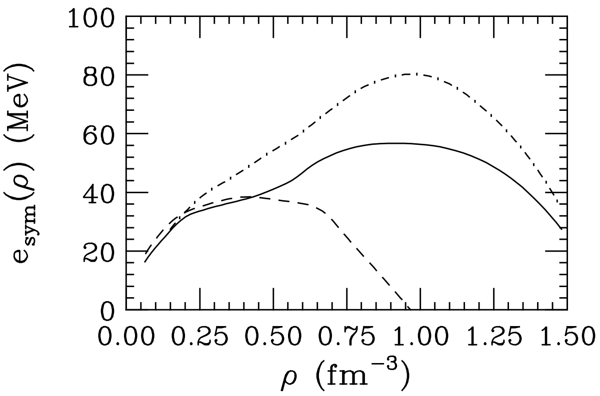

Fig. 1: Symmetry energy predicted by variational many-body calculations using the realistic forces and three-body terms AV14+UVII (solid line), UV14+UVII (dot-dashed), and UV14+TNI (dashed); figure from [12].

There is hope that experimental constraints for the symmetry term may be derived from heavy-ion reactions in which nuclear matter is probed at different densities. Multifragmentation is of particular interest here as hot and possibly compressed initial reaction stages are followed by a final breakup believed to occur at low average density.

Qualitatively new features are also expected for the nuclear liquid-gas phase transition if the isotopic degree-of-freedom is treated explicitly. A region of chemical instability, in addition to the spinodal region of mechanical instability, appears in the phase diagram for asymmetric nuclear matter [4]. Its consequences are a topic of high current interest. Unstable modes are predicted by most authors to be predominantly isoscalar [5, 6], while the effect of isospin fractionation, a variation of the isospin asymmetry with density, has been demonstrated in dynamical calculations with particles in a box [7, 8] and in the lattice gas model [9]. Experimental signatures of fractionation effects [10] have to be distinguished from the effects expected in equilibrium breakups from the dominant role of the heaviest fragments as neutron reservoirs, the latter being governed by the symmetry and Coulomb terms in the liquid drop description of nuclei [11].

For reviews on isospin physics in heavy-ion collisions, the reader is referred to the article of Li, Ko and Bauer [12] and to the collection of articles in the recent book edited by Li and Schröder [13]. The Hirschegg Workshop of 1999 was devoted to multifragmentation and related reaction phenomena [14].

2 Isotopic Yield Ratios and Grand-canonics

Isotopic yield ratios and their variation with reaction parameters can be measured quite precisely. The predominant observation made is their exponential dependence on the isospin asymmetry of the emitting source, a property revealed in many and different types of experiments with stable and unstable beams and with different techniques of controlling the N/Z ratio of the system [15, 16, 17, 18]. It has been used to study the degree of isospin equilibration that is reached in the collision but also, in experiments with projectiles or targets of varying asymmetry, to identify the sources of emission.

Equilibrium in the isotopic degree of freedom is seen in mass-asymmetric collisions at intermediate energies [15]. In central collisions of more mass-symmetric systems and incident energies above about 40 MeV per nucleon, a partial transparency appears to prevent the global equilibration of the N/Z degree of freedom [16, 19]. The transparency, or lack of nuclear stopping, can be determined quantitatively if the N/Z dependence of the measured ratios is calibrated, e.g., with cross-bombardments (isospin tracing [19]).

In order to address the exponential dependence of isotope ratios on N/Z, as well as the significance of the slope parameters, it is useful to refer to the grand-canonical approximation [20, 21]. Here the production yields $Y(N,Z)$ of isotopes with N neutrons and Z protons may be written as

$$Y(N,Z) \propto A^{3/2} \cdot \exp(\frac{\mu(N,Z)}{T}) \cdot \omega(N,Z) \qquad (2)$$

where $\mu(N,Z)$, $\omega(N,Z)$, and T denote the chemical potential and the internal partition function of the species considered and the temperature of the system. In equilibrium, the chemical potential is given by

$$\mu(N,Z) = N \cdot \mu_{\rm n} + Z \cdot \mu_{\rm p} + B(N,Z) \tag{3}$$

in terms of the chemical potentials for free neutrons and free protons, $\mu_{\rm n}$ and $\mu_{\rm p}$, and of the binding energy $B(N,Z)$. In yield ratios of isotopes, $Y(N+k,Z)/Y(N,Z)$, the chemical potentials cancel except for k powers of $\mu_{\rm n}$ (or, equivalently, of $\mu_{\rm p}$ for isotones). The approximately linear dependence of the chemical potentials on N and Z then immediately explains the observed exponential behavior of the yield ratios and the systematics of the slope parameters.

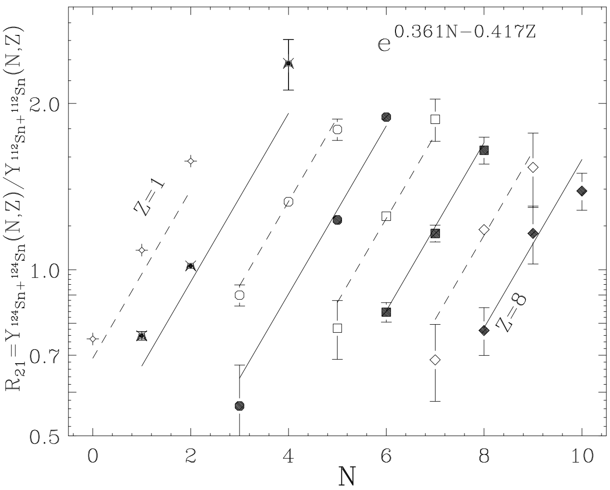

Fig. 2: Experimental isoscaling behavior exhibited by the central ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn collisions at 50 MeV per nucleon. The nuclide yield ratios from the two reactions, $R_{21}(N,Z)$, are plotted as a function of N. Different elements lie along different lines. The solid and dashed lines represent the best fit to Eq. 4 with the parameters given in the figure (from [24]).

Absolute values of single yield ratios of isotopes depend, besides on N/Z, still on the density (via $\mu_{\rm n}$ or $\mu_{\rm p}$) and on the temperature of the emitting system. By forming double yield ratios of appropriately chosen pairs of isotopes, the chemical potentials can be completely eliminated, leading to observables that depend only on T. This is the basis of the double-ratio method for determining breakup temperatures in nuclear reactions which is being widely used [14, 18, 22, 23].

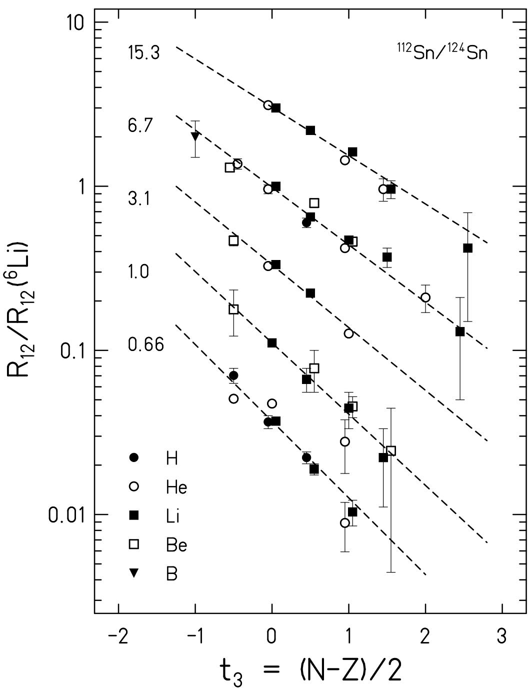

Fig. 3: Isotopic yield ratio R_{12}, for reactions of 0.66, 1.0, 6.7 GeV p, 3.1 GeV d and 15.3 GeV α incident on ^{112}Sn and ^{124}Sn targets, normalized with respect to $R_{12}(^6\mathrm{Li})$, versus the third component of the fragment isospin t_3. The measured H, He, Li, Be, and B fragments are distinguished by different data symbols as indicated. The lines are the results of exponential fits according to Eq. 5; figure from [28] with data from [29].

3 Isotopic Scaling

An alternative access to the same phenomena is provided by the isotopic effects observed when studying otherwise identical reactions with isotopically different projectiles or targets. The probably most popular pair of isotopes used in such experiments are the tin isotopes ^{112}Sn and ^{124}Sn with a difference of 12 neutrons between them and N/Z values of 1.24 and 1.48. It has been observed that in fragmentation reactions the ratio of production yields for the two reactions depends exponentially on the proton and neutron number of the product [24]. The scaling expression

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C \cdot exp(\alpha \cdot N + \beta \cdot Z) \tag{4}$$

describes rather well the measured ratios for a wide range of complex particles and light fragments (Fig. 2). This behavior is known as isotopic scaling or isoscaling and found to be present also in other reactions as, e.g., deep-inelastic collisions or compound evaporation [25]. In the grand-canonical approximation (Eqs. 2,3), assuming that the temperature T is approximately the same, the scaling parameters α and β are equal to the differences of the chemical potentials for the two systems, $\alpha = \Delta\mu_{\rm n}/T$ and $\beta = \Delta\mu_{\rm p}/T$.

The usually rather similar absolute values of the scaling coefficients (cf. Fig. 2) permit a rewriting of the scaling relation with only one parameter, $\beta_{t3} \approx 2 \cdot \alpha$, in a good approximation as

$$R_{12}(N,Z) = Y_1(N,Z)/Y_2(N,Z) = C \cdot exp(-t_3 \cdot \beta_{t3}), \tag{5}$$

where t_3 is the third component of the isospin of the detected fragment (Fig. 3). This property of fragmentation reactions was first reported by V.I. Bogatin [26] (see also [27] and references therein).

4 The Symmetry Term from Multifragmentation

Isotope ratios measured in five pairs of reactions induced by light particles ranging from protons of 0.66 GeV to α-particles of 15.3 GeV incident energy on ^{112}Sn and ^{124}Sn targets, normalized with respect to the ratio for ^{6}Li, are shown in Fig. 3. Isoscaling is observed for all five reactions with parameters β_{t3} (Eq. 5) that decrease from 1.08 to 0.68 with increasing energy [28]. The comparison of the inverse parameters $1/\beta_{t3}$ with isotope temperatures, deduced from the yields of He and Li isotopes, indicates that their evolution with energy is caused by an increase of the average temperature of the emitting system while the potential differences $\Delta\mu_{\rm n}$ and $\Delta\mu_{\rm p}$ remain about the same (Fig. 4).

In the Statistical Multifragmentation Model (SMM [30]), the isoscaling coefficients are connected with properties of the produced fragments. In particular, their symmetry energy is $E^{sym}_{N,Z} = \gamma(N-Z)^2/A$, where $\gamma \simeq 25$ MeV is the symmetry energy parameter, reflecting also the symmetry energy of nuclear matter. It turns out that the potential differences depend essentially only on the coefficient γ of the symmetry term and on the isotopic compositions of the sources. For the neutron chemical potentials, e.g., the analytic expression

$$\Delta\mu_{\rm n} = \mu_{\rm n}^{112} - \mu_{\rm n}^{124} \approx -4\gamma(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}) \tag{6}$$

has been derived. With SMM calculations, it has been confirmed numerically to be valid for any temperature in the grand-canonical approximation and, with the microcanonical calculations, for the regime of multifragmentation at temperatures near or exceeding $T = 5$ MeV (Fig. 5). It is thus possible to experimentally determine the symmetry energy coefficient at this temperature. It requires that (i) the isoscaling parameters and the asymmetry of the emitting sources are extracted from the experiment, and that (ii) the temperature is determined in an independent way. Since the secondary deexcitation of the produced fragments can influence the isoscaling parameters, the corresponding correction has to be applied.

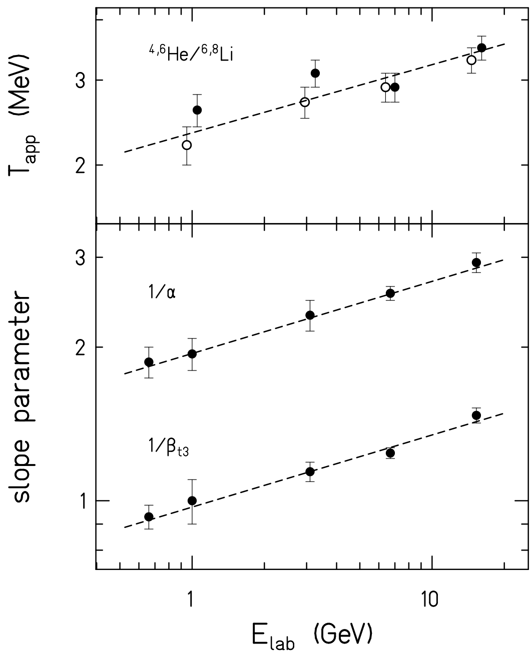

Fig. 4: Apparent isotope temperature $T_{\rm app}$ deduced from ^{4,6}He and ^{6,8}Li yield ratios (top) and the inverse isoscaling parameters (bottom) $1/\alpha$ (Eq. 4) and $1/\beta_{t3}$ (Eq. 5) as a function of the total projectile energy. The dashed lines represent the average rise of $1/\beta_{t3}$, multiplied by appropriate factors for comparison with the trends observed for $1/\alpha$ and $T_{\rm app}$ (from [28]).

By using this method for the p(6.7 GeV) and α(15.3 GeV) data from the set of reactions shown in Fig. 3, a symmetry energy parameter $\gamma = 23$ MeV was obtained [28]. This is very close to the value used in the SMM for the produced fragments which are assumed to have normal nuclear densities, and in this sense confirms the model assumption. On the other hand, one may argue that a low average breakup density should also be reflected in the parameters of the equation of state and that, in the studied light-ion-induced reactions, the mean fragment multiplicity may be too small to observe this effect. This important point requires further study. However, the similarity of the isoscaling coefficients with those measured for the central Sn + Sn collisions at 50 MeV per nucleon (Fig. 2), together with the probably similar temperatures, do not very strongly support this expectation. One is thus led to the more general question of whether low-density nuclear matter is actually probed in multifragmentation processes. A dominating clustering tendency may prohibit it, here as well as in other, e.g., astrophysical environments.

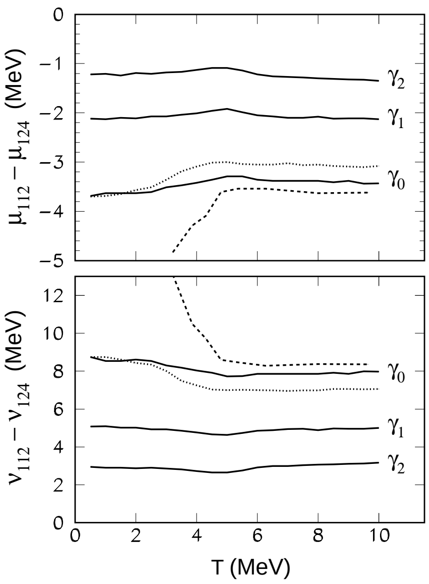

Fig. 5: Differences of the chemical potentials $\mu = \mu_{\rm n}$ (top) and $\nu = \mu_{\rm p} - \mu_{\rm n}$ (bottom) for the ^{112}Sn and ^{124}Sn systems as a function of the temperature and for symmetry term coefficients $\gamma_0 = 25$ MeV, $\gamma_1 = 14.4$ MeV and $\gamma_2 = 8.3$ MeV. Solid and dotted lines represent grand-canonical calculations for $\rho = \rho_0/3$ and $\rho = \rho_0/6$, respectively. The dashed lines are microcanonical Markov-chain calculations for $\rho = \rho_0/3$ (from [28]).

5 Dynamical Approaches

With dynamical reaction models, designed to follow the full history of the reaction from the beginning to the final stages, the accumulated effects of the symmetry term at non-normal densities may be studied. In a detailed analysis [31], stochastic transport simulations [32] for the ^{112,124}Sn + ^{112,124} systems at 50 MeV per nucleon have been used for the comparison with the measured data. Special attention was paid to the effects of secondary decay.

Isoscaling has been obtained in these calculations, with scaling parameters that differ by about 10% for the asy-stiff and asy-soft assumptions for the symmetry energy term. The more neutron rich fragments are predicted with the asy-stiff input, an effect traced back to the, in this case, shallower symmetry potential at sub-normal density during the later reaction stages. Even though this is a very significant effect, no final conclusions were drawn by the authors because the overall behavior of the isotopic distributions could not be reproduced with the corresponding accuracy. The important role of pre-breakup emissions is also highlighted in this study.

Collective phenomena originating in the early high-density phases of high-energy collisions should be particularly sensitive to the increasingly deviating predictions for the symmetry energy (cf. Fig. 1). Within an isospin-dependent hadronic transport model, the high-density behavior was shown to uniquely determine the isospin asymmetry of the nuclear matter formed at these early stages [33]. The proton-neutron differential flow in neutron-rich systems has been suggested as a potential experimental probe, a property that should extend to the differential flow patterns of light isobars. The selection of particles with high transverse momenta in more exclusive experiments will increase the sensitivity to the dynamics at high-density. Reactions at relativistic energies have been suggested for the study of the microscopic structure of the symmetry term [34]. Also π^-/π^+ yield ratios as possibly useful observables have been investigated [35].

6 Outlook

Beams from radioactive-beam facilities have become standard tools for spectroscopic studies of exotic nuclei. The recent experimental and theoretical activities have demonstrated that high-energy secondary beams are potentially also very useful for reaction studies aiming at the determination of the symmetry term of the nuclear equation of state and of its density and temperature dependence. High energies and large asymmetries, i.e. projectiles with a large neutron excess, seem to be best suited for this purpose. Even though comparisons have to be made on an absolute scale, it is not excluded that useful constraints for the symmetry energy far from normal conditions can be obtained. It will help to reduce the uncertainties in supernova simulations and neutron star models.

The study of multifragmentation as a manifestation of the nuclear liquid-gas phase transition promises new phenomena if the isotopic degrees of freedom and the two-component nature of nuclear matter are explicitly taken into account. Isospin effects also contain novel information on the properties of highly excited fragments and on the mechanisms of their formation.

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