Exploring isospin effects on the level density and the density dependence of the symmetry energy

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Abstract

Two experiments coupling the 4π multidetector INDRA and the VAMOS spectrometer have been performed to explore both the isospin dependence of the level density and the density dependence of the symmetry term of the nuclear equation of state. Preliminary results show an isospin dependence of the Ar+Ni fusion-evaporation cross section. The isotopic resolution, which will allow to constrain the symmetry energy, has been achieved.

Introduction

Heavy ion collisions are one of the most powerful way to study the nuclear matter behaviour in extreme conditions of temperature and density, that can otherwise be encountered only in astrophysical environments.
The availability of radioactive beams, as the ones produced by the `SPIRAL` facility, allows for the very first time both to test the influence of the mass asymmetry of the entrance channel on the fusion cross section and to study the density dependence of the asymmetry term in the equation of state (EOS) for asymmetric nuclear matter.

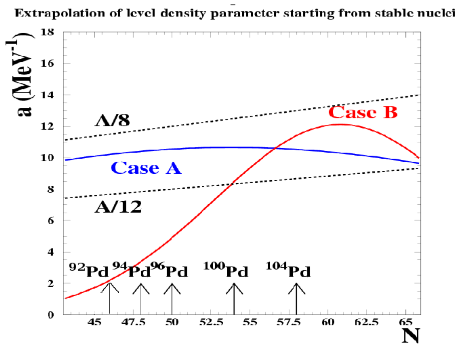

Figure 1: Evolution of the level density parameter according to two different parametrisations for different Pd isotopes (see ref.[2]). Experimental values $A/8$ and $A/12$ obtained for low and high excitation energies respectively are also reported.

Isospin dependence of the level density Fusion reactions, where the composite system de-excites mainly by evaporation, allow to experimentally access the nuclear level density $\rho(E)$, in order to study its N/Z dependence.
The nuclear level density is an important quantity for the study of both thermal and decay properties of excited nuclei and for the determination of cross sections used in nuclear astrophysics calculations [1]. Moreover ρ is an essential ingredient in calculating the statistical decay of a compound nucleus (CN) in statistical models, and it allows to access fragment primary quantities.
At present empirical parametrizations extrapolating the level density parameter a towards the p-drip line are available [2], see fig.1. However within the N/Z range produced by stable beams, contradictory results have been found [2, 3, 4]. It is therefore of primary importance to test the effect of the isospin on level densities through the evaporative charged particle emission by forming more exotic systems, such as those produced by radioactive beams.

Density dependence of the symmetry energy Knowledge on the density dependence of the nuclear symmetry energy (E_{sym}) is essential for understanding not only the structure of radioactive nuclei [5], but also many important issues in astrophysics [6]. However relatively weak constraints exist on the isospin-asymmetry term of the EOS and on its stiffness: recent experimental results [7], deduced from different observables measured in heavy ion collisions, are contradictory and more data are required to constrain theoretical models.
The isotopic distributions of complex fragments produced in multifragmentation reactions at intermediate energies are expected to be a good observable to extract

information [8]. Indeed, in these reactions, complex fragments are expected to be formed at subsaturation densities and finite temperature [9]. However surface effects could be important, as at saturation densities, leading to differences between E_{sym} extracted from multifragmentating system and the infinite nuclear matter E_{sym}. This question has been recently addressed by A. Ono *et al.* in ref.[8]. The authors have shown, by means of AMD simulation of ^{40,48,60}Ca+^{40,48,60}Ca and ^{46}Fe+^{46}Fe collisions at 35AMeV, that the symmetry energy at finite temperature and subsaturation densities extracted from the primary fragment isotopic distributions corresponds to the volume term of the symmetry energy in infinite nuclear matter. These results obviously require experimental confirmation. Quantitative information about E_{sym} are difficult to extract, due to secondary decay of excited primary fragments, which can distort signatures of the symmetry energy contained in primary fragment isotopic distributions. The detailed decay paths for these primary fragments, *i.e.* the level densities, are then required to perform the comparison.

The experiments

To fix some constraints on isospin dependence of the level density and on density dependence of the symmetry energy two experiments have been performed, taking advantage of the coupling of the 4π detector INDRA [10] and the VAMOS spectrometer [11].

^{34}Ar, ^{36}Ar and ^{40}Ar ion beams with energies of $\sim$ 13 AMeV have been accelerated and impinged onto isotopically enriched ^{58,60,64}Ni targets, in order to produce fused Pd nuclei, with mass number varying from 92 to 104. The N/Z of the compound systems ranges from 1.00 (^{92}Pd) to 1.26 (^{104}Pd).
The thermodynamical properties of different isotopes produced in quite the same conditions of formation and detection are studied precisely choosing the incident energies for each projectile to get the same excitation energy per nucleon of compound nuclei ($\sim$ 2.9 AMeV).

^{40}Ca and ^{48}Ca ion beams with energies of 35 AMeV have been accelerated and impinged onto isotopically enriched ^{40,48}Ca targets, in order to measure isotope production cross sections over a wide range of Z and N. The isotope production cross sections are studied for both peripheral collisions, which provide informations on the contribution of the surface term of E_{sym} at finite temperature and densities close to the saturation density, and for multifragmentation events, which provides access to the symmetry energy at subsaturation densities.

The INDRA multidetector [10], designed to study the deexcitation properties of hot nuclei produced during a heavy ions collision, has a structure in rings centered on the beam axis. Telescope detectors, constituted by an ionization chamber, a high resolution silicon detector and a CsI(Tl), provide the detection and the identification of all reaction products.

The large acceptance mass spectrometer VAMOS [11] has been designed to select and identify (Z, A and E) heavy reaction-products. The VAMOS focal plane detection system consists of two position sensitive detectors coupled with an ionization chamber, a silicon and a CsI detector walls, which provide ΔE, E, Z, position and time-of-flight measurements. The scattering angle at the target, $B\rho$ parameters and the mass A of each particle are obtained by software trajectory reconstruction.

The coupling of these two detectors allows to have an event by event complete information on the evaporation residue or on the PLF, with a high isotopic resolution (VAMOS), on the associated light charged particles (INDRA), and at last, but not the least for importance, on the neutron multiplicity by means of mass conservation. The correct weighting of the different decay channels allows to put constraints on the values of the level density parameter, a, for nuclei along the deexcitation chain. Moreover INDRA provides information on temperature for all decay chains and allows to have a complete event characterization (b, $E^{\star}$, particle multiplicity) to precisely select events of interest.
Further details on the experimental set-up can be found in ref. [12].

Preliminary results

Isospin dependence of the level density As a first step of the data analysis the isospin dependence of the Ar+Ni fusion-evaporation cross sections (σ_{FE}) has been studied. The analysis has been limited to INDRA data and the residue selection has been performed on general consideration (see ref.[12]), being not available neither the energy calibration nor the mass and charge identifications.
A comparison between the measured Ar+Ni differential fusion-evaporation cross sections and results obtained with `GEMINI` simulation has been performed. Both distributions have rather similar shape and show the same trend, a strong decrease of $d\sigma_{FE}/d\theta$ as the CN mass decreases, giving confidence in a proper description, by `GEMINI`, of the occurring physics processes. Based on `GEMINI` the fusion-evaporation (FE) cross sections have been extrapolated and compared with the values reported in literature. The extrapolation of σ_{FE} is very sensitive to pos-

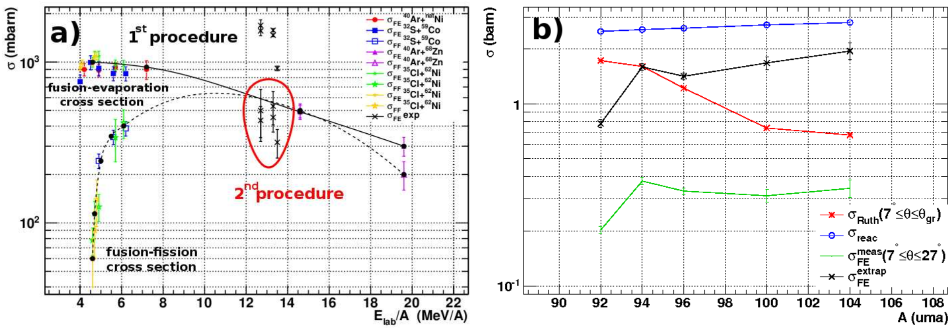

Figure 2: a) Experimental results found in literature for both FE (full symbols) and FF (open symbols) cross sections. Data are for ^{40}Ar+^{nat}Ni, ^{32}S+^{59}Co, ^{40}Ar+^{68}Zn, and ^{35}Cl+^{62}Ni [13]. The lines are only to drive the eyes. b) Integrated Rutherford cross section ($\sigma_{Ruth}(7^{\circ} \leq \theta \leq \theta_{gr})$), reaction cross section (σ_{reac}) and the extrapolated (σ_{extrap}) cross section as function of the CN mass is plotted.

sible uncertainties, being the measured angular distributions less than 25% of the total angular distributions. In order to be independent from GEMINI calculation, a new procedure is actually under analysis. Taking advantage of the expected Gaussian form of the differential FE cross section ($d\sigma/d\Omega$), a linear fit of $ln(d\sigma/d\Omega)$ vs. $\sin^2\theta$ allows to determine the analytic shape of $d\sigma/d\theta$. The integral of such function gives the σ_{FE}.
Experimental results, both for FE and fusion-fission (FF) reactions, found in literature are displayed in fig.2(a). We would like to remark that the FF cross section is comparable with the FE one ($\sim$ 600 mbarn for ^{40}Ar+^{60}Ni), but FF events have been removed during the analysis. The high cross section values obtained with the first procedure are not in agreement with the values present in literature, while the others show a better agreement. The main uncertainty in the first procedure comes from the assumption of identical shapes of the angular distributions in the experiment and in `GEMINI`. For the two procedures the absolute values rely on the parametrization of $\sigma_{el}/\sigma_{Ruth}$.

However, independently of the extrapolation procedure, a strong decrease of the fusion-evaporation cross section is observed for the lighter system, ^{92}Pd. Being the decrease of σ_{FE} bigger than the σ_{reac} one, it cannot be explained in terms of a smaller number of partial waves participating to the reaction. Moreover the decrease of σ_{FE} can be due neither to the behaviour of σ_{Ruth}, which has the opposite trend, nor to the percentage of measured $d\sigma/d\theta$, which increases when decreasing the CN mass. We verified that the effect can neither be ascribed to a detector threshold effects, which is less than 0.3% for all the analyzed reactions. All these observations are summarized in fig.2(b). The decrease of σ_{FE} suggests then a de-

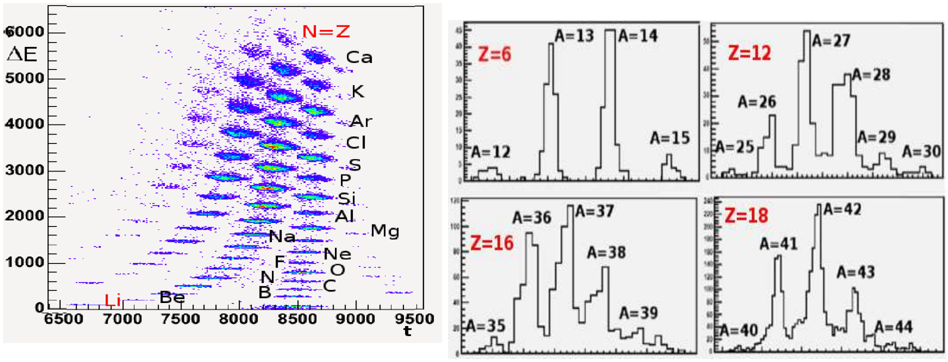

Figure 3: Typical $\Delta E - t$ correlation (a) and mass distributions (b).

pendence of the fusion-evaporation cross section from the isospin of the reactions. The strong decrease of σ_{FE} for the ^{92}Pd, lying close to the p-drip line in the nuclide chart, could also be explained by the opening of new de-excitation channels, such as the multifragmentation one. This idea is supported by the detection of IMF, with Z up to 7, in coincidence with a residue in VAMOS.
A further analysis including the VAMOS data will allow to get information on the peak region of the residue angular distributions and the absolute value of σ_{FE}.

Density dependence of the symmetry energy The aim of the first step of the analysis is to show that a good isotopic resolution, which allow to estimate the fragment yields, is present in experimental data. The analysis has been limited to one VAMOS silicon detector for a chosen $B\rho$ value.
The energy loss and the time of flight measurements provided by VAMOS Si detectors allow to obtain a good charge and mass resolution in $\Delta E - t$ spectra: fragments up to Ca are identified both in Z and A (see fig.3(a)). Starting from a $\Delta E - t$ spectrum, a parametrization of ΔE as function of the fragment charge Z allows to extract Z. Moreover taking advantage of the spectrometer relation, $B\rho = \frac{A}{q}v$, the ratio between the fragment mass (A) and charge state (q) can be deduced. The assumption of completely stripped fragments allows to reconstruct a Z vs. A/Z correlation. The mass distributions for each fragment show a very good resolution up to the projectile charge, as shown in fig.3(b). Once selected central collisions by analysing INDRA particle multiplicity, the deduced yields are combined to obtain the variable K, as suggested in ref.[8], and information on the symmetry energy can be deduced. However it is important to remark that, in order to compare the experimental data with the AMD predictions of ref.[8], it is strictly necessary to take into account the secondary decay, taking advantage from the information on the level densities.

References

[1] Donati P. *et al.*, *Phys. Rev. Lett.*, **72**, (1994) 2835

[2] Al-Quraishi I. *et al.*, *Phys. Rev. C*, **63**, (2001) 065803

[3] Charity R. J. *et al.*, *Phys. Rev. C*, **67**, (2003) 044611

[4] Gelli N. *et al.*, *Search for isospin effects on the level density on nuclei involved in the decay of* ^{139}Eu in *Recent Achievements and Perspectives in Nuclear Physics: proceeding of the* 5^{th} *Italy-Japan Symposium* (2004)

[5] Brown B. A., *Phys. Rev. Lett.*, **85**, (2000) 5296

[6] Lattimer J. M. *et al.*, *Astrophys. J.*, **550**, (2001) 426

[7] Tsang M. B. *et al.*, *Phys. Rev. Lett.*, **92**, (2004) 062701 and **102**, (2004) 122701 and refs. therein; Klimkiewicz A. *et al.*, *Phys. Rev. C*, **76**, (2007) 051603; Trautmann W. *et al.*, nucl-ex/0907.2822; Di Toro M. *et al.*, *PPNP*, **62**, (2009) 389; Galichet E. *et al.*, Phys. Rev. C 79 (2009) 064614 and 064615.

[8] Ono A. *et al.*, *Phys. Rev. C*, **70** (2004) 041604

[9] Tan W. P. *et al.*, *Phys. Rev. C*, **68**, (2003) 034609

[10] Pouthas J. *et al.*, *Nucl. Instr. and Meth. A*, **357**, (1995) 418 and **369**, (1996) 222

[11] Savajols H. *et al.*, *Nucl. Instr. and Meth. B*, **204**, (2003) 146

[12] Marini P., Ph.D. thesis, Universitá di Bologna (2009)

[13] Gauvin H. *et al.*, *Phys. Lett. B*, **58**, (1975) 163; Gutbrod H. H., *IAEA*, **2**, (1973) 309; Coffin J. P. *et al.*, *Phys. Rev. C*, **30**, (1984) 539; Fahli A. *et al.*, *Phys. Rev. C*, **34**, (1986) 161; Sikora B. *et al.*, *Phys. Rev. C*, **25**, (1982) 1446; Scobel W. *et al.*, *Phys. Rev. C*, **14**, (1976) 1808