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Abstract

A completely exclusive experiment was performed by the INDRA collaboration to study the isospin dependence of the level density parameter. Over a large N/Z range, the fusion-evaporation charged products of ^{34,36,40}Ar+^{58,60,64}Ni reactions were measured and identified both in charge and mass by coupling INDRA and VAMOS spectrometer. Preliminary results obtained by combining data of both detectors are presented for the ^{36}Ar+^{58}Ni at 13.3 A MeV. The analysis method of relevant observables for such an ambitious investigation are discussed and the progress of the data analysis are reviewed.

1 Introduction

Being able to describe the competition among the various decay modes of excited nuclei has been one of the main goals of research in nuclear physics.

Fusion process at low bombarding energy is well suited to produce such nuclei in a controlled way. At low energies the properties of the compound nucleus are well known. However incomplete fusion, linked to the fast emission of nucleons before the composite nucleus reaches thermal equilibrium, already occurs at 6 or 7 A MeV for light systems [1].

The level density parameter is a fundamental quantity in such a study. It is involved in several aspects of nuclear reactions, for instance in statistical models used in nuclear physics, astrophysics and in the search for superheavy elements. It is related to the effective mass, a property of the effective nucleon-nucleon interaction that is sensitive to the neutron and proton content of the nuclei. The level density governs the statistical decay of excited nuclei. Knowledge of the level density is thus highly needed at low and high excitation energies and for the largest possible range of N and Z, from the valley of stability to the drip lines. Indeed in the multifragmentation process observed at Fermi energies, excited neutron deficient fragments are assumed to be formed, and their de-excitation is not well constrained [2].

In the Fermi-gas framework the density of states ρ can be related to the excitation energy $E^\star$ and the level density parameter a by

$$\rho \simeq \exp 2\sqrt{a \times E^\star}$$

This expression is obtained within a single particle model and used in most statistical model calculations. Collective effects (many body and effective mass) can be included by using an effective a which depends on excitation energy [3].

The effective nucleon mass is expected to decrease with increasing temperature T while $T \leq 2$ MeV. This implies a decrease of the level density parameter but also an increase of the kinetic symmetry energy contribution to the nuclear binding energy $E_{sym}(T) = b_{sym}(T) \times (N-Z)^2/A$ as T increases. These effects would experimentally appear as a change in the particle multiplicity and in the relative yields of the exit channels [4]. While a cannot be directly measured at high energy, the temperature T and $1/T = \mathrm{d}\ln\rho/\mathrm{d}E^*$ can be extracted from the exponential slope of kinetic energy spectra of evaporated particles. Multichance emission is taken into account by comparison with statistical model calculations such as GEMINI [5]. Comparison with calculations [6] constrains the dependence of a with E^* and T and verifies the consistency with other data for known isotopes. a was shown to evolve from $A/8.5$ MeV^{-1} at low temperature to $A/15$ MeV^{-1} around T =4-5 MeV [7].

The predicted isospin dependence of level density within the Fermi gas model is a decrease with increasing $(N - Z)$. In this framework the level density parameter exhibits a small variation with isospin:

$$a \simeq mA[1 - \frac{1}{9}(\frac{N-Z}{A})^2].$$

A significantly larger dependence would have important implications for other fields (r-process). Different extrapolations starting from stable nuclei lead to empirical parametrisations of the form [8]

$$a = \alpha A \exp[\beta (N-Z)^2].$$

Those parametrisations lead to quite important variation of the estimated values of the level density parameter. The availability of stable and radioactive beams at new nuclear facilities offers a great chance to perform precise measurements on a large range of isotopes.

Experimental data far from the valley of stability are very scarce. Up to now, as only stable beams were available, level densities were studied for nuclei close to the valley of stability, on the neutron-poor side. Moreover, experiments consisted in inclusive measurements, determining either mass (charge) distribution of evaporation residues, and eventually fission products, or multiplicities of light charged particles associated with fusion. At the dawn of this century, some experiments measured evaporation residues (ER) in coincidence with one or two light charged particles [5, 9]. A first completely exclusive experiment was performed recently by the INDRA collaboration who studied the ^{78,82}Kr+^{40}Ca at 5.5 AMeV. The fission channel is 25% higher for the neutron deficient system, including very asymmetric fission configurations [10] while the extrapolated evaporation residue cross-section for both systems are similar within the error bars.

In the present very ambitious project we aimed at obtaining highly exclusive data by detecting and identifying event by event the residue and all the accompanying charged particles. The fundamental goal is to explore the variation of de-excitation properties and thus level density parameters with the N/Z of the compound nucleus when going from the proton-drip line to stable nuclei. Indeed the advent of radioactive beams, coupled to judiciously chosen targets, allows for the very first time to explore the properties of a large number of isotopes of compound nuclei of a given Z. Finally we can test the influence of the mass asymmetry of the entrance channel on the different components of the fusion cross section (ER, fission ...).

2 Experiment

2.1 The studied systems

The experiment was performed at Ganil/SPIRAL. In order to search for any evidence of a N/Z dependence of the level-density parameter from the study of the de-excitation properties of Pd isotopes formed by fusion, several collisions were carried-out between different Ar projectiles and Ni targets: ^{34}Ar+^{58}Ni, ^{36}Ar+^{58}Ni, ^{36}Ar+^{60}Ni, ^{40}Ar+^{60}Ni and ^{40}Ar+^{64}Ni. In order to reach a compromise between reduced preequilibrium effects and a sufficient recoil energy for nuclear charge identification of residues, as well as to get the same excitation energy per nucleon of compound nuclei ($\sim$2.9 A MeV) and very similar angular momentum ranges, the incident energy for each beam was chosen around 13 A MeV.

Five Pd isotopes were thus sampled with N/Z ranging from 1.00 (^{92}Pd) to 1.26 (^{104}Pd). The ^{92}Pd formed with exotic ^{34}Ar allows to touch the p-drip line [11]. In this case special de-excitation properties might be observed as for the semi-magic nucleus ^{96}Pd.

2.2 Experimental set-up

The INDRA multidetector [12] was coupled to the large acceptance mass spectrometer VAMOS [13] allowing a 4π coverage. INDRA is made of 17 rings centered on the beam axis. Each one of these contains multi-stage telescopes composed of Ionisation Chambers, Silicon and Caesium Iodide detectors (for this experiment, the first 3 rings were removed to allow coupling to VAMOS). INDRA is dedicated to detecting the emitted light charged particles (LCP).

VAMOS provides the charge, mass and velocity of the evaporation residues (ER). Its focal plane detection system was composed of two emissive foils (SeD) coupled with an ionization chamber (IC) and a silicon detector wall (Si) providing ΔE, E, Z and position measurements. The scattering angle at the target (θ) and the magnetic rigidity ($B\rho$) are obtained by software trajectory reconstruction. The time-of-flight (ToF) of evaporation residues is measured between the target and the SeDs (or Si) using the high frequency signal of the cyclotron as reference. With such long flight distances, mass (A) and charge state (Q) identifications are achieved. We set different angular positions of the spectrometer to cover the residue angular distribution ($\sim 0^\circ - 12^\circ$) to avoid any bias of the relative weights of the different exit channels. We placed a carbon foil of 70 μg/cm^2 at a distance of about 50 cm from the target in order to reach the equilibrium charge state distribution [5], independently of the compound nucleus production position within the target.

This experimental setup is crucial as it allows direct measurement of both the evaporation residue in VAMOS and the associated light charged particles in INDRA.

3 Analysis plan

The detection efficiency was maximized to obtain a large number of complete events of fusion (detection of the total charge of the compound system). The 4π angular acceptance allows to differentiate more easily fusion reactions from deep inelastic collisions or incomplete fusion thanks to recoil energy criteria [1]. In fusion-evaporation events, the multiplicity of the undetected neutrons will be derived by the difference between the compound nucleus mass and those of all detected de-excitation charged products.

All decay chains will be precisely characterized: isotopic composition of emitted particles and their multiplicity added to the residue characteristics (A, Z) and their kinetic energies event by event. Moreover, we will obtain the percentage with which different chains lead to the same residue. The energy spectra (slope) of all de-excitation products will provide information on apparent temperature for all decay chains. For example, in this experiment, the Ni(Ar,αxn)Ru channel can be disentangled from the Ni(Ar,2p(x+2)n)Ru and Ni(Ar,pd(x+1)n)Ru channels and correctly weighed.

The detection of complete events will put additional strong constraints on the values of a for nuclei along the de-excitation chain for theoretical models; this has never been done up to now.

4 Present status of the project

Before the data can be analysed for physics, it is necessary to have a good calibration for both INDRA and VAMOS detectors. Presently identifications and calibrations of the INDRA array are nearly ready for all the systems. The Z and A identification of LCPs is achieved.

The data reduction of the VAMOS part is more delicate. We are in the final process of getting the mass and charge of the evaporation residues, after reconstruction of the trajectories in the spectrometer and the calibration of ToFs. The obtained mass separation in VAMOS for the ERs in the ^{36}Ar+^{58}Ni reaction is shown in fig 1. A preliminary selection of ERs is realized by taking into account only complete events with $Z_{tot} > 40$ and $M_{f5} = 1$ where $Z_{tot} = \sum_i^{events} Z_i$ and M_{f5} is the multiplicity of fragments with $Z \geq 5$. The most striking feature in fig 2 is these spots associated to each mass along horizontal ridges corresponding to Q. The integer value of each Q is then easily identifiable. By multiplying it by the ratio A/Q, we obtain a well defined mass distribution as shown in the bottom right panel.

The analysis is still premature to extract physics results. Nevertheless,

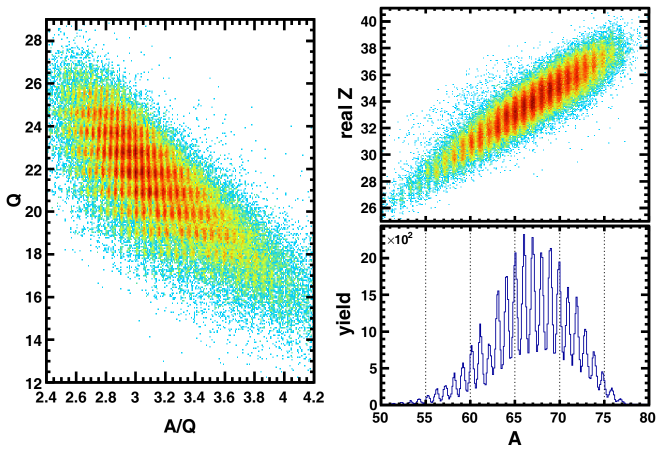

Figure 1: Mass separation (A) of evaporation residues produced in ^{36}Ar+^{58}Ni reaction and measured within VAMOS at Bρ_0 = 0.638 T.m and $\theta_{VAMOS} = 0°$. Left: distribution of charge state (Q) versus A/Q deduced from ToF, reconstructed $B\rho$ and/or energy measured in all silicon detectors. Right: Distribution of measured atomic charge (real Z) versus mass (A). The mass (A) is obtained by multiplying the reconstructed A/Q ratio by the integer value of Q for 16≤Q≤27.

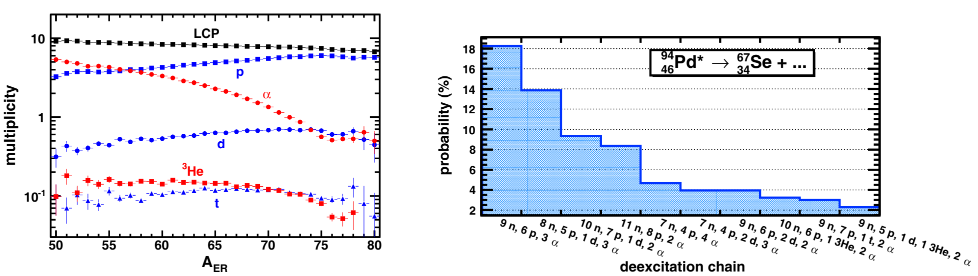

Figure 2: Example of new information available thanks to the detection of complete events for ^{36}Ar+^{58}Ni reaction and within INDRA and VAMOS at Bρ_0 = 0.638 T.m and $\theta_{VAMOS} = 0°$. Left: multiplicities of charged particles as a function of the mass of the evaporation residue in coincidence (see text for details about the ER selection). Right: probablities of the ten most probable deexcitation chains of ^{94}Pd leading to the ^{67}Se residue.

here and now we can have a general survey of what we can expect for the following as illustrated in fig 2, where some preliminary information that can be only extracted from a complete event detection are presented. The left panel shows partial multiplicities of different charged particles as a function of the mass of ERs detected in VAMOS placed at 0° with $B\rho_0$=0.638 T.m. With this kind of detection it is possible to focus any study on some deexcitation chains leading to a given ER, as shown in the right panel of fig 2 where the probabilities of the ten most likely deexcitation chains of ^{94}Pd leading to the ^{67}Se residue are plotted. These very accurate and selective information will bring new strong constraints for the study of the evolution of the level density parameter from the deexcitation of compound nucleus.

5 Conclusion

In summary, the E494S INDRA-VAMOS experiment represents a great opportunity to explore the isospin dependence of the level density parameter by coupling a 4π charged particle multi-detector to a high resolution magnetic spectrometer. At present, both INDRA and VAMOS data sets are being combined to give the full information about each decay channel of evaporation residues and the current physics analysis is on the threshold of releasing the new expected constraints on the level density parameter.

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