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Decay competition in IMF production in the collisions ⁷⁸Kr+⁴⁰Ca and ⁸⁶Kr+⁴⁸Ca at 10 AMeV

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Abstract. De-excitation modes of compound systems ¹¹⁸Ba and ¹³⁴Ba, produced respectively in the ⁷⁸Kr+⁴⁰Ca and ⁸⁶Kr+⁴⁸Ca collisions at 10 A.MeV, are investigated. In particular, the competition between the various disintegration decay paths of medium mass compound nuclei, formed by fusion processes and the isospin (related to N/Z) of the entrance channel influence on the decay process, are studied. Data were taken at the INFN-Laboratori Nazionali del Sud (LNS) in ISODEC experiment, by using the CHIMERA array. The experiment complements and improves the previous experiment performed at GANIL where the same mechanisms were studied at lower excitation energies. The results show the presence of a relaxed component in the reaction mechanism, evident staggering effects in the Z distributions, as well as different isotopic composition and neutron enrichment for the reaction products in the two systems.

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1. Introduction

In the recent years, one of the principal aim in the field of the nuclear reactions is the study of the influence of the entrance channel N/Z ratio, on the reaction mechanism and on the formation and production of the fragments in the exit channel.

In this context, particular interest is focused on the heavy-ion reactions at low energy (E/A< 10-15 AMeV), where the fusion process are predominant. Indeed, one expects that the N/Z ratio, directly connected to the isospin degree of freedom, plays an important role on the compound nucleus decay and on the emission process, providing crucial information on fundamental nuclear parameters as the level density, the fission barrier and the viscosity. Thus the chemical composition influences the fission dynamics and a program of systematic measurements of fission cross-section for a large isotopic chain of compound nuclei, from neutron rich to neutron-poor, provides careful information on this mechanism.

In this work, we present the up to date results of the ISODEC experiment, realized to study the competition between the various disintegration modes of ^{118,134}Ba compound nuclei produced in the reactions ⁷⁸Kr+⁴⁰Ca (neutron poor system) and ⁸⁶Kr+⁴⁸Ca (neutron rich system) at 10 AMeV. The experiment was performed at the INFN Laboratori Nazionali del Sud (LNS) in Catania by using the CHIMERA detector. It complements and improves the data obtained at 5.5 MeV/A for ^{78,82}Kr+⁴⁰Ca reactions [1], previously realized with beams delivered by GANIL facility in Caen (France) and by using the INDRA detector.

The investigated systems allow to produce compound nuclei in a large domain of N/Z (from 1.11 to 1.39) considering the use of stable beams, and similar both spin distribution and excitation energy. Such a set of data also will provide new constraint on sophisticated models attempting to describe statistical and/or dynamical properties [2] of excited nuclei.

2. Experimental Setup

The presented scientific program needs the measurements of several key observables such as the cross sections, multiplicities, angular and kinetic energy distributions of the reaction products (Intermediate Mass Fragments - IMFs, Light Charge Particles – LCPs and Fission Fragments - FF). The measurement of these observables requires a good isotopic resolution and a low energy thresholds for LCPs and IMFs, a high granularity and a broad angular acceptance.

The presence at LNS of a second generation 4π multi detector, CHIMERA [3], and the availability of beams with very good intensity and timing characteristics, strongly pushed to perform the experiment in Catania.



Figure 1. The CHIMERA detector at LNS

Briefly, CHIMERA consists of 1192 detector telescopes, arranged on 9 rings in the forward part and 17 rings, in spherical configuration, in the backward part; the covered polar angle goes from 1° to 176° and the efficiency is the 94% of the total solid angle. In figure 1, a picture of the detector in its experimental scattering chamber at LNS is presented.

The single detection cell consists of a silicon detector (Si, thickness about 300 μ m) followed by a Caesium Iodine–Thallium doped crystal, (CsI(T1), thickness from 3 cm to 12 cm), coupled to a photodiode.

The identification methods employed are:

 Δ E-E for charge identification of particles punching through the Si detector and stopped in the CsI(Tl) with also mass identification for particles with Z<10;

E-TOF (Time of Flight) for mass identification, velocity and energy measurement of the particles stopped in the Si detector;

PSD (Pulse Shape Discrimination) in CsI(Tl), for isotopic identification of more energetic light charge particles;

PSD (Pulse Shape Discrimination) in Si detector, for charge identification of the particles stopped in the Silicon detector.

This latter technique [4,5] was the last implementation made on the CHIMERA array and allows the use of this device to study reaction mechanism also in the low energy domain, extending the investigation dynamical range from fusion to multifragmentation reactions.

In figure 2 is reported as an example the Energy (E_{si}) vs Rise Time (RT_{si}) plot obtained by the PSD methods in silicon detector, for the n-poor system ⁷⁸Kr+⁴⁰Ca at 10 AMeV at $\vartheta = 34^{\circ}$.



Figure 2. Energy-RiseTime plot for ⁷⁸Kr+⁴⁰Ca

Besides, the CHIMERA multidetector is characterized by a low energetic detection threshold, that is less of 0,5 MeV/A for heavy ions and 1 MeV/A for light particles. These characteristics allowed the complete identification of LCP in a wide energy range, the complete identification in charge and mass of the IMF (3 < Z < 8) products, the charge identification up to Z =14-16 for products stopped in the Silicon, and up to about Z = 30 for the most energetic particles stopped in CsI.

In figure 3 is shown an example of the typical matrix ΔE -E to show the good charge resolution discrimination of the array.



Figure 3. ΔE_{Si} - $E_{CsI(TI)}$ plot for ⁷⁸Kr+⁴⁰Ca

Figure 4 shows an example of isotopic identification for particles punching-through the silicon detector. The mass distribution for Carbon isotopes is obtained at polar angle of 15° for the two studied reactions [6].



Figure 4. Carbon isotopes distributions at 15° for the two studied reactions

In the experiment, self-supporting 1 mg/cm² thick ⁴⁰Ca and ⁴⁸Ca targets, prepared in collaboration between INFN-LNL and INFN-LNS Target Laboratories, were bombarded by ^{78,86}Kr beams at 10 AMeV, delivered by the LNS Superconductive Cyclotron, with typical beam intensity of 800-1000 pA. The pulsed beam was delivered with a timing resolution about 800 ps - 1 ns. Inclusive and coincidence measurements were realized.

3. Experimental Results

3.1. Mass distribution

In order to study the influence of the isospin degree of freedom it is essential to get the isotopic identification at least of part of the detected fragments. The capability of the CHIMERA detector allows us to get the mass distributions for the IMF $2 \le Z \le 8$.

In figure 5 the mass distribution for Z = 3, 4, 5 and for the two studied systems are reported [7,8].



Figure 5. Mass distributions for Z=3,4,5, for the n-poor system and n-rich system

One can see the different isotopic composition and relative enrichment in correspondence of the same Z, for the compared systems. In particular this effect is evident for the Be element, in which the isotopic composition goes from A=7, 9, in the n-poor system, to A= 9,10, in the n-rich one. These differences in the two systems show that a memory of the entrance channel is still present in this class of reaction products, and this could be to an effects of the isospin influence on reaction mechanism or on the structure of the emitted fragments. The research on these effects is in progress.

3.2. Kinetimatical features

Relevant information on the reaction mechanism can be obtained from the kinetic energy spectra of the detected fragments. In figure 6, the Z=6 centre of mass energy spectra are reported for the neutron rich system, measured at the laboratory angles angle $\vartheta = 10.75^\circ$, 12.25° , 13.75° , 15.25° . For each angle, the spectra for the identified isotopes are shown.



Figure 6. Center of mass Energy spectra for C isotopes for neutron rich system at different angles.

In figure 7 the centre of mass energy spectra for Z=12, at laboratory angle $\vartheta = 10.75^{\circ}$, 12.25°, 13.75°, 15.25° and for the neutron poor system is shown.

One notes the Gaussian-like shape of the spectra and that they are centred at the same energy value, independently from the detection angle. The same result is obtained for the energy spectra of the $1 \le Z \le 17$ fragments and for both the studied systems.



Figure 7. Centre of mass Energy spectra for Z=12 at different angles, for the neutron poor system

From the energy spectra the average velocity in the centre of mass $\langle v_{cm} \rangle$ can be calculated for $3 \leq Z \leq 17$. The results are presented in figure 8 for various laboratory angles and for the neutron poor system. One notes that for a given Z the average velocity in the centre of mass is essentially constant regardless of the emission angle.

The general behaviour observed for the emitted fragments, both in the energy spectra and in the average velocity, indicates an high degree of relaxation in the production mechanism.



Figure 8. Average velocity distribution (see the text)

3.3. Angular distributions

Fundamental information can also be deduced from the angular distribution of the emitted fragments, allowing for example to distinguish totally equilibrated processes, as the compound nucleus formation followed by evaporation or fission, from partially equilibrated process as the fast-fission or the DIC (deep inelastic collisions) processes.

To get this kind of information the angular distribution for $\leq Z \leq 14$ are compared with the *1/sen* ϑ distribution behaviour, that is a clear indication of the isotropic emission typical of the compound nucleus emission. In figure 8, this comparison is shown for Z=8,10,12, 14 for the neutron poor

system; the $1/sen \vartheta$ distribution behaviour is reported with dashed line. This comparison gives a clear indication of the isotropic emission typical of the compound nucleus emission.



Figure 8. Angular distributions of Z=8,10,12,14 for the neutron poor system, compared with *l/sen* ϑ distribution behaviour (dashed line)

3.4. Charge distributions

As said before, one of the principal aim of the experiment is the study of the influence of the isospin or of the connected observables, on the reaction mechanism and on the fragments productions. This should appear also in the charge distribution, as already observed in the Ganil experiment.

A preliminary comparison between the fragments yields of the studied systems is presented in figure 9. The results are obtained by integrating the yields of particles with 3<Z<15, identified with Δ E-E and PSD method on Si detector, in the angular range $10^{\circ} \le \theta \le 16^{\circ}$.



Figure 9. Charge distribution for the two studied systems and comparison with preliminary results from DNS-model.

In the figure, one can see a strong odd-even staggering of the Z yield for Z < 10 detected fragments, and this effect persists for higher Z with a smaller amplitude.

Besides, comparing the two systems with different isospin, the yields of the IMF exhibit an even-odd staggering that is more pronounced for the neutron-poor system. This effect in the comparison appears also in other examples in the literature [9]

It seems that the neutron excess in the entrance channel affects the yields of the light fragments; the extraction of the absolute cross section of the reaction products, which is in progress, will confirm this

result. An influence can be originated also by structure effects [10] linked to the pairing forces and that is important for the studies on Symmetry Energy.

In figure 9 the lines are the preliminary results obtained by calculations with the dynamical DNS (Di Nuclear System) model, for Z<10. Following this model a dinuclear system is formed in the beginning of the reaction, that can go towards a not fully equilibrated fast-fission or towards an equilibrated fissioning compound nucleus. A detailed description of the model can be found in [11]. The calculation seems to be in a better agreement in the case of the neutron poor system, where the oscillation of the staggering of the yields is decreasing as the atomic number increases in agreement with the experimental findings.

4. Conclusions

Experimental methods and some results of the ISODEC experiment were illustrated. The experiment aims the study of the 78,86 Kr+ 40,48 Ca reactions at 10 AMeV incident energy and complements and improves the 78,82 Kr+ 40 Ca reactions at 5.5 MeV/A, realized at GANIL facility by using the INDRA detector.

Some of the results on the experimental features of the produced fragments were shown; in particular charge and mass distributions, as well as kinematical features and angular distributions were reported and compared for the two systems. These results indicate an high degree of relaxation of the system formed in the collision, before of its breakup, that is typical in compound nucleus and fission-like reaction mechanisms.

Staggering effects are evident in the Z distributions, as well as different isotopic composition and neutron enrichment for the reaction products in the two systems.

The observed effects could be due to the role of the N/Z degree of freedom on the decay channels. Data analysis and more refined comparisons with theoretical models are in progress.

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