Isospin physics by CHIMERA detector

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Abstract. This contribution presents some recent results relative to the studies of isospin-asymmetric nuclear matter in experiments using the 4π detector CHIMERA and the beams delivered by the Superconductive Cyclotron at INFN-Laboratori Nazionali del Sud in Catania. In particular, we report the results of the experiments named “Reverse” and “Isodec”, both included in the EXOCHIM activity supported by the CNSIII of INFN. In the Isodec experiment, the two systems $^{78}_{-}Kr+^{40}_{+}Ca$ (neutron poor) and $^{86}_{-}Kr+^{48}_{+}Ca$ (neutron rich) at 10A MeV were studied, looking at the competition between the various disintegration decay paths of medium mass compound nuclei, formed by fusion processes and at the isospin influence on the decay process. The results show the presence of a relaxed component in the reaction mechanism, the evidence of staggering effects in the Z distributions, as well as different isotopic composition and neutron enrichment for the reaction products in the two systems. In the Reverse experiment, mass asymmetric projectile-target combinations $^{124}_{-}Sn+^{64}_{+}Ni$ and $^{112}_{-}Sn+^{58}_{+}Ni$ were investigated at 35A MeV. We provide evidence that the Dynamical Fission process is about two times more probable than the equilibrated (statistical) Fission one in the neutron rich $^{124}_{-}Sn+^{64}_{+}Ni$ system with respect to the $^{112}_{-}Sn+^{58}_{+}Ni$ neutron poor one. The observed difference in the strength of the dynamical effects could arise from the difference in the entrance channel Isospin (N/Z) content.

1. Introduction

In recent years, one of the principal aim in the field of heavy ion reactions is to study the influence of the entrance channel N/Z ratio on the reaction mechanism and the fragments formation and production in the exit channel. In this context, particular interest is focused on the heavy-ion reactions at low energy [1] ($E/A < 10-15$ MeV), where the fusion process is predominant and at intermediate energy, where statistical and dynamical processes in the fragment emission can coexist in a complex way.

At low energy, indeed, one expects that the N/Z ratio, directly connected to the isospin degree of freedom, plays an important role in the compound nucleus decay and 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, at section 3, we present the up to date results of the ISODEC experiment, realized to study the competition between the various disintegration modes of $^{118,134}_{+}B$ compound nuclei produced in the reactions $^{78}_{-}Kr+^{40}_{+}Ca$ (neutron poor system) and $^{86}_{-}Kr+^{48}_{+}Ca$ (neutron rich system) at 10A MeV. The investigated systems, making use of stable
beams, allow to produce compound nuclei in a large domain of N/Z (from 1.11 to 1.39) with similar spin distribution and excitation energy. Such a set of data will provide new constraints on sophisticated models attempting to describe statistical and/or dynamical properties [2] of excited nuclei.

At intermediate energy, and in particular in semi-peripheral reactions, the production of Intermediate Mass Fragment (IMF, Z ≥ 3) and Light Charged Particles (LCP) in the velocity region between the PLF and TLF has been experimentally observed and the features of a dynamical origin have been clearly evidenced in many works (see [3–8] and references therein). In addition, a clear signature of an emission chronology related to the IMF size was demonstrated [3–5, 9, 10]. It was found that lighter IMF (Z ≤ 9) in the midvelocity region are likely to be emitted during the re-separation process of the primary interacting Projectile and Target Like Fragments (PLF* and TLF* respectively) in prompt neck-rupture mechanism (time < ∼ 120 fm/c) [3, 4, 6, 9]. Conversely, emission of heavier IMF (Z ≥ 9) was shown to happen at the late stage of the neck expansion process (time ≥ 120 fm/c), and was associated with the “Dynamical Fission” mechanism [5, 9–12]; this is nearly a two-step sequential reaction: scattering of primary nuclei (PLF*-TLF*) followed by fast non-equilibrated fission-like process. In this work, at section 4, results of cross sections associated to Dynamical and Statistical Fission mechanisms for neutron rich 124Sn+64Ni and neutron poor 112Sn+58Ni reactions at 35A MeV were evaluated [10]. It was shown that Dynamical Fission process is about two times more probable in the neutron rich 124Sn+64Ni system than in the 112Sn+58Ni neutron poor one. This sizable difference in the cross section associated to Dynamical Fission gives indication of a strong influence of the entrance channel isospin content on the reaction mechanism. Both the experiments were performed at the INFN Laboratori Nazionali del Sud (LNS) in Catania by using the 4π array CHIMERA with beams delivered by the Superconductive Cyclotron.

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,
namely 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 of the second generation $4\pi$ multi detector CHIMERA [3], and the availability of beams with very good intensity and timing characteristics, make the LNS in Catania particularly favourable to perform such a program.

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 $1^\circ$ to $176^\circ$ 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 $\mu$m) followed by a Caesium Iodine Thallium doped crystal, (CsI(Tl), thickness from 3 cm to 12 cm), coupled to a photodiode. The identification methods employed are: $\Delta E$-$E$ 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 of particle stopped in the Si detector and velocity measurement of all the particles; 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 [13, 14] 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 range of reaction mechanism investigation from low energy fusion to multifragmentation reactions.

In figure 2, left panel, 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 $^{78}$Kr+$^{40}$Ca at 10A MeV at $\theta_{lab}=34^\circ$.

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

![Figure 2.](image-url)
stopped in the Silicon detectors, and up to about \( Z = 30 \) for the most energetic particles stopped in CsI. In figure 2, right panel, is shown an example of the typical matrix \( \Delta E-E \) illustrating the good charge resolution discrimination of the array.

3. Isodec, experimental results
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 with charge \( 2 \leq Z \leq 8 \). In figure 3 the mass distribution for \( Z = 3, 4, 5 \) and for the two studied systems are reported [15–17]. It is clearly seen that, for the same charge \( Z \), in the two systems the isotopic composition and relative neutron enrichment is extremely different. In particular this effect is evident for the Be element where the isotopic composition spans from \( A = 7, 9 \) for the n-poor system to \( A = 9, 10 \) for 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; it seems evident the influence of the isospin degree of freedom of the entrance channel on reaction mechanism or in the structure properties of the emitted fragments.

Relevant information on the reaction mechanism can be obtained from the kinetic energy spectra of the detected fragments. In figure 4 the centre of mass energy spectra for \( Z=12 \), at laboratory angle \( \theta = 10.75^\circ, 12.25^\circ, 13.75^\circ, 15.25^\circ \) 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 fragments with charge \( 11 \leq Z \leq 17 \) for both the studied systems.

As said before, one of the principal aim of the experiment is the study of the influence of the isospin and the related observables, on the reaction mechanism and on the productions and de-excitation properties of the emitted fragments, as already observed in the Ganil [1] experiment. A
preliminary comparative study between the fragments yields of the studied systems is presented in figure 5. The results are obtained by integrating the yields of particles with charge $3 \leq Z \leq 15$, identified by $\Delta E$-E and PSD method on Si detector, in the angular range $10^\circ \leq \vartheta \leq 16^\circ$.

Figure 5 shows 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. Indeed, by comparing the two systems, the yields of the IMFs exhibit an even-odd staggering that is more pronounced for the neutron-poor system. The same effect, by comparing systems with different N/Z neutron to proton ratio, appears also for other reactions in the literature [18].

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. Structure effects linked to nuclear pairing forces certainly play a role [19] and their understanding is relevant, for example, for constraining the density dependence of the symmetry energy in asymmetric nuclear matter.

In figure 5 the line show results from preliminary calculations using the dynamical DNS (Di

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**Figure 4.** (Color online) Centre of mass Energy spectra for $Z=12$ at different angles, for the neutron poor system.

**Figure 5.** (Color online) Charge distribution for the two studied systems and comparison with preliminary results from DNS-model.
Nuclear System) model, for \( Z < 10 \). In 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 [20]. The calculation, normalized at \( Z = 6 \), seems to be in a better agreement with the neutron poor system data, where the oscillation of the charge distribution yields staggering is decreasing as the atomic number increases in agreement with the experimental findings.

4. Dynamical Fission, experimental results

For the two reactions \(^{124}\text{Sn} + ^{64}\text{Ni}\) and \(^{112}\text{Sn} + ^{58}\text{Ni}\) studied at 35A MeV, in order to select peripheral collisions, the method of Cavata [21] was used to estimate the impact parameter from the total charged-particle multiplicity. This method assumes a purely geometrical monotonic correlation between the total charged-particle multiplicity of the collision process and the impact parameter. Figure 6 shows the correlation between the experimental total charged particles multiplicity and the estimated reduced impact parameter \( \frac{b}{b_{\text{Max}}} \) where \( b_{\text{Max}} \) corresponds to the total geometrical cross section. Note that at a fixed \( \frac{b}{b_{\text{red}}} \) the neutron poor system produces a higher multiplicity. In fact, as predicted by calculations [22, 23], in the neutron poor system the dynamical and pre-equilibrium phases lead to more light charged particles (mainly protons) emission than in neutron rich one where, in contrast, neutron emission is favored.

After selecting, in both systems, peripheral collisions with condition \( \frac{b}{b_{\text{red}}} > 0.7 \), the two heaviest fragments of the chosen subset of events, named as Heavy (H) and Light (L) according to their atomic number \( Z \), were analyzed in those events that satisfy the following conditions: (i) the combined charge of the two selected fragments \( Z_{2F} = Z_H + Z_L \) is close to the charge of the projectile \( (Z_{\text{proj}} = 50) \), that is, \( 37 < Z_{2F} < 57 \), and (ii) the Heavy-to-Light-fragment mass ratio is \( A_H/A_L < 4.6 \), so that the Light fragment has charge \( Z_L \approx 9 \). Applying such conditions, the Heavy fragments have the component of the velocity parallel to the beam axis \( (V_{\text{par}}^H) \) very close to the value of \( \sim 7.5 \text{ cm/ns} \), that is, slightly below the beam velocity of \( \sim 8 \text{ cm/ns} \), while the Light fragments have a wider distribution of the parallel velocity, ranging from the velocity of the TLF \( (\sim 1 \text{ cm/ns}) \) up to velocities exceeding the PLF ones. This is shown in figure 7, where, using a logarithmic intensity scale, the \( V_{\text{par}} \) versus \( V_{\text{per}} \) Galilean-invariant plots for Light fragments produced in the \(^{124}\text{Sn} + ^{64}\text{Ni}\) reaction are presented, for three ranges of mass asymmetry \( A_H/A_L \) (columns), and for three ranges of the total kinetic energy of the two selected fragments.

![Figure 6](image_url)

**Figure 6.** (Color online) Estimated reduced impact parameter \( \frac{b}{b_{\text{red}}} \) plotted as function of the experimental total charged particles multiplicity for the \(^{124}\text{Sn} + ^{64}\text{Ni}\) and \(^{112}\text{Sn} + ^{58}\text{Ni}\) reactions at 35A MeV, as obtained by applying the method of Cavata.
Figure 7. (Color online) Invariant $V_{\text{par}}$ versus $V_{\text{per}}$ plots for the Light fragments in the $^{124}$Sn+$^{64}$Ni reaction at 35A MeV. Different panels correspond to different values of mass asymmetry $A_H/A_L$ and total kinetic energy $E_{2F} = E_H + E_L$. The distributions are shown in logarithmic scale. The red color corresponds to the largest cross sections and the arrows indicate the beam velocity.

fragments $E_{2F} = E_H + E_L$ (rows). The quantity $E_{2F}$ is a measure of the collision violence: larger values of $E_{2F}$ are associated with more gentle (peripheral) collisions, while more violent collisions are associated with smaller $E_{2F}$ values. In all panels of figure 7 it is possible to observe the characteristic Coulomb rings centered slightly below the beam velocity; the presence of such rings points to PLF* as a well-defined decay source and proves the scenario of two separate reaction steps: first the scattering of the PLF*, followed by its splitting into two fragments (H and L). In almost symmetric divisions after less dissipative collisions [$E_{2F}=3450-4000$ MeV and $A_H/A_L =1.0-1.6$], the Light fragments distribution is forward-backward symmetric, that is, the Light fragments have equal probability to be emitted forward or backward in the reference frame of the PLF* source. This result is characteristic of an equilibrated fission, where the nucleus is supposed to be completely equilibrated in all its degrees of freedom; there, the PLF* splitting is expected to occur a long time (1000 fm/c or more) after at least one complete rotation.

In more dissipative collisions and/or more asymmetric splits, the population of the Coulomb ring is no longer forward-backward symmetric. In fact, Light fragments have the tendency to populate preferentially the low-velocity side of the Coulomb ring, which means that they are backward emitted in the PLF* reference frame, that is, toward the TLF*. Nonetheless, a forward-backward symmetric component is still present. Therefore, the observed distributions can be interpreted as a superposition of a forward-backward symmetric component and an asymmetric one. The observed forward-backward asymmetry is the main signature of the Dynamical Fission; that indicates that PLF* fission-like splitting has to be a fast process. After selecting Light fragments populating the Coulomb ring by gating on $V_{\text{par}}$ (see Ref. [5] for details), in order to disentangle and estimate isotropic and anisotropic fission-like splitting in the two Sn+Ni sytems, the differential cross sections $d\sigma/cos(\theta_{\text{prox}})$ have been evaluated. That
Figure 8. (Color online) $\cos(\theta_{\text{prox}})$ angular distributions of the PLF break-up fragments for the $^{124}\text{Sn}+^{64}\text{Ni}$ (circles) and $^{112}\text{Sn}+^{58}\text{Ni}$ (triangles) at 35A MeV, for three different bins of the total kinetic energy ($E_{2F}$) and mass asymmetry $A_H/A_L$.

is shown in figure 8 for the three bins of the mass asymmetry $A_H/A_L$ and three bins of the $E_{2F}$. The $\theta_{\text{prox}}$, defined in left panel of figure 9, is the angle between the PLF* flight direction (in the CM reference frame) before fission-like splitting, and the breakup axis, defined by the relative velocity of the two fission-like fragments $V^H - V^L$. The value of $\cos(\theta_{\text{prox}}) = 1$ corresponds to the Heavy fragment moving forward along the PLF* flight direction, while the Light fragment is emitted backward along the PLF*-TLF* direction. In the case of equilibrated

Figure 9. (Color online) Left panel: $\theta_{\text{prox}}$ definition: angle between the breakup axis, oriented from the light L to the heavy fragment H, and the recoil velocity in the center of mass of the projectile-like fragment (noted VPLF) reconstructed with the two fission fragments, from [12]; right panel: example of extrapolation of Dynamical and Statistical Fission from $\cos(\theta_{\text{prox}})$ distribution.
splitting, a symmetric distribution around the value of $\cos(\theta_{\text{prox}}) = 0$ is expected, as observed in figure 8 for almost symmetric splitting in more peripheral collisions. Instead, by progressively increasing the mass asymmetry and inelasticity ($\text{lower } E_{2F}$), an increase of a forward peaked distribution, superimposed to a symmetric one around the value of $\cos(\theta_{\text{prox}}) = 0$, is clearly seen; that is associated to the Dynamical Fission. In order to isolate the equilibrated component, a symmetrization around $\cos(\theta_{\text{prox}}) = 0$ of the backward part, $\cos(\theta_{\text{prox}}) < 0$, of the distribution has been done, by assuming that the latter is not influenced by Dynamical Fission. The Dynamical contribution is then obtained by subtracting the extrapolated Statistical Fission distribution from the total experimental one. A sketch of this procedure is shown in the right panel of figure 9. It results that the Statistical Fission cross section is approximately the same in the two systems. In contrast the Dynamical component is larger for the neutron rich system by a factor of about 2 as compared with the neutron poor one, as can be found in tables published in Ref. [10]. This sizable difference in the cross section associated to Dynamical Fission indicates a strong influence of the entrance channel on the reaction mechanism. Since the two systems have a large difference in the Isospin content it appears quite natural to link this to an Isospin effect; however, a possible influence of the system size can not be a priori excluded.

In order to disentangle entrance channel Isospin effects from the possible dependence of these results upon the initial different mass of the two systems, in April 2013 we carried out a new experiment, named InKilIsSy (Inverse Kinematic Isobaric Systems) [24], using a projectile/target combination having the same mass as the neutron rich $^{124}$Sn+$^{64}$Ni system and a N/Z near to value of the neutron poor $^{112}$Sn+$^{58}$Ni one, that is $^{124}$Xe+$^{64}$Zn at the same bombarding energy of 35A MeV; the analysis is in progress.

From theoretical side, the Dynamical Fission phenomenon has been studied by transport model simulations. The Stochastic Mean Field simulation (SMF) [25] is a good approach in order to describe the gross features of Dynamical Fission. However, the simulation can hardly follow the complete time evolution of the deformed PLF up to the scission point. Many features of the Dynamical Fission processes could be reproduced in quantum molecular dynamics models like the Constrained Molecular Dynamics (CoMD-II) [9]. The main feature of this last model is a self-consistent N-body approach that solves the equations of motion using procedures to satisfy event-by-event the Pauli principle and the total angular momentum conservation law. Then, we plan to perform future studies using both SMF and CoMD-II models in order to shed light on the observations here reported.

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