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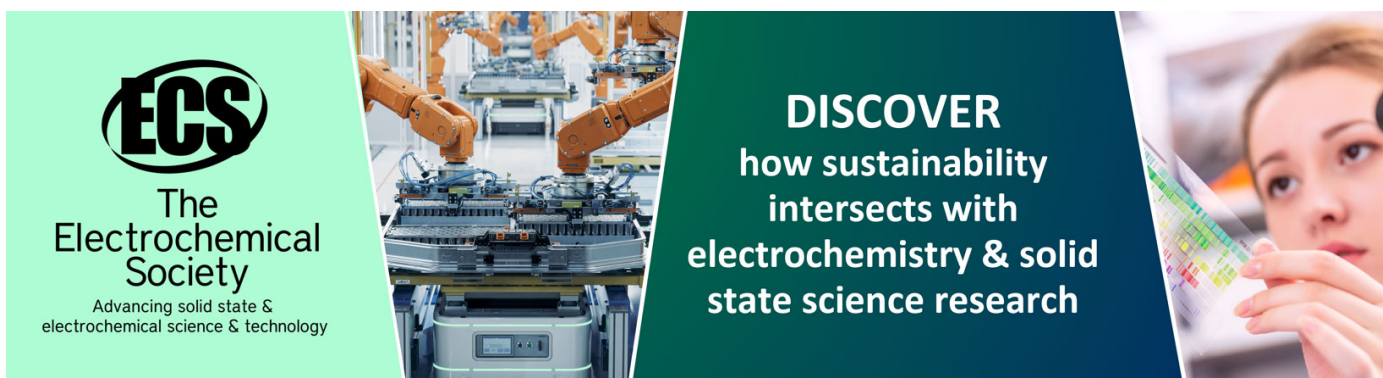
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## Isospin Effect on fragment productions and reaction mechanisms for Ni+Ca systems at 25 AMeV.

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**Abstract.** Main features of fragments produced in  $58\text{Ni}+40\text{Ca}$  and  $58\text{Ni}+48\text{Ca}$  systems at 25 AMeV, collected by Chimera multidetector at INFN Laboratori Nazionali del Sud (Italy), are analysed in order to study properties of moderately excited systems ( $E_x=2-5$  AMeV) formed in central collisions. By means of correlations between specific global variables, sensitive to the centrality of the collision, a stringent selection of Fusion-Evaporation residues, Multifragmentation sources and their decay products has been performed. The influence of the isospin contents of the systems on the reaction mechanism is carefully investigated and relevant observables such as isospin asymmetry  $N/Z$  or charge and mass of fragments, are discussed in order to probe the fragmentation path, characterised by short living ( $\sim 100\text{fm}/c$ ) low density states of nuclear matter out of equilibrium. Preliminary comparisons with predictions of the BLOB model, in a semi-classical mean field framework, are presented, investigating cluster production emerging from the occurrence of low-density instabilities in central collisions.



## 1. Introduction

Heavy ion collisions can be considered a powerful tool to explore the nuclear equation of state (EOS) of nuclear matter under laboratory-controlled conditions. In particular, stable and radioactive beams over a wide range of  $N/Z$  asymmetries allow one to explore the density dependence of the symmetry energy term, which characterizes the EOS of asymmetric nuclear matter.

The Fermi energy regime generates very elaborate scenarios of the reaction mechanism evolving from a one-body dissipation mechanism, predominant at low energies where mean field effects dominate, to two-body dissipation mechanisms, typical of high energy regimes, where nucleon-nucleon interactions predominate.

In particular, in central collisions, models predict that after an early stage in which projectile and target interact to form a compressed phase, the system undergoes an expansion phase during which fragments are formed. Key parameters in the fragment formation are the properties of the nuclear matter and the equation of state far from stability. The aim of the present work is to study fragment formation in sources formed in central collisions for  $58\text{Ni}+40,48\text{Ca}$  at 25 A MeV.

## 2. The Experiment

The experiment was performed at the INFN Laboratori Nazionali del Sud (LNS), where  $58\text{Ni}$  beams were accelerated at 25 A MeV by the Super Conducting Cyclotron. Reactions produced with  $48\text{Ca}$  and  $40\text{Ca}$  targets have been studied. Produced fragments were detected by the CHIMERA  $4\pi$  multi-detector, consisting of 1192 Silicon-CsI(Tl) telescopes, arranged in 26 rings covering 95% of the total solid angle [1].

The atomic number  $Z$  of reaction products punching through the silicon detectors were determined by means of the standard CHIMERA  $\Delta E-E$  identification technique. Same technique was used to obtain the mass of fragments with  $3 \leq Z \leq 8$ , detected at laboratory polar angles greater than 13 degrees. Fragment velocities were determined by time-of-flight (TOF) measurement performed using the cyclotron radio frequency and the silicon signals. Combining the TOF and energy measurements, the mass of particles stopped in silicon detectors was also evaluated. For the present analysis, the identification of light charged particles by means of Fast-Slow technique has not been included, slightly affecting the global event reconstruction.

In order to reject incomplete or incorrectly reconstructed events, we restricted our analysis to events where the sum of the charges ( $Z_{\text{tot}}$ ) of all detected fragments was in the range  $80\% < Z_{\text{tot}} < 105\%$  and the total reconstructed longitudinal momentum ( $P_z$ ) (i.e. projection of the total momentum on the beam axis) was in the range  $80\% < P_z < 105\%$  of the linear momentum of the projectile.

## 3. Centrality selection

In order to select the most central collisions, a careful study of global variables, sensitive to the impact parameter of the reactions, was performed. In particular, the event sorting was developed inspecting the correlation of the Total Kinetic Energy (TKE), i.e. the sum of the kinetic energies of all the reactions products detected in the event, and the Flow angle  $\theta_{\text{FLOW}}$ , defined as the angle formed by the beam direction and the main axis of the ellipsoid of the momentum tensor, corresponding to largest eigenvalue [2].

As shown in figure 1, for  $58\text{Ni}+40\text{Ca}$  system, values of TKE greater than 1200 MeV select very peripheral events, where a quasi-elastic reaction occurred and two fragments with charge, mass and velocity very close to projectile ( $A=58, Z=28, V_z=2.7$  cm/ns in CM reference frame) and target ( $A=40, Z=20, V_z=-5$  cm/ns in CM reference frame) emerged from the collision.

Imposing  $700 < \text{TKE} < 1200$  MeV, more dissipation occurs, and deep inelastic collisions are selected, with a Projectile-like Fragment (PLF) and a Target-like Fragment (TLF) emerging from the collisions as well as fragments of intermediate size, characterized by velocities close to the center of mass velocity of the reaction (CM).

Finally, selecting events where  $TKE \geq 700$ , the most dissipative collisions are chosen, where projectile and target can be pictured interacting with vanishing impact parameters.

#### 4. Results

The central collisions, purpose of the present research, were thus selected imposing a  $TKE < 700$  MeV. Only 10% of the total well reconstructed events satisfy this latter condition, causing a drastic reduction of the statistics involved in the present analysis. As shown in Figure 1 (where charge of the fragments is correlated with parallel velocity  $V_{PAR}$ ), central collisions are dominated by events where a massive fragment, with a velocity close to the center of mass one, is emitted together with some light charged particle, associated to collisions where an Evaporation Residue emerges in the final states, due to predominance of a one-body dissipation mechanism, signature of mean-field behavior.

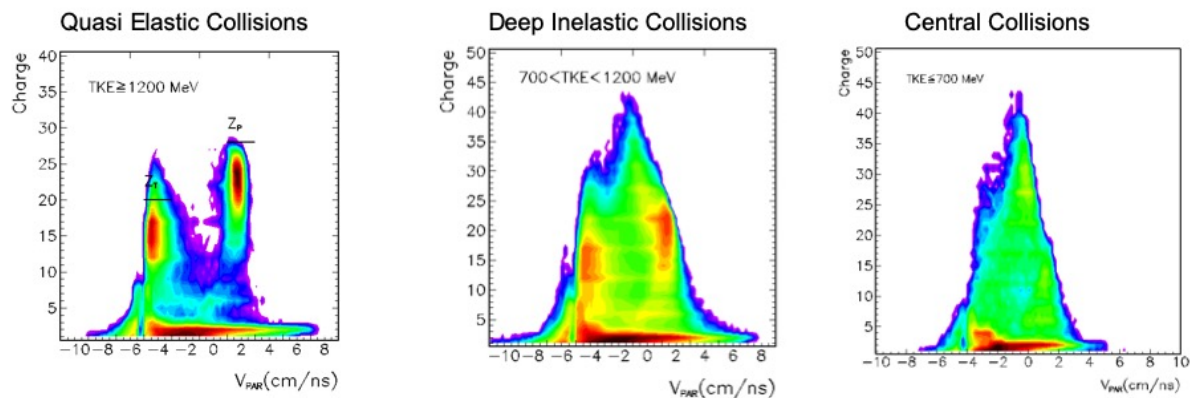


Figure 1: Correlation of the charge of emitted fragments as a function of the velocity parallel to the beam direction in the CM reference frame.

In this respect, looking at the total multiplicity of Intermediate Mass Fragments (IMF, i.e. fragments with  $Z \geq 3$ ), we observed a maximum peaked at  $M_{IMF} = 2-3$  with a tail extending to  $M_{IMF} = 5-6$  (left panel of figure 2). In addition, the  $58Ni+40Ca$  system exhibits higher cross section for events at higher Multiplicity ( $M_{IMF}$ ) of IMF (with respect to the  $58Ni+48Ca$  system), possibly due to a stronger Coulomb repulsion that favours the formation of several fragments (or Cluster).

The IMF multiplicity distribution supports the picture where most of the central events are characterized by the presence of an Evaporation Residue (ER) but also shows the occurrence of events where more than three IMFs are emitted. These kinds of event are good candidates for Multifragmentation events, where the composite system enters in a region of instability in which fragments are simultaneously formed and emitted within 100-200 fm/c from the initial impact. In addition, events with  $M_{IMF} = 2,3$  evidence the presence of fission fragments, generated by a fissioning compound nucleus [3]. In order to investigate the nature of the events with higher IMF multiplicity, we studied in great detail the correlations of the charges of the three biggest fragments in each event, using the  $M_{IMF}$  as a sorting variable to identify ER like events ( $M_{IMF} < 4$ ) or Multifragmentation events ( $M_{IMF} \geq 4$ ). The middle panel of figure 2 shows the charge distribution for the two classes of events while the right panel correlates the charge of the biggest fragment as a function of the sum of the second and third fragments. An alternative explanation of events with a  $M_{IMF} = 4-6$ , at these low energies, could be ascribed to a multiple sequential decay of the composite system.

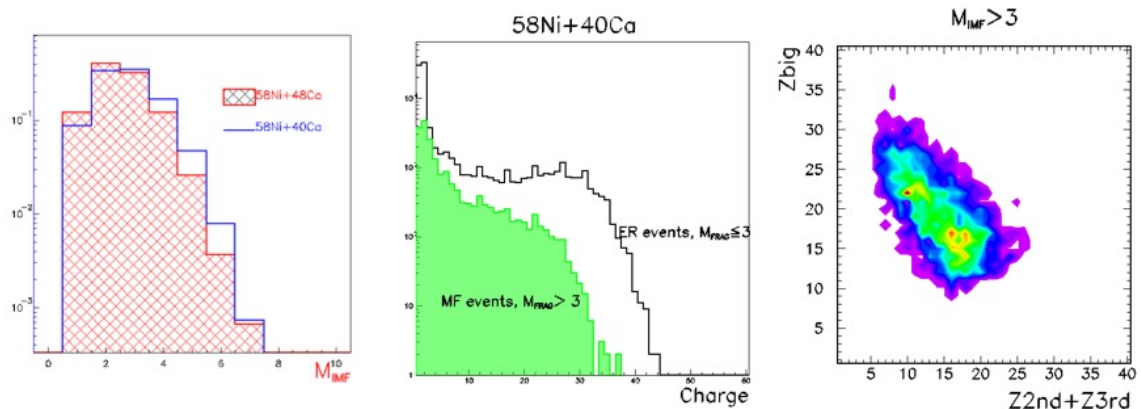


Figure 2: the IMF multiplicity distribution for the two system for central events (left panel); the charge distribution for fragments emitted in ER events ( $M_{\text{IMF}} \leq 3$ ) or MF events ( $M_{\text{IMF}} > 3$ ) (middle panel); the charge of the biggest fragment ( $Z_{\text{big}}$ ) of each event as a function of the sum of the charge of the second and third biggest fragments ( $Z_{\text{big}} < Z_2 < Z_3$ ) (right panel).

#### 4.1. Model Predictions

In order to investigate the origin of the fragments emerging from central collisions, comparisons with the predictions of a dynamical approach based on the Boltzmann-Langevin-One-Body (BLOB) [4] model were conducted. The BLOB approach describes clusterization as a result of large amplitude fluctuations acting in a semi-classical mean field framework, with the addition of a stochastic two-body collisional term. In heavy ion collisions, extreme values of density and incompressibility may result in unstable conditions, usually reached below saturation density. An example is the spinodal region where volume instabilities amplify fluctuations, inducing clusterization. To isolate volume perturbations, the system should reach high values of excitation energies in order to let the density drop to a value around a third of the saturation density. Experimentally this can be obtained in central collisions at Fermi energies. On the other end, in peripheral collisions, where neck-like structures are formed, fragment formation can be related to surface fluctuations.

Simulations were obtained for central collisions, imposing  $b=0$ , for  $58\text{Ni}+40\text{Ca}$  and  $58\text{Ni}+48\text{Ca}$  systems at 25 A MeV.

BLOB predictions portray a first stage of pre-equilibrium emission, which leads the  $58\text{Ni}+40\text{Ca}$  system towards a value of  $N/Z$  of the emitting sources close to the stability valley, due to a predominant emission of protons, while the  $N/Z$  of the emitting sources for the  $58\text{Ni}+48\text{Ca}$  system maintains a constant value close to 1.4 (typical of the stability valley values for that mass region). After 300 fm/c, pre-equilibrium emission can be considered exhausted and simulations predict mostly a source of  $A=60-70$  u.m.a and atomic number  $Z=30$  with an excitation energy of 2 A MeV. In addition, 20% of the events have a fragment multiplicity equal two. These primary fragments undergo a sequential secondary decay that we simulated resorting to the GEMINI sequential code [5]. The final products are displayed in figure 3 (right panel), where the charge of the “cold” fragments is displayed as a function of the  $V_{\text{par}}$ . We noticed that, as in the experimental data, fragments recalling evaporation residues are mainly produced together with some IMFs and light charged particles. The simulated IMF multiplicity distribution is very different from the experimental one, exhibiting a tail up to 3 fragments, so predicting fewer fragments per event as experimentally observed. But at the same time, the secondary decay of the primary predicted sources cannot produce as many fragments as observed, corroborating the idea that events with a multiplicity larger than 4 cannot be produced by a sequential decay of an evaporation residue but they must originate from a multifragmentation phenomenon. A better tuning of model input parameters as

surface energy and nucleon-nucleon collisional term is in progress in order to obtain a better agreement of the simulated variables with the experimental ones, crucial to extract information on fundamental properties of nuclear matter.

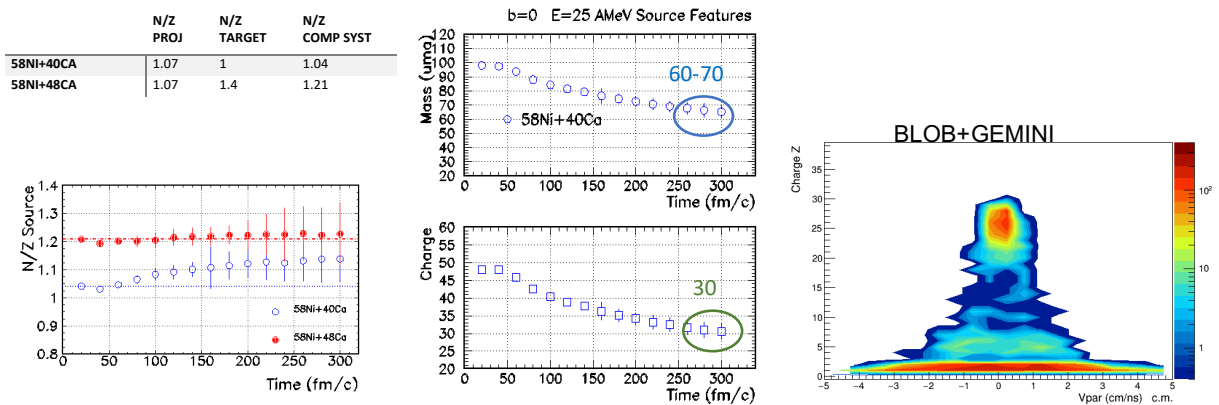


Figure 3: BLOB Model predictions for N/Z (left panel), mass and charge (middle panel) of primary sources produced in central collisions. Charge versus Vpar of fragments after secondary decay (right panel).

#### 4.2. Isotope variables

The influence of the isospin contents of the systems on the reaction mechanism was carefully investigated and relevant observables such as isospin asymmetry N/Z of fragments, were analyzed in order to probe the fragmentation path. The yield of isotopes for fragments with  $Z=3-8$  for 58Ni+48Ca and 58Ni+40Ca systems were obtained and an increase in the production of neutron rich isotopes was observed for the neutron rich system, as often reported in the literature [6].

At Fermi energies, studies of peripheral collisions in systems where projectiles and targets have different isospin asymmetries (N/Z) are a sensitive tool to study effects of the isospin diffusion, namely the equilibration of the N/Z of the two partners of the collisions, enhanced by the isospin gradient of the two colliding nuclei [7]. In other cases, the presence of regions of low density can induce an isospin drift, where a neutron enrichment is observed, driven by a gradient of density [8]. In this study we analyzed fragments produced in central collisions, where we assume that an equilibrated composite system is formed, with excitation energies around 2-4 AMeV. The system will then evolve through a sequential deexcitation, producing an Evaporation Residue and light charged particles or small fragments, or it can de-excite through Fission. Alternatively, as observed at incident energies above 20-30 AMeV, after an early stage where projectile and target form a compressed and excited system, the system will enter in a dilute phase (the spinodal region), where fragments are formed and multifragmentation is observed. In this study of central collisions, we did not expect to observe any isospin diffusion or isospin drift, but we wondered if the isospin composition of the fragments is sensitive to the reaction mechanism. In particular, we analyzed the isospin content of fragments ( $3 < Z < 8$ ) emitted together with a ER or in a Multifragmentation events, inspecting the N/Z of the fragments, as well as the second (variance) and third moment (skewness) of the N/Z distribution, for the two reaction mechanisms, and we did not observe difference within the experimental errors for the two reaction mechanisms, even if the poor statistics for the two subsamples made a definitive conclusion difficult to be reached.

## 5. Conclusions

Central collisions have been selected for  $^{58}\text{Ni}+^{40,48}\text{Ca}$  systems at 25 AMeV. At least two reaction mechanisms, corresponding to events where an Evaporation Residue emerged from the collisions and Multifragmentation events, were observed. A smooth transition, between the two reaction mechanisms is observed, correlated with the IMF multiplicity.

Comparisons with BLOB Model predictions support the idea that the Multifragmentation phenomenon is present also at this low incident energies. A careful tuning of the surface energy and collisional terms is envisaged in order to better reproduce the experimental variables.

Attempts are in progress to develop a correlation method that can disentangle fragments emitted by a sequential decay from those formed as primary in a multifragmentation process.

Isospin content of fragments emitted in central collisions confirms that the sources formed have fully equilibrated the isospin contribution of the partners of the collision. A careful comparison of isospin content related experimental variables with Model Predictions will allow one to test the density dependence of the symmetry energy in the nuclear equation of state [9].

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