Competition between fusion-evaporation and multifragmentation in central collisions of 58Ni+48Ca at 25 AMeV (postprint)

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Abstract

The experimental data concerning the 58Ni+48Ca reaction at Elab(Ni)=25A MeV, collected by using the CHIMERA 4π device, have been analyzed in order to investigate the competition among different reaction mechanisms for central collisions in the Fermi energy domain. As a main criterion for centrality selection we have chosen the flow angle (flow) method, making an event-by-event analysis that considers the shape of events, as it is determined by the eigenvectors of the experimental kinetic-energy tensor. For the selected central events (flow>60°) some global variables, good to characterize the pattern of central collisions have been constructed. The main features of the reaction products were explored by using different constraints on some of the relevant observables, like mass and velocity distributions and their correlations. Much emphasis was devoted, for central collisions, to the competition between fusion-evaporation processes with subsequent identification of a heavy residue and a possible multifragmentation mechanism of a well defined (if any) transient nuclear system. Dynamical evolution of the system and pre-equilibrium emission were taken into account by simulating the reactions in the framework of transport theories. Different approaches have been envisaged (dynamical stochastic BNV calculations + sequential SIMON code, QMD, CoMD, etc.). Preliminary comparison of the experimental data with BNV calculations shows reasonable agreement with the assumption of sequential multifragmentation emission in the mass region of IMFs close to the heavy residues. Possible deviations from sequential processes were found for those IMFs in the region of masses intermediate between

the mass of heavy residues and the mass of light IMFs. Further simulations are in progress. The experimental analysis will be enriched also by information obtained inspecting the IMF–IMF correlation function, in order to elucidated the nature of space-time decay property of the emitting source associated with events having the largest IMF multiplicity.

Full Text

Preamble

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Competition between fusion-evaporation and multifragmentation in central collisions in 58Ni+48Ca at 25A MeV

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Abstract

Experimental data for the 58Ni+48Ca reaction at Elab(Ni)=25A MeV, collected using the CHIMERA 4π device, have been analyzed to investigate the competition among different reaction mechanisms for central collisions in the Fermi energy domain. As the main criterion for centrality selection, we employed the flow angle (flow) method, performing an event-by-event analysis that considers the shape of events as determined by the eigenvectors of the experimental kinetic-energy tensor. For the selected central events (flow>60°), we constructed several global variables that effectively characterize the pattern of central collisions. The main features of the reaction products were explored by applying different constraints on relevant observables, such as mass and velocity distributions and their correlations. For central collisions, particular emphasis was devoted to the competition between fusion-evaporation processes with subsequent identification of a heavy residue and a possible multifragmentation mechanism of a well-defined transient nuclear system (if any). Dynamical evolution of the system and pre-equilibrium emission were accounted for by simulating the reactions within the framework of transport theories. Different approaches were envisaged (dynamical stochastic BNV calculations + sequential SIMON code, QMD, CoMD, etc.). Preliminary comparison of the experimental data with BNV calculations shows reasonable agreement with the assumption of sequential multifragmentation emission in the mass region of IMFs close to the heavy residues. Possible deviations from sequential processes were found for those IMFs in the region of masses intermediate between the mass of heavy residues and the mass of light IMFs. Further simulations are in progress. The experimental analysis will be enriched by information obtained from inspecting the IMF–IMF correlation function, in order to elucidate the space-time decay properties of the emitting source associated with events having the largest IMF multiplicity.

Key words: Heavy ion collisions, Intermediate energy, Flow angle, Fusion-evaporation, Multifragmentation

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Introduction

The study of nuclear heavy-ion collisions at medium energies—around the Fermi domain (40 MeV/nucleon)—provides a unique way to investigate the competition among different nuclear processes expected to play a role in the transition from a mean-field dissipation mechanism (one-body dissipation) dominating at bombarding energies close to the Coulomb barrier between the two interacting nuclei, to the nucleon-nucleon collision process (two-body dissipation) that becomes the dominant mechanism in the relativistic domain.

In the past, one clear experimental signature of this transition was the observation of large values of Intermediate Mass Fragment (IMF, fragments with charge Z>2) multiplicity, especially in central collisions, that was more than one order of magnitude larger than expected from the de-excitation of an equilibrated nuclear system at normal density produced in fusion-evaporation reactions at lower bombarding energy [**?**].

To explain this multifragmentation phenomenon, typically observed in central collisions, different reaction models were envisaged, ranging from prompt dynamical emissions simulated in the context of transport theories, to statistical multifragmentation emissions from a (supposed) low-density and short-lived nuclear system at chemical equilibrium [**?**]. However, multiple emission of fragments has also been observed in semi-central collisions, so experimental studies of multifragmentation processes under various conditions are important in order to disentangle among different reaction mechanisms ranging from quasi-elastic to the most dissipative collisions, as a function of impact parameter.

In this paper, we emphasize characterization of collisions at small impact parameters, where maximum formation of single highly excited sources is expected to occur. We describe a careful selection of central collisions in the reaction 58Ni+48Ca [**?**] in order to pin down the competition between sequential fusion-evaporation and prompt multifragmentation emission of an unstable system formed at sub-saturation nuclear density.

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2 Experiment

The experiment was performed by the NUCLEX-ISOSPIN collaboration using the CHIMERA apparatus located at LNS–INFN (Catania). A beam of 58Ni ions was accelerated to 25A MeV energy by the LNS Superconducting Cyclotron and impinged on a thin 48Ca target. Reaction products were detected by the 1192 Si-CsI(Tl) telescopes of the CHIMERA 4π multidetector, covering approximately 94% of the total solid angle [**?**, **?**]. Events were recorded when at least two silicon detectors were fired, i.e., when the charged particle multiplicity (MCP) was larger than two hits (MCP$ $2).

Using the ΔE–E identification technique, we determined the atomic number Z of reaction products punching through the silicon (n-planar-300 m) detector and stopping in the CsI(Tl) crystal, as well as the charge and mass of those IMFs with 3≤Z$ $8 detected at laboratory angles larger than 13°. Time-of-flight (TOF) technique provided velocity measurements using the cyclotron radiofrequency reference time as start and the silicon time signal as stop. Combining energy and TOF information, we evaluated the mass of particles stopped in the first stage of the telescopes.

In this analysis, Pulse Shape Discrimination (PSD) technique in CsI(Tl) for identification of light charged particles (LCP) was not performed; however, this only slightly affects the global reconstruction of the reaction pattern performed on an event-by-event basis.

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3 Event Selection

The analysis was performed on "complete events," selected by requiring that the total detected charge and total measured linear momentum range between 70% and 105% of the total charge and projectile momentum, respectively. This selection yielded 11.5% of the total collected events (see region in square box in Fig.1).

For peripheral and semi-peripheral collisions, where events retain memory of the binary character of the reaction, the shape of the tensor is elliptic and flow assumes small values («90°), while for more central collisions a more spherical shape is predicted, causing flow to assume larger values up to 90°.

[Figure 1: see original paper] (Color online) Correlation between total detected charge and total longitudinal momentum for all detected events. Events in the square box (11.5% of total events) were selected as complete events.

3.1 Centrality Selection

The method adopted for centrality selection is based on imposing several cuts on the global variable "flow angle," flow, which is related to the shape of the event in momentum space [?]. This variable is constructed from the Cartesian coordinates of the measured linear momenta in the center-of-mass frame (CM) for all fragments (Z$ $3) detected in each event. The kinetic flow tensor, Qij, is built event-by-event as follows:

This tensor is a generalization of the sphericity tensor, widely used in high-energy particle physics and adapted to heavy-ion nuclear reactions in which composite fragments are produced. In its diagonal form, Qij defines an ellipsoid in momentum space with three principal axes oriented along the three eigenvectors, whose corresponding eigenvalues f1, f2, and f3 are sorted according to the inequalities f1>f2>f3>0 [?, ?]. The orientation of the main axis of the ellipsoid (eigenvector corresponding to f1) measured with respect to the direction of the incident beam defines the flow angle flow.

Flow angle assumes values ranging from 0 to 90 degrees. For peripheral and semi-peripheral collisions, where events retain memory of the binary character of the reaction, the shape of the tensor is elliptic and flow assumes small values («90°), while for more central collisions a more spherical shape is predicted, so that flow assumes larger values up to 90°.

[Figure 2: see original paper] (Color online) Total Kinetic Energy (TKE) and flow angle correlation for all complete events.

Figure 2 shows the correlation plot between Total Kinetic Energy (measured by the sum of kinetic energy of all detected fragments in each event) and the flow angle variable [?]. An increase in flow values results in selection of more dissipative collisions.

Following the pattern of emissions in terms of the correlation between the longitudinal component (i.e., along the beam axis) of the velocity vpar and the mass number A for each detected reaction product, we observe that with increasing flow angle values, the contribution from fragments with velocity values (vproj = 6.5 cm $\cdot$ ns^{-1}) and masses around 40–45 amu (indicated by PLF) and from slow-moving fragments corresponding to target remnants (TLF)—dominant at low flow angle values (close to zero degrees) and strongly indicative of binary peripheral collisions—is progressively reduced until it completely vanishes at high flow values of 60° and beyond (Fig.3). Moreover, in the region of flow angle larger than 60°, the longitudinal velocity spectrum becomes increasingly centered around the value of vCM, and a relevant emission component due to fragments with mass values larger than those of projectile or target, also exceeding 60 amu, is clearly observed.

Therefore, in the following we refer to events in the third region of flow angle (flow$ $60°) as central events, which comprise 6.2% of the complete events.

[Figure 3: see original paper] (Color online) Correlation between parallel velocity component (cm/ns) and mass (amu) for all reaction products in three regions: flow$ $0°(a), 30° < \vartheta flow$ $60° (b), and flow>60° (c).

3.2 Central Events: Event-by-Event Analysis

In these central collisions, we first analyze the behavior of the heaviest fragment (Abig) in each event. We observe a broad distribution of Abig mass values, ranging from about 20 amu up to values around 80 amu (Fig.4).

Typically, the class of events with the largest Abig values (50–80 amu) is reminiscent of a heavy residue formation evaporation mechanism where the decay chain is dominated by emission of light charged particles (LP), neutrons, gamma rays, and few light fragments. To what extent the lower Abig values (less than 30–40 amu) could also be produced in a fusion-evaporation mechanism will be discussed in the following. However, the presence of events characterized by such lower mass values of the heaviest fragment provides a good candidate for an experimental signature of possible coexistence between statistical fusion-like evaporation decay mechanism and a "prompt" multifragmentation process.

To disentangle between these two mechanisms, we chose to analyze two classes of events, preliminarily imposing an arbitrary cut at a value of the mass of the heaviest fragment equal to 50 amu. To better characterize our choice, the mean values of IMF multiplicity, , and the mean values of LP multiplicity, , are shown in the inset of Fig.4 for both classes.

The biggest fragment with mass 50 amu or larger is preferentially emitted as a unique heavy fragment (43.5% of events in the upper box of Fig.4) in coincidence with 4–5 light charged particles (Z=1, Z=2) or, alternatively, together with a few (1–2) light fragments. In contrast, inspecting the lower box of Fig.4 reveals that the fragment multiplicity MIMF spans a substantially wider range of values, with a mean of =3 and reaching maximum values as high as MIMF=6. For these latter events, the light charged particle multiplicity is lowered to a mean value of about three particles per event.

Complementary observation of the behavior of the two classes of events comes from analysis of Dalitz plots in Fig.5. We briefly remind the reader that each reaction event corresponds to a point in the Dalitz plot, and that the position of each point inside the triangle provides information about the relative asymmetry in mass of the three heaviest fragments: events with a heavy residue are located at the vertices, events characterized by binary behavior (more or less symmetric splitting) occupy the sides, and events with multifragmentation emission of fragments with nearly equal mass are located at the center of the triangle.

Examining the left panel of Fig.5 (class of events with Abig>50 amu), we observe that most events are located at the vertices of the plot, indicating dominance of a heavy residue and light particles, displaying characteristic features of typical fusion-evaporation phenomena. Conversely, events in the right panel (class of events with Abig<50 amu) show approach toward more symmetric splitting of the primary source, filling the area inside the triangle and depleting the vertices and sides.

[Figure 4: see original paper] (Color online) Mass (amu) and longitudinal velocity (cm/ns) for the heaviest fragment for central events.

[Figure 5: see original paper] (Color online) Dalitz plot for events in Fig.4.

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4 Comparison and Calculation

We compared mass and multiplicity distributions for selected central events (without differentiation of multifragmentation-like events) with those predicted by a two-step mechanism: dynamical stochastic BNV calculation followed by sequential de-excitation of a composite source (SIMON code) [**?**]. The source information was obtained from BNV calculation, including pre-equilibrium emission of about 20 amu, corresponding to a source with mass equal to 94 amu, atomic number Z=43, and excitation energy of 400 MeV ($±$50 MeV). In these calculations we considered, as a preliminary evaluation, only events produced in central collisions with vanishing angular momentum (L=0).

[Figure 6: see original paper] shows the comparison between fragment multiplicity distributions (left panel) and mass distributions for experimental data (black line) and calculations (red line). At this stage of comparison, the simulation results are not yet filtered; i.e., energy and mass resolutions, detector efficiency, and trigger threshold are not included. We notice quite good agreement in reproducing the shape of the multiplicity distribution. Taking into account that filtering effects (not yet included) are expected to change the shape of the calculated distribution mostly in the region of large mass number A, the experimental data for both heavy and light reaction products are also well reproduced. Any deviations between simulated and experimental mass distributions are located around mass values of about 30 amu.

[Figure 6: see original paper] (Color online) Comparison between experimental and simulated MIMF distribution. Mass distribution for experimental data (a) and results of simulation (b).

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5 Conclusion and Perspective

The experimental data for 58Ni+48Ca reactions at Elab(Ni)=25A MeV, collected using the CHIMERA 4π device, have been analyzed to investigate the competition among different reaction mechanisms for central collisions.

As the main criterion for centrality selection, we employed the flow angle method, performing an event-by-event analysis that considers the shape of events in momentum space. For the selected central events (flow>60°), mass-velocity correlations constructed for all emitted fragments show a typical broad mass spectrum centered at vCM velocity. Besides a component of IMFs with mass number A<20, we observe the presence of a well-shaped quasi-Gaussian component with high mass values (50–80 amu), strongly indicating formation of a heavy residue from a fusion-evaporation statistical decay process of highly excited compound nuclei at equilibrium.

Through further analysis concerning the multiplicity of fragments (MIMF) and charged light particles (MLCP), and the mass distribution of the heaviest fragment emitted in well-selected central collisions, we investigated a possible signature for the coexistence of two different reaction mechanisms in the observed mass spectrum. The reaction dynamics was simulated by stochastic BNV transport evaporation model simulations, accounting for pre-equilibrium emission and subsequent statistical evaporation decay.

Preliminary comparisons of experimental data with results from reaction simulations in the framework of stochastic BNV model coupled, as a second step, with statistical evaporation show reasonable qualitative agreement with the assumption of sequential multifragmentation emission. However, to test this preliminary conclusion, further comparisons with dynamical transport models based on different assumptions are needed. Calculations with dynamical molecular models (QMD, CoMD, etc.) are also in progress.

Furthermore, an extension of the present analysis to light charged particles is envisaged in order to investigate relevant characterization of the emitting source, such as temperature (by investigating the slope of the spectra, Tslope, and by means of double ratio analysis, Tratio, or isotopic ratio thermometer), as well as evaluations of excitation energy and nuclear density at the freeze-out configuration.

Recently, the CHIMERA group has been working on an upgrade of the apparatus to extend its detection capabilities toward identification of both charged and neutral particles [**?**].

The experimental analysis will also be enriched by complementary information obtained from inspecting IMF-IMF correlation functions, in order to elucidate the nature of space-time decay properties of sources and thus disentangle sequential versus simultaneous emission [**?**].

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Note: Figure translations are in progress. See original paper for figures.