Emission of fragments in Ca+Ca reactions at 25 MeV/nucleon

I. Lombardo1, L. Acosta2, C. Agodi2, F. Amorini2, A. Anzalone2, L. Auditore2, I. Berceanu8, M. Buscemi1, G. Cardella3, M.B. Chatterjee7, E. De Filippo3, E. Geraci3,4, G. Giuliani9, L. Grassi10, J. Han2, E. La Guidara3, G. Lanzalone2,6, D. Loria5, C. Maiolino2, T. Minniti5, A. Pagano3, M. Papa3, S. Pirrone3, G. Politi3,4, F. Porto2,4, F. Rizzo2,4, E. Rosato1, P. Russotto2, S. Santoro5, A. Trifirò5, M. Trimarchi5, G. Verde3, M. Vigilante1

1 Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN-Sezione di Napoli, Via Cintia, I-80126, Napoli, Italy
2 INFN - Laboratori Nazionali del Sud, Via S. Sofia, Catania, Italy
3 INFN - Sezione di Catania, Via S. Sofia, Catania, Italy
4 Dipartimento di Fisica e Astronomia, Università di Catania, Via S. Soia, Catania, Italy
5 Dipartimento di Fisica, Università di Messina, and INFN-Gr.Coll. Messina, Italy
6 Facoltà di Ingegneria ed Architettura, Università Kore di Enna, Enna, Italy
7 Saha Institute of Nuclear Physics, Kolkata, India
8 Institute for Physics and Nuclear Engineering, Bucharest, Romania
9 Texas A&M University, College Station, TX, United States
10 Ruder Boskovic Institute, Zagreb, Croatia

E-mail: ivlombardo@na.infn.it

Abstract. We discuss experimental data concerning 40,48Ca+40,48Ca reactions at 25 MeV/nucleon; the 4π multi-detector Chimera has been used as detection device. Effects that can be attributed to the neutron to proton ratios (N/Z) degree of freedom have been investigated. From the analysis of experimental data it seems that the neutron richness of the interacting system plays an important role on the evolution of fusion-like sources formed in semi-central collisions. In particular, it is observed that the larger is the neutron content and the larger is the emission of heavy residues. Experimental data have been compared with CoMD-II model calculations; a moderately stiff symmetry energy should be used to reproduce satisfactorily the data. A thermodynamical analysis on fusion-like sources has been also performed. In semi-peripheral collisions, isospin diffusion signals have been found. They have been investigated by analyzing isobaric emission (7Li/7Be) of quasi-projectile sources. Experimental data indicate that an incomplete N/Z mixing is reached during the interaction phase.

1. Introduction
The emission of light and heavy fragments in nuclear reactions at medium-low bombarding energies (i.e. near 20 MeV/nucleon) represents an useful probe to disentangle various reaction scenarios in this energy domain [1, 2, 3]. Moreover, when projectile-target combinations with large differences in the neutron to proton ratio (N/Z) are used, it is possible to investigate various effects related to the isospin degree of freedom such as: (1) the co-existence of various

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competitive mechanisms; (2) the neutron exchange between the two reaction partners of binary collisions (isospin diffusion); (3) the neutron enrichment of dilute regions formed in peripheral collisions (isospin drift) [4, 5]. These phenomena have been proved to be an useful tool to extract details about the behavior of the Symmetry Term of the Nuclear Equation of State, a topic of relevant interest also to solve Nuclear Astrophysics and Nuclear Structure problems [6, 7].

In the case of medium-mass colliding nuclei, at semi-central impact parameters the presence of incomplete fusion phenomena (in competition with binary-like and multi-fragment emission) has been observed [8, 9, 10, 11, 12]. In this case, the analysis of size and velocity of the biggest fragments represents an useful way to discriminate among the various reaction mechanisms [13, 14]. Recently, by investigating Ca+Ca reactions at 25 MeV/nucleon it has been reported that the N/Z of the total system plays an important role in the competition between various mechanisms [15, 16, 17, 18], as predicted by many theoretical models [19, 20, 21, 22]. This analysis allows moreover to extract information about the density dependence of the Symmetry Term in the Nuclear Equation of State at near-saturation density [15, 19, 20, 21].

It is also interesting to analyze the isotopic composition of light particles emitted in coincidence with heavy residues formed in fusion-like mechanisms [23]. For example, we can investigate to what extent the N/Z of fusion-like sources is altered (if compared to the N/Z of the entrance channel) by pre-equilibrium emission. Furthermore, we analyze the temperature of fusion-like sources by using the double isotopic ratio method; in this way it is possible to disentangle the role played by the N/Z degree of freedom on the thermodynamics of hot sources formed in central events [24, 25].

Semi-peripheral nuclear reactions involving various combinations of projectile/target nuclei are also useful to investigate the isospin exchange between the reaction partners. If the reaction time is equal or longer than the isospin relaxation time, due to the minimization of the free energy, the neutron excess uniformly distributes between the two partners of binary reactions, leading to quasi-projectile and quasi-target sources characterized by similar N/Z [26]. This effect has been experimentally observed in low energy deep-inelastic reactions [27]. When the projectile velocity becomes increasingly higher, the interaction time between the two partners is more and more reduced, and this leads to an incomplete charge equilibration in the dinuclear system. This effect can be evidenced by analyzing the neutron content of isotopically resolved fragments emitted by the quasi-projectile (or quasi-target) source at the re-separation time, as discussed in Refs. [28, 29, 30] for Sn+Sn, Ni+Au or Ca+Sn collisions at 50 and 32 MeV/nucleon respectively. Therefore, it is interesting to investigate the bombarding energy region (at fixed impact parameter) where the transition from complete to incomplete isospin equilibration (isospin diffusion) is observed: this point could represent a powerful tool to estimate the relaxation time scale of the N/Z degree of freedom in heavy ion collisions [26].

To investigate these subjects, we studied the emission of fragments in $^{40,48}$Ca +$^{40,48}$Ca collisions at 25 MeV/nucleon. In this way, we are able to study various medium-mass nuclear systems covering a very large range of N/Z of the total system (going from the symmetric system $^{40}$Ca +$^{40}$Ca up to the very neutron rich reaction $^{48}$Ca +$^{48}$Ca, having N = 1.4Z). Results of this analysis are discussed in the following sections.

2. Experimental apparatus

The experiment was performed at INFN-Laboratori Nazionali del Sud in Catania. $^{40,48}$Ca beams, accelerated at 25 MeV/nucleon by the Super-Conducting Cyclotron, impinged on isotopically enriched self-supporting target of $^{48}$Ca (2.7 mg/cm$^2$ thick) and $^{40}$Ca (1.2 mg/cm$^2$ thick). In order to check effects biased by the slightly different mass and mass asymmetry of entrance channels, the $^{40}$Ca+$^{46}$Ti reaction at the same bombarding energy has been also investigated.

Reaction products were detected by using the 4π multi-detector Chimera [31, 32]. It covers a large part of the whole solid angle (around 94% of 4π). It is constituted by 1192 Si-CsI(Tl)
Figure 1. Correlation between the velocities of the two biggest fragments (\(v_1\) and \(v_2\) respectively) emitted in the \(^{40}\text{Ca} + ^{46}\text{Ti}\) reaction at 25 MeV/nucleon. Different charged particle multiplicity (\(m_{cp}\)) selections have been used. Similar behavior has been observed for the other studied systems.

telescopes. The nominal thickness of silicon detectors is 300 \(\mu m\), while CsI(Tl) thickness varies as a function of the polar angle, going from 3 cm (at backward angles) up to 12 cm (at forward angles). This apparatus offers the opportunity to identify in charge and/or in mass the reaction products by applying various identification methods. They are respectively: (1) the counter telescope \(\Delta E - E\) method, that is useful to discriminate the charge of fragments that punch through the Si detector, and also to give isotopic identification of fragments with \(Z < 10\) (on average); (2) the Time of Flight (ToF) method, that is useful to estimate the mass of (slow and heavy) fragments stopped in Si detectors; (3) the analysis of fast and slow components in CsI(Tl) light output, that allows to obtain isotopic identification of light charged particles, such as hydrogen and helium nuclei; (4) the pulse-shape technique applied to the study of the rise time of signals in Si detectors, that is useful to determine the charge of (slow) fragments stopped in Si. Further details about the Chimera array and its detection and identification capabilities can be found in Refs. [31, 33, 34, 35, 36]. Time resolution obtained in this experiment is \(\approx 1\) ns; it is due mostly to timing characteristics of the beam. The obtained mass resolution \((\Delta m/m)\) is around 5\% [15, 18] for nuclei having mass \(A \approx 50\).

We consider in the data analysis only complete events, i.e. events where at least the 80\% of the total charge and the 70\% of the total parallel momentum have been detected. An upper constraint on the total detected charge (less than the 100\% of the total charge) has been imposed. These selections allow to discard spurious events of reaction on oxygen contaminant in the target and pile-up events. Very peripheral and uninteresting quasi-elastic events were removed during the data acquisition by requiring the detection of at least 3 charged particles.

3. Semi-central events of reactions: heavy residue emission

The centrality of reaction events can be selected, in a reasonable way, by using various bins of charged particle multiplicity \(m_{cp}\) [37]. We verified this assumption by studying the correlation between the velocities of the two biggest emitted fragments (\(v_1\) and \(v_2\), respectively) as a function
Figure 2. $\Delta M_{nor}$ distributions for semi-central events in $^{40}\text{Ca}+^{40}\text{Ca}$ (black dotted line), $^{40}\text{Ca}+^{48}\text{Ca}$ (red dashed line) and $^{48}\text{Ca}+^{48}\text{Ca}$ (blue solid line) reactions. In the insert, the percentage of events corresponding to $\Delta M_{nor} \geq 0.4$ are shown as black stars. The red-dotted, blue-dashed and green-dot-dashed lines refer to CoMD-II model calculations for the Stiff1, Stiff2 and Soft options, respectively.

of $m_{cp}$. We include in this analysis also heavy residues that have been identified in mass by using the time of flight technique. Results are shown in Figure 1, for the case of $^{40}\text{Ca}+^{46}\text{Ti}$ system (similar results have been obtained for the other investigated systems). At low $m_{cp}$ selections, the velocities of the two biggest fragments ($v_1$ and $v_2$) are similar to the target and projectile velocities ($v_P \approx 0.23c$), as expected in gentle peripheral collisions. By selecting higher $m_{cp}$ bins, the shape of the correlation changes, and the most populated region of the scatter plot corresponds to events where the mean velocity of the biggest fragment ($v_1$) is similar to the center of mass one, while the velocity distribution of the second fragment ($v_2$) lies between center of mass and projectile velocities. This is behavior is typical of events with high centrality and large energy damping, as for fusion-like phenomena. In this case, a heavy residue (the biggest fragment) is emitted with velocity similar to the center of mass one, while the part of the projectile that does not fuse with the target escapes with velocities larger than the center of mass one. Therefore it seems that, in agreement with previous investigations [37], $m_{cp}$ can represent an useful tool to roughly discriminate the centrality of events.

In order to investigate the competition between various reaction mechanisms that can be observed at small impact parameters, we firstly select the centrality of events by a constraint on the charged particle multiplicity, $m_{cp}$ ($m_{cp} \geq 5$ or 6, depending on the neutron content of the system [15, 18]). We selected moreover events where the second or third biggest fragment has a velocity larger than the center of mass one ($v_2$ or $v_3 \geq 0.13c$); by using this constraint, we focus our attention on massive transfer phenomena, where a part of the incoming projectile fuses with the target.

For these events, we can discriminate the main reaction mechanisms by investigating the correlation between the masses of the two biggest fragments, $m_1$ and $m_2$. To this aim, we define the $\Delta M_{nor}$ quantity as $\frac{m_1 - m_2}{m_{tot}}$, where $m_{tot}$ is the total mass of the system (the normalization to $m_{tot}$ is useful to reduce effects biased by the slightly different total mass of investigated systems). Large values of $\Delta M_{nor}$ are associated to heavy residue (HR) emission in fusion-like
events, while low values of $\Delta M_{\text{nor}}$ are due to binary-like, fusion-fission and multi-fragmentation events. In Figure 2 we show the experimental $\Delta M_{\text{nor}}$ distributions for $^{40}\text{Ca}+^{40}\text{Ca}$, $^{40}\text{Ca}+^{48}\text{Ca}$ and $^{48}\text{Ca}+^{48}\text{Ca}$ systems. As shown in Figure 2, by increasing the N/Z of the total system, $\Delta M_{\text{nor}}$ distributions are pushed towards high values. It seems therefore that the relative emission of HR is increasingly larger by increasing the neutron excess of the total system formed. As discussed elsewhere [15, 18, 19], these effects could be attribute to the interplay between the Coulomb and Symmetry terms of the Nuclear Equation of State (EoS). Comparisons of experimental data with Constrained Molecular Dynamics model (CoMD-II) [19, 38, 39] calculations allow to extract information on the behavior of the Symmetry term of Nuclear EoS [15, 18, 19]. We can consider events with $\Delta M_{\text{nor}} \geq 0.4$ (in a sharp cut-off approximation) as HR events. The percentage of these events is shown in the insert of Figure 2, for the three studied systems, as a function of the N/Z of the entrance channel. As observed before, by increasing the N/Z, the percentage of HR events is increasingly larger. These data can be compared with calculations performed with the CoMD-II model, by assuming different degree of stiffness for the Symmetry (Potential) of the EoS. In particular, we used density functional form commonly adopted in static EoS calculations [40]. The Stiff1, Stiff2 and Soft options here used correspond to the power law of density $(\rho_0^\gamma)$ with $\gamma=1.5$, 1.0 and 0.5 respectively. As shown in the insert of Figure 2, experimental data are nicely reproduced by calculations performed by using the Stiff2 option. This result confirms our previous findings on this topic, and seems to indicate that a moderately stiff option for the Symmetry Potential has to be used to reproduce successfully the data (further details on these investigations are discussed in Refs. [15, 18]). This finding is in agreement with recent results obtained by studying semi-peripheral events of Sn+Ni reactions at 35 MeV/nucleon [32, 41].

4. Behavior of Fusion-like sources: neutron content and temperature
We can study in more detail the behavior of hot nuclear sources formed in fusion-like phenomena. The Chimera array allows in fact to investigate the emission of light particles and fragments in coincidence with heavy residues. As discussed in the introduction, the inspection of light particles and fragments is a powerful tool to deeply investigate the details of an emitting source [42]. For example, we can probe the neutron content of fusion-like sources after that pre-equilibrium particles (mainly neutrons and protons) are emitted. Therefore, we can investigate to what extent pre-equilibrium emission changes the original N/Z rank given by the N/Z of entrance channels. To investigate this effect, we analyze the emission of light charged particles (hydrogen isotopes) in coincidence with heavy residues (having masses larger than 46 mass units). With proper selections on the center of mass emission angle (i.e. by selecting light charged particles emitted at $40^\circ < \theta_{\text{Lab}} < 140^\circ$, [43]), pre-equilibrium contaminations can be strongly reduced, and the resulting emission can be mainly attributed to the evaporation from the excited fusion-like source. In this way, qualitative information on the N/Z of fusion-like sources can be achieved: the largest is the N/Z of the source, the largest will be the probability of emitting a neutron rich hydrogen isotope. In Figure 3 we show the trend of the isotopic ratios d/p, t/d and t/p as a function of the N/Z of the entrance channel. An exponential-like correlation between the isotopic ratios and the N/Z is observed. Therefore, it seems that pre-equilibrium emission does not destroy the original N/Z rank given by the various projectile+target combinations used in this experiment at 25 MeV/nucleon.

Another interesting question concerns the investigation on the values of temperature reached by fusion-like sources formed by using systems having large N/Z differences. To do this, the double isotopic ratio method has been used, and Li-C apparent temperatures have been obtained [44]. In Figure 3 (right panel), apparent temperatures of fusion-like sources are reported as a function of the N/Z of the entrance channel. The obtained values of temperature are quite similar, being of the order of 4.5 MeV. This finding seems to indicate a small influence of the N/Z
Figure 3. (Left panel) Isotopic ratios of hydrogen isotopes (p,d,t) emitted in coincidence with heavy residues in $^{40,48}$Ca+$^{40,48}$Ca and $^{40}$Ca+$^{46}$Ti reactions. Solid lines are exponential fits to the experimental data (Right panel) Apparent temperatures of fusion-like sources estimated by using the double isotopic ratio Li-C, as a function of the N/Z of the entrance channel.

degree of freedom on the temperature of hot sources formed in central collision, in agreement with other recent investigations [25]; anyway, to give more solid conclusions, further investigations are needed [45]. In particular, it would be desirable to reconstruct, in a quantitative way, the N/Z of the hot nuclear sources investigated [45]. In this respect, the recent development of high coverage neutron arrays, that can be coupled with 4π detectors for charged particles, represents an interesting opportunity [46].

5. Semi-peripheral collisions: isospin diffusion effects

The investigation of semi-peripheral events in isospin-asymmetric heavy ion reactions represents an useful way to probe the exchange of neutrons during the interaction phase, that can lead to the presence of charge equilibration or isospin diffusion effects. The analysis of semi-peripheral events of $^{40,48}$Ca+$^{40,48}$Ca reactions allows to probe these phenomena, for example, by studying the neutron content of quasi-projectile (QP) sources after the interaction phase [28, 30, 47]. It is worth noting the important role played by the symmetric systems $^{40}$Ca+$^{40}$Ca and $^{48}$Ca+$^{48}$Ca; for these systems, no isospin diffusion is expected (only isospin drift effects, driven by density gradient, could be present), and therefore they represent good reference points to be compared with data of mixed systems.

An observable sensitive to the N/Z of a given nuclear source is the $^7$Li/$^7$Be isobaric ratio, that has been reported to be correlated (in an exponential-like way) to the N/Z of the source [48]. Following this assumption, isobaric ratios of QP sources where extracted by means of a moving source analysis of $^7$Li and $^7$Be energy spectra. To improve statistics, the fit was extended to all the reaction data set considering that, for geometrical reasons, semi-peripheral collisions prevail (an average impact parameter of the order of 6-7 fm can be estimated from geometrical arguments). We underline that the inspection of the isotopic content of QP sources is favored by the kinematical boosting of projectile, that allows to overcome easily the identification threshold. Experimental results on isobaric emission from QP sources are shown in Figure 4. Data are ordered as a function of the N/Z of the total system; for clarity reasons we indicate explicitly the projectile+target combination. By comparing QP isobaric ratios of symmetric and mixed systems we can infer that, during the interaction phase, a net neutron exchange from the neutron-rich partner to the neutron poor one takes place. Moreover, it is interesting to note that, for the two mixed systems, two different values of isobaric ratios are found. In particular, we observe a “memory effect” of the used projectile. In fact, if the neutron-poor projectile ($^{40}$Ca) is used to form the mixed system, the isobaric ratio of the QP source is lower if compared to the case involving the neutron rich projectile ($^{48}$Ca). Therefore it seems that the N/Z mixing between the two interacting reaction partners is not complete.
The amount of N/Z mixing is an useful information to be compared with dynamical calculations. We can derive, for example, details on the strength of the Symmetry Energy in the Nuclear EoS and also on the relaxation time of the isospin degree of freedom in heavy ion collisions. An (approximate) method to estimate the amount of N/Z mixing may be the following. We can reasonably assume (following statistical multi-fragmentation models) that the isobaric ratio \( ^7\text{Li}/^7\text{Be} \) is exponentially linked to the N/Z of a given source. In this way we can use isobaric ratios of symmetric systems as reference points, due to the fact that, in absence of isospin diffusion effects, isobaric ratio can be directly linked to the N/Z of the projectile source. A linear calibration in semi-logarithmic scale takes into account the exponential trend of isobaric ratios as a function of the N/Z of the source. If complete isospin mixing takes place, experimental points of isobaric ratio for QP sources formed in the mixed systems should stay on the calibration line; for this reason, we call this line as "equilibration line". On the contrary, if a partial isospin mixing is reached, experimental points of mixed systems would be far from the equilibrium line. By using the equilibrium line as reference, we can obtain estimates of the N/Z of QP sources formed in the mixed systems (see the green arrows of Figure 4). Following Ref. [30], we define the fraction of equilibrium as:

\[
 f_{eq} \equiv \frac{N_{Z\text{QP}} - N_{Z\text{P}}}{N_{Z\text{TOT}} - N_{Z\text{P}}} \tag{1}
\]

If complete N/Z mixing is reached, \( f_{eq} = 1 \) is expected. By using the \( N/Z_{QP} \) values obtained by applying the method described above, we find (averaging the values for the two mixed systems) \( f_{eq} \approx 0.63 \). This value is coherent with \( f_{eq} \) reported in Ref. [30] for similar systems at slightly higher bombarding energy. starting from these results it could be very interesting to perform, in future experiments, a systematic study of \( f_{eq} \) for medium mass systems at various bombarding energies and impact parameters. In this way, more details on the relaxation time scale of the isospin degree of freedom in heavy ion collisions could be obtained.

6. Conclusions

In this paper we discuss effects related to the N/Z degree of freedom in heavy ion collisions involving Ca+Ca systems with different neutron richness at 25 MeV/nucleon. These effects
have been studied thanks to the good event reconstruction and isotopic identification given by the Chimera 4π array, that has been used as detection device.

At semi-central impact parameters, the relative yields of heavy residues formed in fusion-like phenomena is enhanced when neutron-rich systems are used. This effect has been investigated by studying the mass correlation of the two biggest emitted fragments. Comparisons of experimental data with CoMD-II model calculations allow to obtain information on the degree of stiffness of the Symmetry Energy of the Nuclear Equation of State, a question of large relevance in Nuclear Physics. Analyses of isotopic content of light charged particles and fragments emitted in coincidence with heavy residues have been performed in order to investigate the neutron content and apparent temperature reached by fusion-like sources.

In semi-peripheral collisions, isospin diffusion effects have been investigated by analyzing the emission of $^7\text{Li}$ and $^7\text{Be}$ isobars from quasi-projectile sources. From the experimental data, it seems that incomplete N/Z mixing is reached during the interaction phase. By using the results of symmetric systems $^{40}\text{Ca}+^{40}\text{Ca}$ and $^{48}\text{Ca}+^{48}\text{Ca}$ as reference points, we estimate the amount of N/Z mixing to be around 60%.

All these results stimulate further investigations on isospin effects in medium mass nuclear reactions by using radioactive beams or targets, in order to extend the available systematics to more exotic values of neutron/proton asymmetry.

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