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Entrance channel effects in medium mass nuclear systems at 25 MeV/nucleon

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Abstract. We discuss experimental data concerning ^{48}Ca+^{48}Ca and ^{42}Ca+^{54}Fe reactions at 25 MeV/nucleon obtained by using the 4π multi-detector Chimera. Effects due due to the different neutron to proton ratios (N/Z) of the two systems have been investigated. Charge distributions of forwardly emitted fragments show even-odd staggering whose amplitude is larger for the neutron poor system. Moreover, the neutron excess of the total system influence the evolution of fusion-like sources formed in semi-central collisions. In particular, for the neutron rich system, the relative emission yield of heavy residues is larger, while multi-fragmentation and binary-like events prevail in the neutron poor system.

1. Introduction

The possibility of performing nuclear reactions between heavy ions with different charge and neuron number allows to investigate effects related to the different entrance channels [1]. For example, entrance channels can differ in total mass, projectile/target mass asymmetry, total neutron (N) to proton (Z) number ratio, and also projectile/target neutron to proton (N/Z) asymmetry. The availability of a large range of (stable) isotopes is elements such as Calcium, Nickel, Tin and Xenon allow to perform nuclear reactions aimed to study different projectile/target combinations. In this way, effects related to the various degree of freedom before mentioned can be investigated. As an example, effects related to the mass asymmetry in incomplete fusion events at low energies ($<$ 20 MeV/nucleon) have been investigated [2]. In more recent times, data concerning systems with noticeable differences in N/Z have been increasingly reported in the literature [3, 4]. In this way, it was possible to investigate in details the effects played by the isospin degree of freedom on various aspects of reaction dynamics, such as the co-existence of various competitive mechanisms [5, 6], the neutron exchange between reaction partners (isospin diffusion) [7, 8, 9, 10] and the neutron enrichment of low-density regions formed in peripheral collisions (isospin drift) [5, 10, 11]. The analysis of these phenomena is useful also to obtain details about the behavior of the Symmetry Energy of the Nuclear Equation of State, a topic of relevant interest also in the Nuclear Astrophysics and Nuclear Structure fields [12, 13].

Interesting findings can be obtained by analyzing the distributions of light fragments emitted at forward angles. Z-distributions are characterized by even-odd oscillations that could be attributed to the last steps of the de-excitation phase of excited pre-fragments, as discussed in various paper reported in the literature [14, 15, 16, 17, 18, 19, 20, 22]. It has been observed moreover that, by increasing the N/Z of total system, the amplitude of the even-odd staggering of the Z-distributions is more an more smoothed. As expected from symmetry considerations, even-odd staggering effect has been recently found also for the N-distributions, as reported in [18, 20]. As suggested in Refs. [16, 21], also the reaction mechanism involved could have a small influence on the amplitude of the even-odd effect.

In the case of medium-mass systems, at low values of impact parameter, we can observe the co-existence of incomplete fusion phenomena in competition with binary-like and multi-fragmentation events [23, 24, 25]. In this case the correlation between the mass and velocity of the two or three biggest emitted fragments can represent an useful way to discriminate between the various reaction mechanisms [3, 17]. Recently, by investigating ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon we observed that the N/Z of the total system plays an important role in the competition between these mechanisms [6, 26], as predicted by many theoretical models [27, 28, 29]. Moreover, comparisons of our data with the CoMD-II dynamical model calculations has allowed to extract information about the density dependence of the Symmetry Energy in the Nuclear Equation of state at near-saturation densities [6, 26].

In this paper we focus our attention to the analysis of the two isobaric systems ^{48}Ca+^{48}Ca (N/Z=1.4) and ^{42}Ca+^{54}Fe (N/Z$\simeq$1.09, preliminary results) at 25 MeV/nucleon. The use of isobaric systems allow to reduce the influence of spurious effects due to the bare difference in their total mass. Charge distributions of light fragments emitted at forward angles show even-odd staggering effects with a large amplitude in the case of the more neutron poor system, while for the neutron rich system the relative probability of heavy residue emission is favored. The results of these analysis will be briefly discussed in the following sections.

2. Experimental apparatus

The experiment was performed at the INFN-Laboratori Nazionali del Sud in Catania. ^{42,48}Ca beams, accelerated at 25 MeV/nucleon by the Super-Conducting Cyclotron, were driven on isotopically enriched self-supporting target of ^{48}Ca (2.7 mg/cm^2 thick) and ^{54}Fe (2.0 mg/cm^2 thick).

The reaction ejectiles were detected by means of the 4π multi-detector Chimera [30, 31]. It covers practically the whole solid angle (about 94% of 4π) and it is constituted by 1192 Si-CsI(Tl) telescopes arranged with azimuthal symmetry around the beam axis. The nominal thickness of silicon detectors is $300\mu m$, while caesium iodide thickness varies as a function of the polar angle from 12 cm (forward angles) down to 3 cm (backward angles). The coupling of different identification techniques offers the opportunity to identify in charge and/or in mass the reaction products. These methods are respectively: (1) the ΔE-E method, useful to discriminate the Z of ejectiles punching through the Si detector, and also to give isotopic identification of fragments with Z$\approx$10 or more; (2) the Time of Flight (ToF) method, that allows to obtain the mass of slow

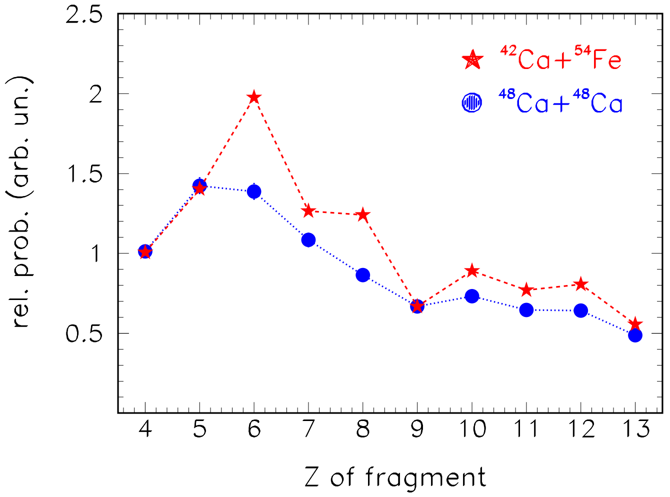

Figure 1. Charge distributions of light fragments emitted at $\theta_{Lab} = 11.5°$ and identified by means of the telescope technique in ^{48}Ca+^{48}Ca (N/Z=1.4, blue full dots), ^{42}Ca+^{54}Fe (N/Z=1.09, red stars) reactions at 25 MeV/nucleon. In both distributions the beryllium yields have been normalized to unit.

fragments stopped in Si detectors; (3) the fast-slow analysis of CsI(Tl) light output, allowing the isotopic identification of light particles, such as hydrogen and helium nuclei; (4) the study of the rise time of signals coming from silicon detectors, useful to determine the Z of stopped fragments. Further details about the Chimera array and its detection and identification capabilities can be found in Refs. [30, 32, 33]. Time resolution obtained in the performed experiment is $\approx 800ps$; it is due mostly to timing characteristics of the beam. The obtained mass resolution ($\frac{\Delta m}{m}$) is around 5% [6, 26] for nuclei having mass $A \approx 50$.

Profiting of the performances of the experimental apparatus, we consider in the data analysis only complete events, having at least the 80% the total charge and the 70% of the total parallel momentum. We impose moreover an upper constraint on the total detected charge: it must be less than the 100% of the total entrance charge. These selections allow to discard spurious events of reaction on oxygen contaminant in the target and pile-up events. Very peripheral quasi-elastic events were removed by the on-line electronic trigger by requiring the detection of at least 3 charged particles.

3. Even-odd staggering effects on Z distributions of light fragments

Charge distributions of light fragments emitted in heavy ion collisions often show the presence of even-odd staggering. This effect has been recognized in a large variety of bombarding energy domains, going from few MeV/nucleon (a regime dominated by Deep Inelastic Collisions and Compound nucleus phenomena) [16, 17, 34] up to 1000 MeV/nucleon (as seen in projectile fragmentation studies) [35]. In recent times, due to the increasingly improved identification power of the detectors, this subject has obtained a renewed interest, as seen in the literature [16, 18, 19, 20, 25].

Even-odd effects can be qualitatively explained by considering the last steps of de-excitation cascade involving excited pre-fragments formed during the dynamical phase of the reaction. The de-excitation cascade is correlated to the one-particle separation energy threshold, and this quantity shows strong even-odd oscillations due to pairing effects [15, 35, 16, 18].

It seems moreover that the amplitude of the even-odd effect is influenced by the N/Z of entrance channels [14, 16, 17]. In particular, by increasing the N/Z of the entrance channel, the amplitude of the even-odd oscillations are more and more softened. In Figure 1 we show the experimental Z distributions for light fragments emitted at $\theta_{Lab} = 11.5°$ and identified by means

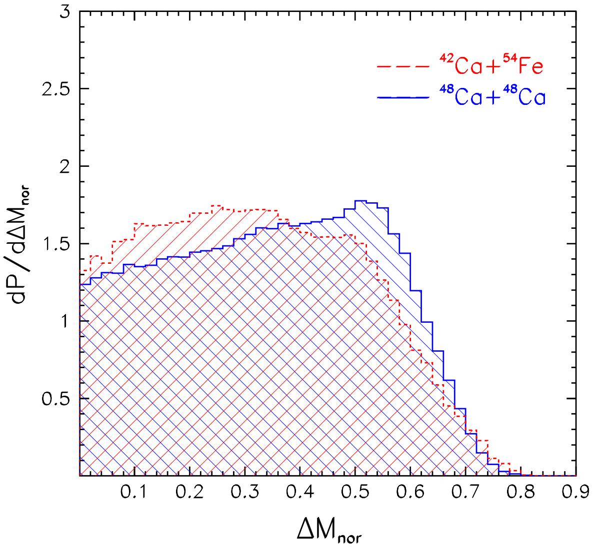

Figure 2. ΔM_{nor} distributions for selected central events of reaction in ^{48}Ca+^{48}Ca (blue solid line) and ^{42}Ca+^{54}Fe (red dashed line, *preliminary results*) systems at 25 MeV/nucleon.

of the telescope technique in ^{48}Ca+^{48}Ca (N/Z=1.4) and ^{42}Ca+^{54}Fe (N/Z=1.09) reactions. In both data sets, data have been matched at Z=4 (beryllium). We can observe that, even if the total mass of the two systems is the same, the amplitude of the even-odd oscillations are more softened for the neutron rich system. This effect can be qualitatively explained by considering that, for neutron rich systems, neutron rich pre-fragments would be formed in the first stage of reaction. These fragments will de-excite preferably by emitting neutrons, and therefore the proton number distributions will be less sensitive to the even-odd staggering of the particle emission threshold distribution. Moreover, for the neutron poor system (^{42}Ca+^{54}Fe) a quite large emission of carbon isotopes is seen, while the yields of boron and fluorine isotopes relatively to beryllium are quite similar for the two systems.

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

The centrality of reaction events can be selected by using constraints on the charged particle multiplicity m_{cp} [36].

In order to investigate the competition between various reaction mechanisms that can be observed in central events of reaction, we firstly select the most central collisions by imposing a proper selection on the charged particle multiplicity m_{cp} [36]. As extensively discussed in [6, 26], two slightly different cut on m_{cp} should be used for systems with very large differences in the total N/Z to adequately take into account the presence of undetected neutrons. In our case we choose $m_{cp} \geq 5$ for the neutron rich system ^{48}Ca+^{48}Ca and $m_{cp} \geq 6$ for the neutron poor ^{42}Ca+^{54}Fe system. Moreover, we focused our attention on events where the second or third biggest fragment has a velocity larger than the center of mass one (v_2 or $v_3 \geq$ 0.13 c). With this constraint, we focus our attention mainly on massive transfer phenomena where a part of the projectile fuses with the target.

For these events, we can discriminate the principal reaction mechanisms by investigating the correlation between the masses of the two biggest emitted fragments, m_1 and m_2. As discussed in details in Refs. [6, 26], we can define the ΔM_{nor} quantity as $\frac{m_1 - m_2}{m_{tot}}$, where m_{tot} is the total mass of the system. Large value of ΔM_{nor} are associated to heavy residue emission in fusion-like events, while low value of ΔM_{nor} are linked to binary-like, fusion-fission and multi-fragmentation events. In Figure 2 we show the experimental ΔM_{nor} distributions for the ^{48}Ca+^{48}Ca and ^{42}Ca+^{54}Fe systems here investigated. As seen in Figure 2, for the neutron rich system, ΔM_{nor} distributions are pushed towards higher values, while the opposite happens for the neutron poor one. It is interesting to note that the shape of the ΔM_{nor} distribution for the ^{42}Ca+^{54}Fe (N/Z=1.09) is similar to the one of ^{40}Ca+^{46}Ti (N/Z=1.05) as reported in [6]. Therefore, combining the results of the present analysis and of Refs. [6, 26] it seems that the relative yield of events leading to the formation of an heavy residue is larger for the more neutron rich systems, and the present effect can be mainly attributed to the N/Z degree of freedom and not to the mass asymmetry or the total mass of entrance channels. As discussed elsewhere [6, 26, 27], these effects can be explained by considering the interplay between the Coulomb and Symmetry terms of the Nuclear Equation of State. We plan to perform CoMD-II dynamical model calculations also for the ^{42}Ca+^{54}Fe data with the aim of refining the estimate of the stiffness of the Symmetry Energy for the Nuclear Equation of State at near-saturation densities [6, 26].

5. Conclusions

In this paper we report experimental results obtained by investigating ^{48}Ca+^{48}Ca (N/Z=1.4) and ^{42}Ca+^{54}Fe (N/Z=1.09) systems at 25 MeV/nucleon. Effects due to the isospin degree of freedom can be studied profiting of the good events reconstruction and isotopic identification given by the Chimera 4π array, that is used as detection device.

The analysis of Z-distributions of light fragments emitted at forward angles shows even-odd staggering effect that can be attributed to the last steps of the de-excitation cascade of excited pre-fragments. In this case, the amplitude of the even-odd effect is enhanced for the neutron poor system ^{42}Ca+^{54}Fe, while it is strongly suppressed in the very neutron rich ^{48}Ca+^{48}Ca system.

We find that, at semi-central impact parameters, the relative emission yield of heavy residues in fusion-like phenomena is enhanced for the neutron-rich system, while binary-like and multi-fragmentation events prevail for the neutron poor system. This effect has been recognized by studying the correlation between the masses of the two biggest emitted fragments.

As discussed in various theoretical papers in the literature, this effect can represent a useful probe to extract information about the density dependence of the Symmetry Energy of the Nuclear Equation od State at near-saturation densities. All these results stimulate moreover to continue the investigation on isospin effects in medium mass nuclear reactions by using radioactive beams or targets, in order to enlarge the range of N/Z of the formed systems.

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