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N/Z effect on reaction mechanisms cross sections in the ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca collisions at 10 A MeV

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Summary. — Nuclear reactions between medium-mass nuclei at low bombarding energy are characterized by the competition between binary and evaporation processes in the compound nucleus decay. A study of the influence of the neutron richness of the entrance channel on the decay paths of the compound nuclei formed in the ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 MeV/A is presented. The experiment has been performed at Laboratori Nazionali del Sud by using the CHIMERA 4π multidetector for charged particles. The kinematical characteristics of the two reactions support the conclusion of a production of the IMFs via long-lived system and the global features suggest a different competition among the various reaction channels. The cross sections of the mechanisms responsible for the fragments production have been extracted. Besides the results relative to the n-poor system are compared to those obtained at GANIL, performed at 5.5 A MeV, in order to study the energy influence on the mechanisms.

1. – Introduction

Heavy-ion collisions are a powerful tool in order to have information about nuclear structure properties and to investigate the characteristics of reaction dynamics. In fact, different incident energies and impact parameters lead the interacting systems to various configurations that result in the observation of a wide variety of reaction channels.

The collisions in the, so-called, low-energy domain ($E/A \leq 15$ MeV) are characterized by the competition between fusion process, where the compound nucleus decays or through evaporation of light particles or through fission, and binary processes. The compound nucleus disexcitation modes produce particles in a wide mass range, in particular the production of fragments with atomic numbers $3 \leq Z \leq 20$, denoted as the Intermediate Mass Fragments, IMFs, is very interesting because of many features that are not well understood yet.

The N/Z ratio, strongly correlated to the isospin degree of freedom, has important effects on the characteristics of the fragments production and it is expected to play a crucial role in the competition among the different decay channels.

In this work, the study of the influence of the neutron enrichment on the decay modes of the compound nuclei formed in the reactions ^{78}Kr + ^{40}Ca (n-poor) and ^{86}Kr + ^{48}Ca (n-rich) at 10 A MeV, will be discussed. In fact these reactions, lead to the formation of two systems with N/Z ratios, 1.11 and 1.39, respectively, providing the maximum difference available with stable beams. The experiment called ISODEC [1-3], where the reactions mentioned before have been realized, has been performed at Laboratori Nazionali del Sud in Catania, by using the beams delivered by the Superconductive Cyclotron and the detection and identification capability of the 4π multidetector CHIMERA [4, 5].

Moreover, some effects of the incident energy will be shown through the comparison between the results relative to the reaction ^{78}Kr + ^{40}Ca performed at 10 A MeV and at 5.5 A MeV, respectively.

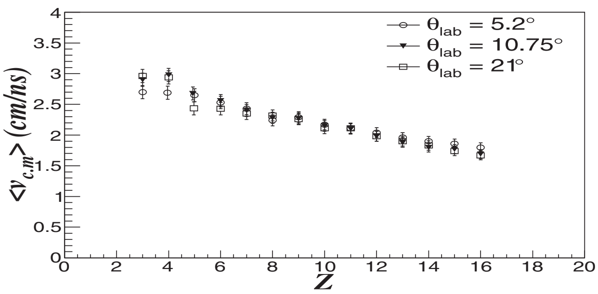

Fig. 1. – Values of the average velocities, in the c.m. frame, *vs.* Z at 3 different laboratory angles for ^{78}Kr + ^{40}Ca at 10 A MeV.

2. – Experimental results

The CHIMERA apparatus is a powerful device for studying the heavy-ion collisions not only for the good identification in mass and/or charge of the reaction products and the complete event reconstruction but also for the precise information about the kinematical features that allow the discrimination among the various reaction channels.

In fact the analysis of the velocity spectra suggests a high relaxation of the degree of freedom [6-8]; plotting (fig. 1 [3]) at different laboratory angles, the average values, obtained in the center-of-mass frame, nearly independent of the emission angles, *vs.* the atomic number it is possible to observe a quasi linear decrease with the increase of the atomic number.

Moreover, as it is shown in fig. 2 [3], the angular distributions of the IMFs in the center-of-mass frame follow a $1/\sin\theta$ behavior confirming a production via a source which has reached an equilibration after the fusion of the target and projectile, thus with a lifetime longer than its rotational period, that implies a loss of memory of the entrance channel direction.

Therefore we can conclude that the major sources of emission of the IMFs are the asymmetric and very asymmetric fission-like mechanisms; another proof is that the emission velocity can be explained in terms of pure Coulomb repulsion between the couple of fragments, as it is demonstrated by the comparison (fig. 3 [3]) between the average

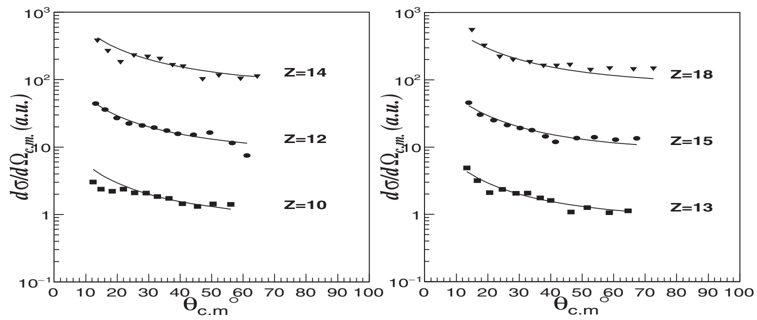

Fig. 2. – For the ^{78}Kr + ^{40}Ca reaction: angular distributions of IMFs, in the center-of-mass frame compared to $1/\sin\theta_{c.m.}$ (solid line).

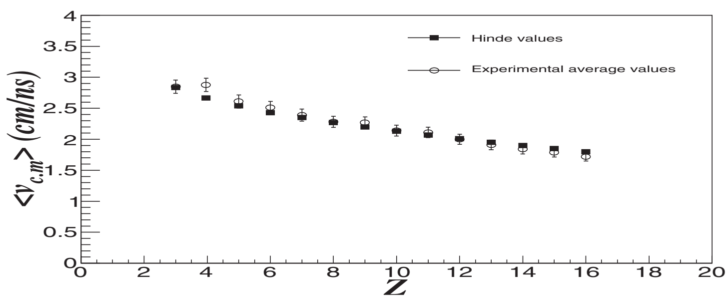

Fig. 3. – For the ^{78}Kr + ^{40}Ca reaction: comparison of the mean values of the velocity, in the center-of-mass frame, averaged over all angles, with the values of Hinde's systematic.

values of the velocity in the center-of-mass frame and the values obtained through the Viola systematic [9], with the correction by Hinde for the asymmetric fission [10], that provides the most probable value of the energy released in a fission process.

The results shown before have been obtained for the n-poor system but similar consideration can be made for the n-rich one; however, despite the production mechanism is the same for the two reactions, there is a big difference in the probability of the IMFs emission.

In fact if we look at the production cross sections of the IMF, as a function the atomic number, up to $Z = 15$, in fig. 4 [3], we can observe a strong influence by the isospin. The fission process would seem to be more probable for the n-poor system, as proved by the higher values of the production cross sections of the IMFs. Moreover, in agreement with other examples in the literature, the preferential production of fragments with an even value of the atomic number, responsible of the presence of an even-odd effect, the staggering [11, 12], in the charge distribution, is more evident for the n-poor system, in particular for fragments with a value of the atomic number less than 10; this effect could be strongly connected to the pairing forces [13]. The staggering is also observed in the plot of IMF's yields *vs.* the neutron number, shown in fig. 5, but in this case it is more pronounced for the n-rich system [11]. One should observe that in the literature there are few examples of this kind of study, as it requires an apparatus allowing a good isotopic discrimination; the CHIMERA device provides, with high resolution, the isotopic

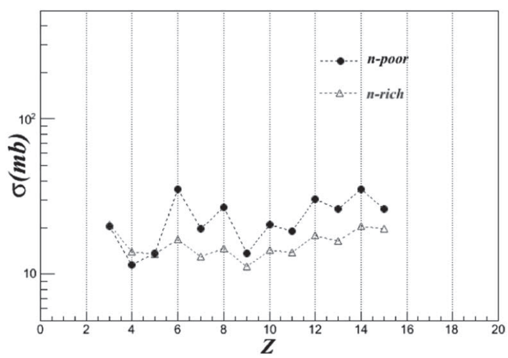

Fig. 4. – Production cross section for fragments with different atomic numbers for the two reactions ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca. The error bars are inside the graphical symbols.

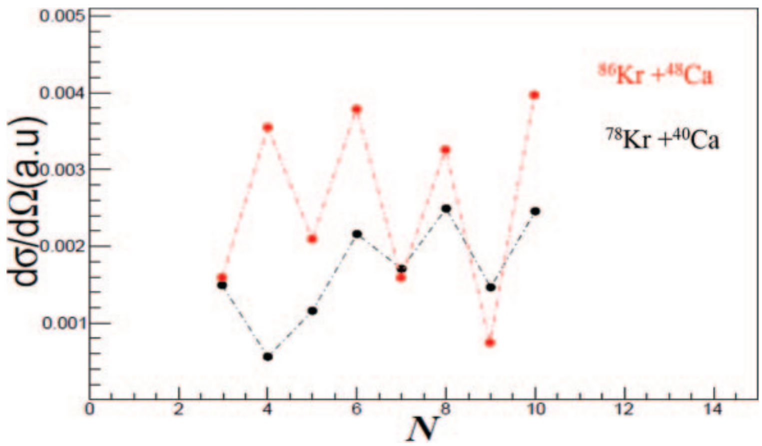

Fig. 5. – IMFs yields *versus* the neutron number, at $\theta \simeq 11°$, in black for ^{78}Kr + ^{40}Ca and in red for ^{86}Kr + ^{48}Ca. The error bars are smaller than the symbols.

composition of the fragments with $Z \leq 9$. The produced IMFs seem to be emitted in an excited state as suggested by a preliminary study of the relative velocity of the IMF and one α particle emitted in coincidence, projected in the reference frame of the fission

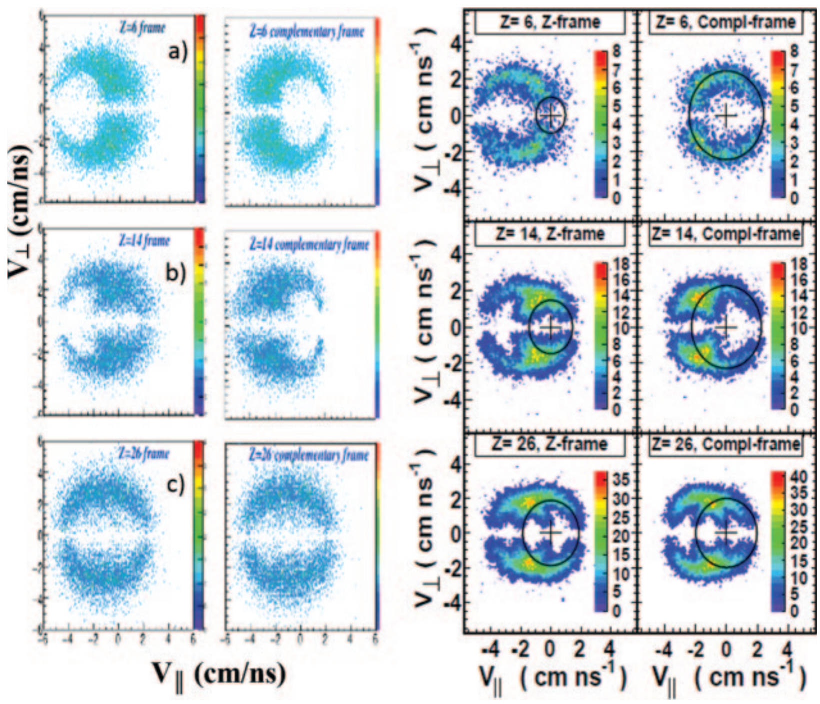

Fig. 6. – $v_\perp$ *vs.* $v_\parallel$ plot for the n-poor system, in the frame of the light fragment and in its complementary partner's frame, on the left for incident energy $E = 10$ A MeV and on the right for $E = 5.5$ A MeV.

fragment. This frame is constituted by the axis in the direction of the velocity of the fragment in the center-of-mass frame and by the plane perpendicular to this axis. The $v_{\perp}$ *vs.* $v_{\parallel}$ plots, in the case of very asymmetric fission, where the emitted IMF is the Carbon (a panel), asymmetric fission, where the emitted IMF is the Silicon (b panel) and symmetric fission (c panel), in the frame of the IMF and in its complementary partner frame, are shown in the left part of fig. 6. By the comparison between the results relative to the ISODEC experiment and those relative to the experiment realized at GANIL, with the INDRA device, where the $^{78}\mathrm{Kr} + {}^{40}\mathrm{Ca}$ reaction was studied at 5.5 A MeV (the right part of the picture) [6] one observes that in the case of very asymmetric fission, at higher energy the $v_{\perp}$ *vs.* $v_{\parallel}$ plot seems to present a Coulomb ring centered at the origin also when the relative velocity are plotted in the frame of the IMF, suggesting that at 10 A MeV, also this fragment is emitted in an excited state.

3. – Conclusions

Some results of the analysis of the experiment ISODEC have been presented, in particular the influence of the isospin degree of freedom on the aspects characterizing the fission process. The two different systems studied, $^{78}\mathrm{Kr} + {}^{40}\mathrm{Ca}$ and $^{86}\mathrm{Kr} + {}^{48}\mathrm{Ca}$, exhibit an odd-even effect, the staggering, presented in both, charge distributions and the IMFs yields *vs.* the neutron number, anyway the oscillation amplitude is more pronounced in the first case for the n-poor system and in the second one for the n-rich system.

Also the energy of the entrance channel influences the emission processes, in fact a preliminary study of the relative velocity of the α particles emitted in the same event with an IMF and the heavy partner of the latter, would suggest an α particle's emission also by the IMF in a very asymmetric fission process, at higher energy.

For better understanding the staggering effect it is necessary to study the coincidence between the light particles and IMFs and the other heavier fragments. Moreover the competition among the different reaction channels could be different between the two studied systems, therefore the cross sections will be calculated, allowing also a better comparison with statistical [7] and dynamical [14] models and between the two different incident energies.

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