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Study on the isospin equilibration phenomenon in nuclear reactions ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{46}Ti, ^{40}Ca + ^{48}Ca, ^{48}Ca + ^{48}Ca at 25 MeV/nucleon by using the CHIMERA multidetector

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Summary. — We report on the results obtained by studying nuclear reactions between isotopes of Ca and Ti at 25 *MeV/nucleon*. We used the multidetector CHIMERA to detect charged reaction products. In particular, we studied two main effects: the *isospin diffusion* and the *isospin drift*. In order to study these processes we performed a moving-source analysis on kinetic energy spectra of the isobar nuclei ^{3}H and ^{3}He. This method allows to isolate the emission from the typical sources produced in reactions at Fermi energy: projectile like fragment (PLF), target like fragment (TLF), and mid-velocity (MV) emission. The obtained results are compared to previous experimental investigations and to simulations obtained with CoMD-II model.

1. – Introduction

In the last twenty years a large attention has been devoted to the *isospin physics*, in order to understand the role played by this degree of freedom in the nuclear reactions dynamics. Among the possible effects linked to the N/Z gradient between the two interacting nuclei the main is the *isospin equilibration*. Indeed, the nuclear forces tend to restore a uniform distribution of N/Z ratio between the two nuclei in interaction. In this work we studied this phenomenon in nuclear collisions ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{46}Ti, ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca at 25 MeV/nucleon. The energy domain of these reactions is traditionally called *Fermi energy domain*. Several investigations show that, for semi-peripheral reactions, this regime is characterized by the presence of three fragment-emitting sources: PLF, TLF and MV. Moreover, it is predicted that two main effects take place in this energy domain: the *isospin drift* and the *isospin diffusion* [1-4]. The first one is related to a density gradient, in the overlap region between the two nuclei, that causes a transition of neutrons towards the low-density region (MV), producing an increase of neutron-rich fragment emitted in this region. The second one is related to an isospin gradient between projectile and target; this causes a net neutron flux from the neutron-rich partner to the neutron-poor one. Consequently, the N/Z ratio of emitted fragments is strongly linked to the entrance channel one. Assuming to have a peripheral collision of an isospin asymmetric system, a di-nuclear transient system composed by the partial overlap of projectile and target is formed. After a time-window of a few hundred fm/c, the PLF and TLF excited sources will re-separated and the N/Z ratio of the PLF will be modified with respect to the ratio of the projectile P [5]. If a complete isospin equilibration is reached between the projectile and the target, the PLF source will show values of N/Z close to those of the total system. The total system, in this case, indicates the system which should be formed if the neutron excess is uniformly re-distributed between the target and the projectile. Consequently, the N/Z ratio of this latter represents the N/Z of a chemically equilibrated system. A common way to estimate the degree of equilibration reached during the interaction relies on the use of the equilibration fraction f_{eq}, defined as [6]

$$f_{eq} = \frac{(\frac{N}{Z})_{PLF} - (\frac{N}{Z})_P}{(\frac{N}{Z})_{TOT} - (\frac{N}{Z})_P}. \tag{1}$$

In this equation the difference between the $(\frac{N}{Z})_{PLF}$ and the $(\frac{N}{Z})_P$ is scaled by the maximum possible difference (neglecting, as a first approximation, pre-equilibrium effects), namely the difference between the value of N/Z of the total system and the N/Z of projectile one [6]. If this value is equal to 1, a complete equilibration is reached, if this value is equal to 0 the equilibration is not reached. In order to investigate the above mentioned effect it is necessary to obtain information on the N/Z of emission sources; to obtain that, we used the *isobaric ratio method* [6] by detecting isobar nuclei ^{3}H and ^{3}He, using the CHIMERA multidetector; for more details on the experimental set-up see [7,8]. We employed the ΔE-E technique for the Z identification of fragments punching through the silicon detectors and the Fast-Slow technique for energetic light charged particles stopped in CsI(Tl) detectors.

2. – Data analysis and results

In order to extract detailed information on the N/Z sources, we analyzed the kinetic energy spectra of ^{3}H and ^{3}He by performing fit that used a Maxwellian moving source parametrization of the emitted particles [9]. To improve statistics, the fit was extended to all the reaction data set considering that, for geometrical reasons, semi-peripheral collisions prevail. From the fit we derived the emission yields of ^{3}H and ^{3}He for the PLF and MV sources, and we built the yield ratios $r_3 = \sigma(^3\text{H})/\sigma(^3\text{He})$. The obtained results

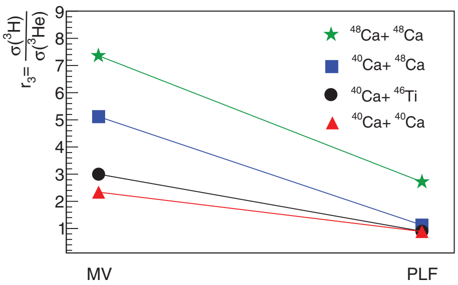

Fig. 1. – Trend of r_3 obtained by the Maxwellian moving source analysis.

for the PLF and MV sources are reported in fig. 1. Due to the detection thresholds it was very difficult to have access to the TLF contribution. In fig. 1 we can observe a MV emission characterized by r_3 values higher than the PLF emission one, also for the isospin symmetric reactions. This finding indicates that the *isospin drift* takes place during the collision. Moreover, the r_3 increases with the N/Z of target nuclei also for reactions involving the same projectile, ^{40}Ca. This shows that the *isospin diffusion* takes place between projectile and target. It is also possible to note that there is a very small difference between the $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ and $^{40}\mathrm{Ca} + {}^{46}\mathrm{Ti}$; this confirms that a moderate size difference between systems with similar N/Z does not cause appreciable variations in the isobaric ratio. The obtained results are in agreement with a previous analysis performed on ^{7}Li, ^{7}Be [10,11] but in the present case we have lower statistical uncertainties, due to the larger statistics of light isobars. In the present analysis the role played by symmetric reactions is of fundamental importance; indeed for these reactions just the effect of *isospin drift* is predicted. For this reason these two reactions can be used as reference systems to make a comparison with the mixed system $^{40}\mathrm{Ca} + {}^{48}\mathrm{Ca}$. Following statistical multi-fragmentation model it is possible to assume that the isobaric ratio is exponentially linked to the N/Z of a given source [6,12]. In fig. 2 it is reported the $\ln(r_3)$ for the PLF source as a function of the N/Z of the total system, for the two symmetric reactions. They can be seen as reference points because, being the *isospin diffusion* process absent by definition, the $\ln(r_3)$ can be linearly related to the N/Z of a given source. The line connecting these points is the *equilibration line*. If a complete isospin mixing takes place, the point of isobaric ratio for PLF source, formed in the mixed system, should stay on

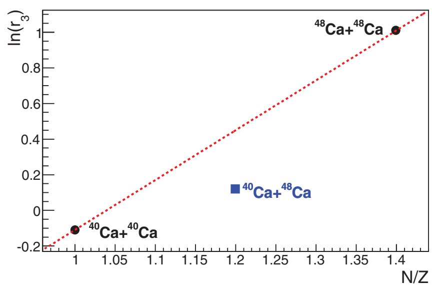

Fig. 2. – In figure is reported the $\ln r_3$ for the PLF source as function of N/Z of the total system. The dotted line is the equilibration line calculated by the symmetric reactions.

the equilibration line. On the contrary, if a complete isospin mixing is not reached, experimental point of mixed system would be distant from the equilibration line. In fig. 2 it is possible to observe that the point for the mixed system is distant from the equilibration line. This finding points out an incomplete isospin equilibration reached by the mixed systems during the interaction phase. Following the procedure discussed in [10] we estimated a value of $(\frac{N}{Z})_{PLF} = 1.080 \pm 0.006$, namely a value of $f_{eq} = 40 \pm 5\%$. This value is slightly different with respect to that obtained from the previous analysis performed on ^{7}Li/^{7}Be, indeed in this case the obtained value was $f_{eq} = 63 \pm 15\%$. This discrepancy could be attributed to different side feeding effects that involve mass 3 and mass 7 isobars and will be explored with detailed statistical model calculations. In any case, it is interesting to observe that a theoretical calculation performed with the CoMD-II [13] shows a $(N/Z)_{PLF}$ value equal to 1.07, in good agreement with the one obtained using the r_3 values reported in the present analysis.

3. – Conclusions and outlooks

We studied the phenomenon of *isospin equilibration*, by using the method of isobaric ratio. We observed a strong neutron enrichment for the MV region, for all studied reactions. This enrichment can be explained through the *isospin drift* phenomenon. We observed also the presence of the *isospin diffusion* for the mixed system, with a $f_{eq} = 40 \pm 5\%$. These results are slightly different with respect to the ones obtained by using mass 7 isobars, pointing out a possible role played by statistical decay effects on the yields of fragment of different masses. This finding deserves further analysis and comparisons with dynamical and statistical models that are currently ongoing [14]. An improvement of the present results will be obtained with a selection in centrality of the events, that is currently under investigation. Using the FRIBs facility we have the possibility to study a wide range of N/Z ratios and proton-rich systems, moreover using the FARCOS multidetector [15] and the GET electronics we can obtain information on TLF.

REFERENCES

[1] DeFilippo E. *et al.*, *Phys. Rev. C*, **86** (2012) 014610.
[2] Lombardo I. *et al.*, *Phys. Rev. C*, **84** (2011) 024613.
[3] DiToro M. *et al.*, *Eur. Phys. J. A*, **30** (2006) 65.
[4] Cardella G. *et al.*, *Phys. Rev. C*, **85** (2012) 064609.
[5] Shetty D. V. *et al.*, *Phys. Rev. C*, **76** (2007) 024606.
[6] Keksis A. *et al.*, *Phys. Rev. C*, **81** (2010) 054602.
[7] Pagano A. *et al.*, *Nucl. Phys. A*, **734** (2004) 504.
[8] DeFilippo E. and Pagano A., *Eur. Phys. J. A*, **50** (2014) 32.
[9] Awes T. C. *et al.*, *Phys. Rev. C*, **25** (1982) 2361.
[10] Lombardo I. *et al.*, *J. Phys.: Conf. Ser.*, **420** (2013) 012094.
[11] Lombardo I. *et al.*, *Phys. Rev. C*, **82** (2010) 014608.
[12] Su J. *et al.*, *Phys. Rev. C*, **84** (2011) 047601.
[13] Papa M. and Giuliani G., *Eur. Phys. J. A*, **117** (2009) 054602.
[14] Papa M. *et al.*, *Phys. Rev. C*, **91** (2015) 041601(R).
[15] Pagano E. V. *et al.*, *Status and perspective of FARCOS: A new correlator array for nuclear reaction studies*, in *Conference Proceedings*, **109(2)** (SIF, Bologna) 2016, p. 1077, *EPJ Web of Conferences*, **117** (2016) 10008 (online version).