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First results on the ^{32}S + ^{40,48}Ca reactions at 17.7 A MeV studied with GARFIELD setup at LNL

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Summary. — The ^{32}S+^{40,48}Ca systems at 17 A MeV have been characterized both for fusion and for peripheral events thanks to the GARFIELD setup, which covers a wide angular range and has high granularity; moreover, isotopic identification for forward emitted ions up to Z around 15 is obtained. The main evidences reported here concern pre-equilibrium emission, which was put into evidence in fusion-evaporation events, and isospin diffusion observed studying the average N/Z of the Quasi-Projectile as a function of the target isospin.

1. – Introduction

This work deals with an experimental investigation of the systems ^{32}S+^{40,48}Ca,^{48}Ti at 17.7 A MeV performed at LNL-INFN (Legnaro, Italy) with the GARFIELD - RCO setup, whose characteristics are described in [1]. Here we only recall the wide angular coverage of the setup (64% of 4π and 70% of the forward hemisphere) and the good performances in terms of isotopic resolution for fragments with $Z < 15$ emitted at polar angles in the range 6°–17°.

In the collected data two main classes of events have been observed: fusion events (fusion-evaporation FE and fusion-fission FF) and binary events ascribable to Deep Inelastic Collisions (DIC). Two main topics have been investigated on the collected data: the pre-equilibrium emission for fusion events and the isospin diffusion process in DIC events.

Pre-equilibrium phenomena are generally investigated because they can give information about the dynamical phase before the complete equilibration of the system. They are usually put into evidence from the discrepancies with respect to the description of the statistical model; for example, in [2], kinetic energy spectra of light charged particles (LCP) with deformed shapes with respect to the prediction of the statistical model are considered to be a proof of pre-equilibrium emission. The estimation of the pre-equilibrium contribution is also relevant for the accurate characterization of hot sources formed in fusion reactions when their decay is studied in details [3, 4].

Isospin transport phenomena (both drift and diffusion process, *e.g.* [5, 6]) are investigated because they give information about the density dependence of the symmetry energy term of the nuclear equation of state, which is not well known far from normal conditions. In the energy regime relevant for this work the isospin drift phenomenon, triggered by the density gradient between the regions of the Quasi-Projectile (QP) and Quasi-Target (QT) at normal density and the more diluted neck zone, is negligible. On the contrary, by using two targets with different isospin, we can put into evidence the isospin diffusion process, driven by the isospin gradient between target and projectile, comparing the isospin of QP and its ejectiles when the N/Z of the target changes from 1 (for ^{40}Ca, equal to the value of the projectile) to 1.4 (for ^{48}Ca).

2. – Event sorting

In order to properly classify the events, it is useful to take advantage of a model able to give a reasonable description of the system. It is well known that in the energy regime of this work, a good description of the main characteristics of the collision can be obtained by means of transport models, as, for example, the Stochastic Mean Field (SMF) [7, 8]. In order to compare with measured quantities, SMF must be coupled to an afterburner (such as GEMINI++ [9]) to de-excite hot primary fragments. We ran the SMF code over the whole impact parameter range up to the grazing value, stopping the calculation at 300 fm/c, where the exit channel can be properly recognized for all the events. The simulation predicts fusion events (*i.e.* events ending with only one fragment) up to $b = 6$ fm and DIC events (*i.e.* binary events) starting from $b = 5$ fm. The quality of the global agreement between experimental and simulated data can be appreciated looking at fig. 1, where the Z *vs.* v_{cm} correlation (where v_{cm} is the centre of mass velocity) for all the particles is presented: left part refers to experimental data, while right part corresponds to simulated data after filtering by means of a software replica of the setup.

Using the simulation as a guide, the events have been classified according to their position on the correlation Z_{tot} *vs.* ϑ_{flow}, where Z_{tot} is the total charge of all the detected fragments and ϑ_{flow} is the flow angle [10], built by including all the detected ions, as shown in fig. 2. DIC events, when only the QP is detected, belong to the continuous gate, while fusion events fall inside the dotted gate; FE events are selected by requiring only one fragment with $Z > 3$ among fusion events.

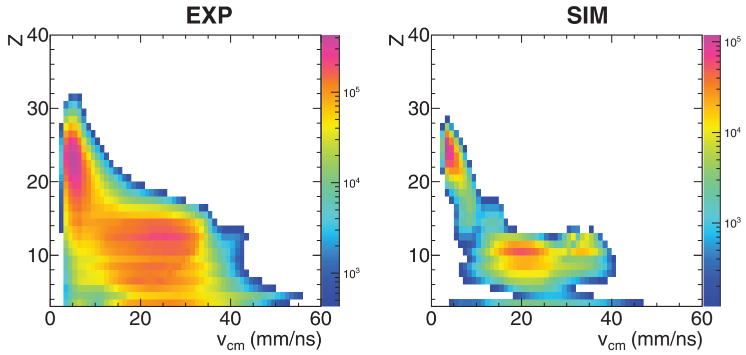

Fig. 1. – Z *vs.* v_{cm} correlation for the ^{32}S+^{48}Ca reaction; left part: experimental data. Right part: simulated data (SMF + GEMINI++), filtered by a software replica of the setup.

3. – Pre-equilibrium emission

Kinetic energy spectra of LCP's detected in FE events have been compared with the predictions of the statistical code GEMINI++ run in the hypothesis of complete fusion (source: ^{80}Kr with $E^* = 4.32$ A MeV). As it is shown in fig. 3 for α particles, kinetic energy spectra of backward emitted particles nicely agree with the model predictions in terms of shape, while a strong discrepancy, with the experimental spectra harder than the simulated ones, is observed for forward emitted particles. As pointed out in sect. **1**, this is an evidence of pre-equilibrium emission. Concerning a quantitative estimate of such an emission, the work is still in progress; some preliminary evaluations can be found in [11], together with a preliminary evaluation of the fusion cross section, which is found to be in agreement with the systematic treatment of [12].

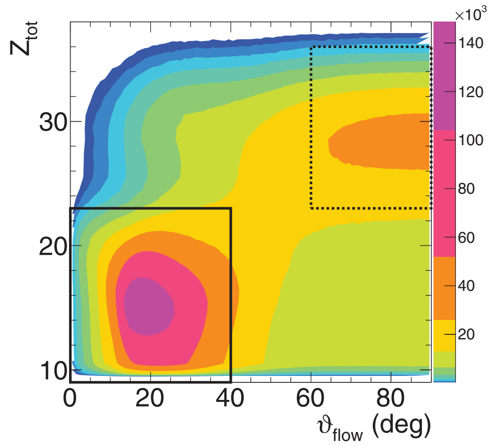

Fig. 2. – Z_{tot} *vs.* ϑ_{flow} correlation for the reaction ^{32}S+^{48}Ca, experimental data. The dotted gate corresponds to the fusion selection, while the continuous gate includes DIC events in which the QP only is detected.

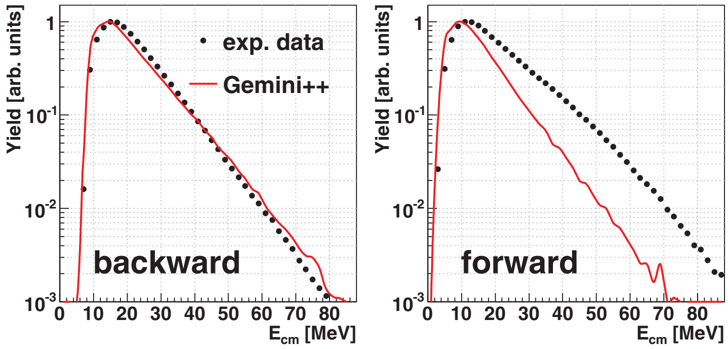

Fig. 3. – Kinetic energy spectra for α particles detected in FE events. Black points: experimental data, red line: GEMINI++ simulation; spectra are normalized to their integral. Left side: particles detected in the angular range 53°–83°; right side: particles detected in the angular range 7°–17°.

4. – Isospin diffusion

The DIC selection (events inside the continuous gate of fig. 2 with only one fragment with $Z > 7$ and polar angle in the centre of mass below 60°) is affected by a background of FE reactions of the ^{32}S+^{12}C system, due to the fact that Ca targets are embedded between two layers of ^{12}C to avoid prompt oxidation. As a consequence, it is necessary to subtract such a contribution on average from all the considered observables by means of the data collected for the ^{32}S+^{12}C reaction, provided that a correct scaling factor can be found. Such a scaling factor has been obtained from the correlation ϑ^{cm}_{rel} *vs.* $Z_1 + Z_2$, where ϑ^{cm}_{rel} is the relative angle in the centre of mass, for events with two fragments (of charge $Z_{1,2}$, respectively), built both for the ^{32}S+^{40,48}Ca reactions and for ^{32}S+^{12}C reaction, analyzed as if it were ^{32}S+^{40,48}Ca (*i.e.* with the wrong centre-of-mass velocity). More details can be found in [11]. The $\langle N\rangle/Z$ of the QP as a function of its charge obtained after subtracting the ^{12}C background is shown in fig. 4 for the three different targets. This figure obviously includes only the fragments for which the isotopic identification is possible, *i.e.* those detected between 5° and 17°, with enough energy to punch through the 300 μm Si layer of the RCO device (see [1] for details). It is clearly evident that for more dissipative reactions, when the QP size is smaller and the nucleon transport process is more efficient, the $\langle N\rangle/Z$ of the QP strongly depends on the isospin of the target, becoming higher for the n-rich ^{48}Ca case. The effects tend to fade out with increasing the QP size, corresponding to less peripheral collisions, where less nucleons are exchanged.

This evidence of isospin diffusion is nicely and independently supported also by the d/p and t/p multiplicity ratios for particles forward emitted with respect to the QP. In fact, as observed also in [13], although for a system at higher energy, the isospin of the products emitted by the QP increases with the isospin of the target.

The dynamical model clearly predicts the charge equilibration process, as shown in fig. 5, where the $\langle N\rangle/Z$ of the primary QP as a function of the charge is shown. Again, for less peripheral collisions the QP enhances its isospin content when the target is neutron rich. In this plot, for the ^{48}Ca case, two different parametrizations of the symmetry energy term of the nuclear equation of state have been tested, "asystiff" (full points)

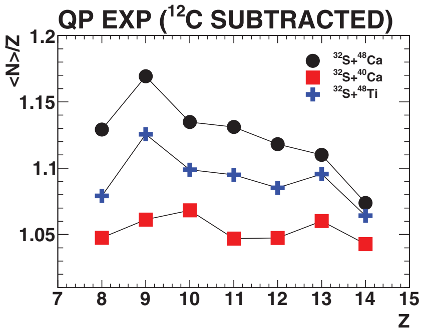

Fig. 4. – Experimental data: $\langle N\rangle/Z$ as a function of the QP charge, after subtracting the ^{12}C background.

and "asysoft" (open points) [5]; the obtained results show a negligible dependence on the adopted parametrization, meaning that the system, during its evolution, is exploring only regions close to the normal density, where all the parametrizations are equal. The application of the afterburner tends to strongly reduce the observed effect, which survives in a significant way only for the lightest QP.

5. – Summary and conclusions

Thanks to the large acceptance of the GARFIELD plus RCO setup, a global description of the reaction classes has been obtained for the ^{32}S+^{40,48}Ca systems at 17.7 A MeV. In particular, data concerning FE and DIC reactions have been presented. Evidence of pre-equilibrium emission in the FE channel has been found on the basis of the discrepancies between the experimental kinetic energy spectra of LCP and those simulated by a statistical code (GEMINI++). The quantitative estimate of such an emission is in progress. The trend to balance the different N/Z ratios of projectile and target (isospin

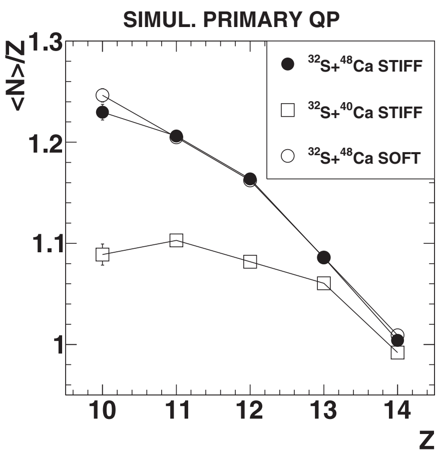

Fig. 5. – Simulated primary data: $\langle N\rangle/Z$ as a function of the charge for the QP.

diffusion) during the collision has been verified by studying the $\langle N\rangle/Z$ of the QP in binary events when the target changes from the ^{40}Ca (which has the same isospin of the projectile) to the neutron rich ^{48}Ca: the QP enhances its isospin when the neutron content of the target increases. This equilibration process is also predicted by the dynamical model SMF. However, the joined application of dynamical and statistical codes, needed to simulate the measured quantities, leads to results which are only qualitatively in agreement with experimental data and need further investigation.

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