IL NUOVO CIMENTO **39 C** (2016) 391
DOI 10.1393/ncc/i2016-16391-9

Colloquia: IWM-EC 2016

Three-α particle correlations in quasi-projectile decay in ^{12}C + ^{24}Mg collisions at 35 A MeV

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received 10 January 2017

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Summary. — Two and multi particle correlations have been studied in peripheral ^{12}C + ^{24}Mg collisions at 35 A MeV with CHIMERA 4π multi detector, in order to explore resonances produced in light nuclei. Correlations techniques have become a tool to explore nuclear structure properties but also to evaluate the competition between simultaneous and sequential channels in decay of light isotopes. The exploration of features such as branching ratios with respect to different decay channels (sequential *vs.* simultaneous) could provide information on in-medium effects on nuclear structure properties, an important perspective for research on the nuclear interaction. The performed experiment is preliminary to further studies to be performed by coupling of CHIMERA to FARCOS (Femtoscope ARray for COrrelations and Spectroscopy, FARCOS TDR available at `https://drive.google.com/file/d/0B5CgGWz8LpOOc3pGTWdOcDBoWFE`) array devoted to measurements of two and multi particle correlations with high energy and angular resolutions.

1. – Introduction

Heavy-ion collisions are a powerful tool to explore nuclear structure and equation of state (EoS) under laboratory controlled conditions. In these complex dynamical systems, particle-particle correlations allow to study the space-time properties of nuclear reactions [1] and to explore certain structure properties of unbound states [2]. During the dynamical evolution of a system, several loosely bound nuclear species are produced over short time scale and subsequently decay. Their unstable states can be identified and explored by constructing two and multi-particle correlations. This allows to study decay modes and disentangle direct and sequential mechanisms. Moreover their relative contribution to the decay width of observed resonances can be estimated. In this contribution, attention has been focused on three-α correlations explored to study the decay of resonances in excited ^{12}C quasi-projectiles. These three α particles can be produced either as the result of simultaneous breakup, *e.g.* $^{12}\mathrm{C} \to \alpha - \alpha - \alpha$, or in a sequence of two binary processes, passing through the formation of intermediate ^{8}Be unbound states, $^{12}\mathrm{C} \to {}^{8}\mathrm{Be}$-$\alpha$ followed by $^{8}\mathrm{Be} \to 2\alpha$.

2. – Experimental details and results

In order to explore two- and multi-particle correlations in Heavy Ion Collisions, an experiment has been carried out using ^{12}C + ^{24}Mg system at 35 A MeV incident energy. The ^{12}C beam has been delivered by Superconducting Cyclotron at Laboratori Nazionali del Sud and INFN of Catania and charged reaction products have been detected by CHIMERA 4π array [3]. In particular only the forward part of the apparatus, that covers polar angle between 1° and 30°, has been used. The overall quality of energy calibration was evaluated analyzing resonant states of light nuclei via two particle correlations (α-α, d-α). In order to select events coming from the decay of excited ^{12}C quasi-projectiles, a condition has been imposed to restrict velocities of fragments.

In particular reconstructed parallel velocity of ^{12}C, obtained from the center of mass of 3-α detected in coincidence, has been required to be larger than 80% of beam velocity

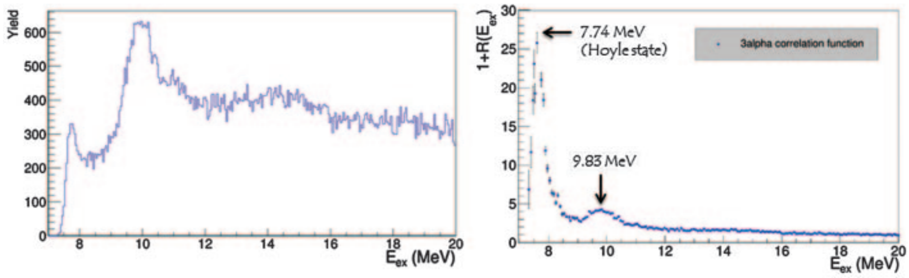

Fig. 1. – Yields of correlated 3-α particles (left panel) and 3-α correlation function (right panel) *vs.* excitation energy of ^{12}C obtained in $^{12}C + ^{24}Mg$ reactions at 35 A MeV.

(7.99 cm/ns). This selection criterion has been suggested by means of simulations performed with HIPSE model calculations [4].

Information on excited states of ^{12}C can be extracted from the 3-α correlation function, defined as

$$1 + R(E_{ex}) = \frac{Y_{coinc}(E_{ex})}{Y_{uncorr}(E_{ex})}, \tag{1}$$

where the coincidence yield spectrum, $Y_{coinc}(E_{ex})$, is obtained from the 3-α particles detected in the same event (left panel of fig. 1), while uncorrelated 3-α spectrum, $Y_{uncorr}(E_{ex})$, is built by randomly choosing α particles from single-particle spectra.

The 3-α correlation function is shown on the right panel of fig. 1 and it is reported as a function of excitation energy $E_{ex} = E_{tot} - Q$, where E_{tot} is the total kinetic energy in the 3-particle center-of-mass reference frame and Q is the Q-value for the corresponding decay channel.

It shows two peaks: the first one, centered around $E_{ex} = 7.74\,\text{MeV}$, corresponds to the Hoyle state ($E_{th} = 7.65\,\text{MeV}$, $\Gamma = 8.5\,\text{eV}$); the second peak, centered at $E_{ex} = 9.83\,\text{MeV}$, arises from the overlap of the states at $E_{ex} = 9.64\,\text{MeV}$ (3^-), $E_{ex} = 10.3\,\text{MeV}$ (0^-) and possibly at $E_{ex} = 9.7\,\text{MeV}$ (2^+). In order to study the decay mechanism of the Hoyle state, Monte Carlo simulations have been performed for each decay process: sequential mechanism $^{12}\text{C}\rightarrow^{8}\text{Be-}\alpha \rightarrow 3\alpha$ (DS) and direct three-α decay according to phase-space equiprobability $^{12}\text{C}\rightarrow 3\alpha$ (DDΦ). In these simulations all experimental effects, such as geometry, angular coverage and energy resolution have been take into account. With the aim of investigating and quantifying the various decay modes, energy distributions of decay products have been analyzed adopting the symmetric Dalitz plots [5], which are particularly suitable for the case of three particles of equal masses.

To construct these plots the following coordinates have been used:

$$X = \sqrt{3}(\epsilon_j - \epsilon_k), \quad Y = 2\epsilon_i - \epsilon_j - \epsilon_k, \tag{2}$$

where $\epsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$ are the energies of particles in the center-of-mass reference frame, normalized to total decay energy.

Figure 2 shows symmetric Dalitz plots for simulated events corresponding to sequential decay (bottom left panel) and direct phase-space decay DDΦ (bottom right panel) of the Hoyle state. The same Dalitz plot has been constructed using experimental data

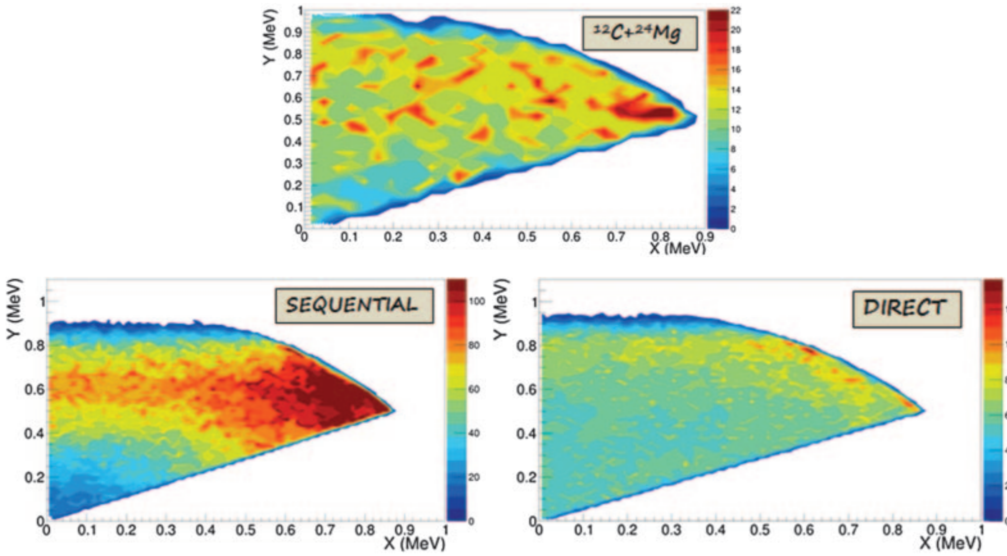

Fig. 2. – Symmetric Dalitz plots of simulated events for sequential (bottom left panel) and direct phase-space (bottom right panel) decay of Hoyle state. Top panel: symmetric Dalitz plot, corresponding to decay from Hoyle state region, constructed with experimental data collected in $^{12}\mathrm{C} + {}^{24}\mathrm{Mg}$ reaction.

collected in $^{12}\mathrm{C} + {}^{24}\mathrm{Mg}$ reaction and it is shown on the top panel of fig. 2; it exhibits a rather uniform distribution and we cannot exclude any of the two decay mechanisms.

In order to have a better understanding, monodimensional ϵ_i distributions [6] have been analyzed. ϵ_i is the highest normalized energy among those of the 3-α particles emitted from the region around the Hoyle state and it provides information about decay processes. In the case of SD mechanism, the first emitted α particle takes away 2/3 of the released energy (287.6 keV). Thus corresponding to about 192 keV; ϵ_i distribution should have a peak around 0.5. In direct processes instead ϵ_i should range between 1/3 and 2/3, corresponding to the case of three α particles with an equal energy, and one of an α particle emitted in a direction opposite to that of the other two α particles, respectively. Experimental ϵ_i distribution (solid points) constructed using data collected in $^{12}\mathrm{C} + {}^{24}\mathrm{Mg}$ reaction, is displayed in fig. 3. It is compared with predictions of the sequential (pink lines) and direct (green lines) decays of Hoyle state, determined through Monte Carlo simulations, taking into account the effects induced by the experimental apparatus. As one may observe, the experimental distribution exhibits a peak typical of a sequential mechanism, but it also displays tails similar to the case of direct processes.

In order to obtain a quantitative estimation for the probability of each decay mechanism, the range from 0.33 to 0.67 of the experimental ϵ_i distribution has been fitted with simulated events in which different percentages of direct and sequential decays have been introduced. Figure 4 shows the comparison of experimental data to simulation corresponding to four different combinations of percentages of sequential and direct decay modes. Increasing the percentage of the direct component, a better agreement between simulated and experimental results is reached. The results reported in fig. 4 allow us to confirm the presence of an important direct decay component that seems lower than 60% but also larger than 20%. These comparisons cannot be used to extract the branching

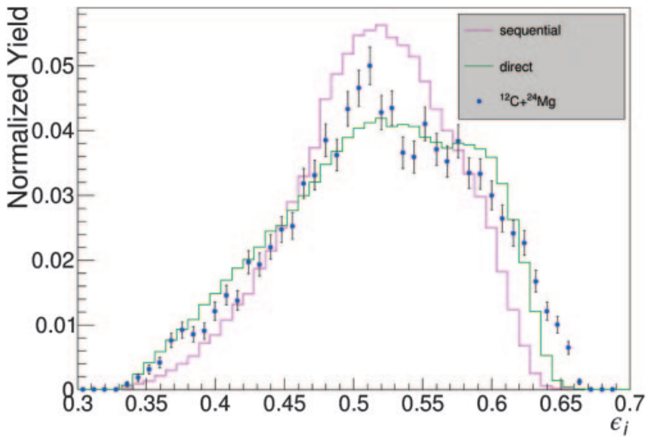

Fig. 3. – ϵ_i distribution. ϵ_i is the highest energy among the decay 3-α particles from the Hoyle state (see text). Solid circles show the experimental data for $^{12}C+^{24}Mg$ reaction. Experimental error bars refer to statistical indeterminacy. The experimental distribution is compared with the results of Monte Carlo simulations for sequential (pink lines) and direct (green lines) decays of Hoyle state.

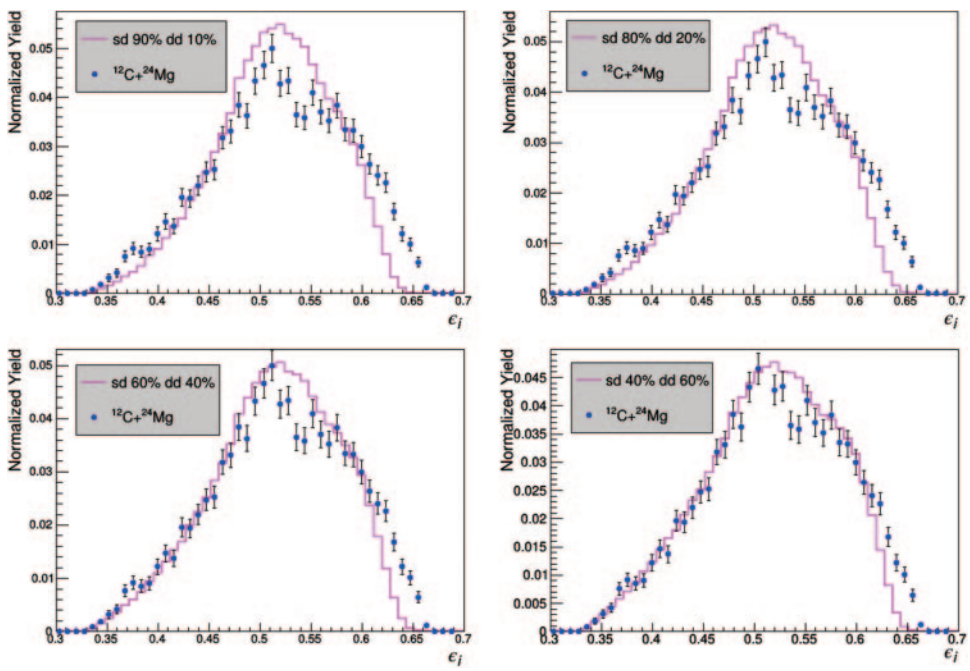

Fig. 4. – Fits of ϵ_i distribution constructed with data collected in $^{12}C + ^{24}Mg$ reaction. The different fits have been obtained using four combinations of percentages related to sequential and direct decay mechanisms.

ratio for direct and sequential 3-α decay of Hoyle state because of the limited energy and angular resolution. However, they seem to show evidence of a significant contribution of direct decay modes for the Hoyle state. Similar results, not reported in this article, are observed for the decay of other states around $E_{ex} = 9.64\,\mathrm{MeV}$.

3. – Conclusions

Multi-α correlations have been analyzed in peripheral $^{12}C + {}^{24}Mg$ reactions at 35 A MeV. The developed methodology, based on Dalitz plot techniques, allows us to estimate the relative contribution of two 3-α decay mechanisms of Hoyle state. The comparison with Monte Carlo simulations displays evidence of a direct mechanism for the analyzed resonance of ^{12}C. The presence of direct processes in Hoyle state decay has been already suggested in reactions such as $^{40}Ca + {}^{12}C$ at $E = 25\,\mathrm{A\,MeV}$ [7] and $^{12}C + {}^{24}Mg$ [8] at $E = 53$ and 75 A MeV studied with CHIMERA and INDRA apparata, respectively. In contrast, experiments performed with direct [9] and inelastic scattering reactions report a very low or even negligible direct contribution in decay of Hoyle state. These discrepancies could be due to in-medium effects on nuclear structure properties. With respect to direct reactions, heavy-ion collisions are characterized by a longer interaction time and by more dissipative processes that may induce modifications of nuclear structure properties. This topics may trigger new directions to study in-medium nuclear structure.

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