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Study of two- and multi-particle correlations in ^{12}C+^{24}Mg and ^{12}C+^{208}Pb reactions at E=35 AMeV

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Abstract

Two and multi particle correlations from the decay of sources produced in $^{12}C+^{24}Mg$ and $^{12}C+^{208}Pb$ collisions at E=35 $AMeV$ have been studied by using the forward part ($1^o < \theta_{lab} < 30^o$) of the CHIMERA multi-detector. Correlations and invariant mass spectroscopy are used to explore simultaneous and sequential decays of resonances in light isotopes with Z∼3-6, produced in peripheral collisions via the break-up of excited quasi-projectiles. Among them we mention ^5Li, ^6Li, ^6Be, ^8Be and the astrophysically important state in ^{12}C decaying into three alpha particles. Results and future perspectives at the INFN-LNS will be presented.

1 Introduction

Heavy-ion collisions at intermediate energy have been extensively studied to produce nuclear systems under extreme conditions of temperature, density and excitation energy and they represent the only terrestrial means to explore the Nuclear Equation of State at low density ($\rho \leq \rho_0 = 0.17 fm^3$). The correlations between different particles emitted during a collision provide important information about space-time properties of emitting sources produced and quantitative understanding of reaction dynamics [1]. Multi-particle correlations are also used to study the decay of unbound states produced during nuclear reactions [2, 3]. In this respect invariant-mass spectroscopy has become a tool to explore spectroscopic properties such as spins [4] but also to evaluate the competition between simultaneous and sequential channels in decay of produced resonances [2, 7]. In this contribution we study the three-α correlations from the decay of ^{12}C quasi-projectiles produced in peripheral $^{12}C+^{24}Mg$,^{208}Pb collisions at 35 $AMeV$. The experiment was performed at INFN-LNS with the aim of exploring decay of resonances in heavy-ion collisions.

2 Experiment and results

The ^{12}C beam at 35 $AMeV$ was delivered by the Superconducting Cyclotron at Laboratori Nazionali del Sud and INFN of Catania and the charged reaction products were detected by the CHIMERA 4π multi-detector [5]. To investigate the reliability of energy calibration, in Fig. 1 the $\alpha - \alpha$ (left panel) and $\alpha - d$ (right panel) coincidence pairs are shown. The plots are reported as a function of excitation energy, $E_{ex} = E_{tot}Q$, where E_{tot} is the total kinetic energy in their pairs center of mass reference frame and Q is the Q-value for the corresponding decay channel i.e., ^{8}Be$\rightarrow \alpha - \alpha$ and ^{6}Li$\rightarrow \alpha - d$, respectively.

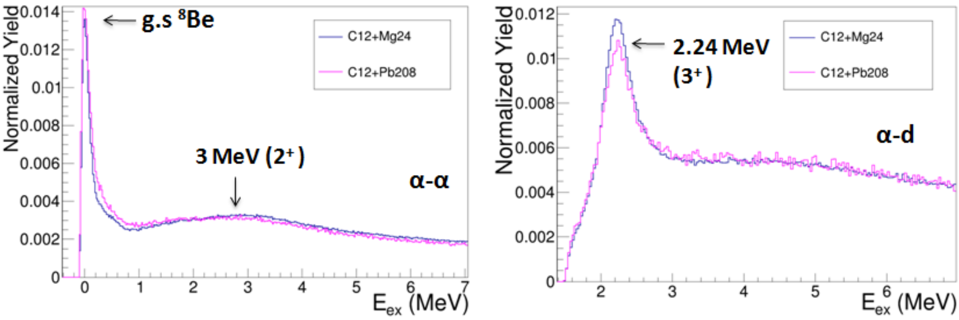

Figure 1: (Colour online) Yield of correlated $\alpha - \alpha$ (left panel) and $\alpha - d$ (right panel) couples as function of excitation energy, for ^{12}C+^{24}Mg (blu line) and ^{12}C+^{208}Pb (pink line) reactions.

The $\alpha - \alpha$ spectrum shows a narrow peak centred at 0 MeV corresponding to the ground state of ^{8}Be (Qvalue =92 keV) and a much broader peak centred around 3 MeV, corresponding to its first excited state at 3.03 MeV (2^+). The $\alpha - d$ spectrum, on the other hand, shows a well-shaped peak centred at $\approx$ 2.2 MeV corresponding to the first excited state of ^{6}Li at 2.18 MeV (3^+). In both cases, the low energy levels are accurately determined, thus showing a good quality of energy calibrations and a good angular resolution of the detector array. The FWHM of the peak at 92 keV in $\alpha - \alpha$ correlation amounts $\approx$ 70 keV, while FWHM of first peak in $\alpha - d$ correlation is about 300 keV. These widths are consistent with those measured in the experiment of Ref. [7] performed with the same experimental setup.

The α particles resulting from the decay of ^{12}C quasi-projectiles, are selected by requiring their parallel velocity, $V_{//}$, to be larger than 80% of beam velocity. This criterion restricts the analysis to the peripheral collisions as it is confirmed by a comparison to simulations performed with HIPSE model calculations [6]. Then information on unstable excited states of ^{12}C may be extracted from the 3α correlation function defined by the following ratio:

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

where the coincidence yield spectrum, $Y_{coinc}(E_{ex})$, is obtained from 3α particles detected in the same event (left panel of Fig. 2), while uncorrelated 3α spectrum, $Y_{uncorr}(E_{ex})$, is built by mixing particles from different events.

The 3α correlation function reported in right panel of Fig. 2 shows two peaks; the first one, centered around $E_{ex} = 7.66\ MeV$, corresponds to the Hoyle state ($E_{ex}^{th} = 7.65\ MeV$, $\Gamma = 8.5\ eV$) [8]. The second peak, centered at $E_{ex} = 9.83\ MeV$, arises from the overlap of the states at $E_{ex} = 9.64\ MeV$ (3^-), $E_{ex} = 10.3\ MeV$ (0^+) and possibly at $E_{ex} = 9.7\ MeV$ (2^+). In order to study the decay mechanisms of the observed resonaces, possibly disentangling sequential decays from direct three body ones, we follow a strategy which is similar to that obtained in Ref. [9].

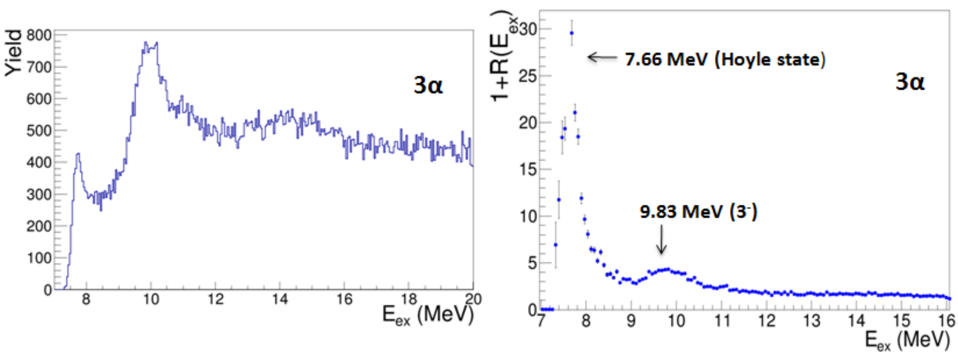

Figure 2: Yields of correlated 3α particles (left panel) and 3α correlation function (right panel) versus excitation energy of ^{12}C obtained in ^{12}C+^{24}Mg reactions at 35 $AMeV$.

In particular we build Dalitz plots with the following coordinates:

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

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 energy of three α decay ($E_{i,j,k}$ are selected with $E_i > E_j > E_k$ for simplicity of the symmetry).

The experimental results, are compared to numerical Monte-Carlo simulations filtered through the geometry and detector response of the CHIMERA multi-detector. Panels (a) and (b) of Fig. 3 show the Dalitz plots constructed using simulated events corresponding to sequential (^{12}C$^* \rightarrow ^8$Be$_{gs} + \alpha \rightarrow 3\alpha$) and direct (^{12}C$^* \rightarrow 3\alpha$) decays of the Hoyle state, respectively. Panels (c) and (d), on the other hand, show the same Dalitz plots constructed with experimental data collected in ^{12}C+^{24}Mg and ^{12}C+^{208}Pb reactions, respectively; they exhibit a more uniform distribution that does not allow us to exclude any of the two decay mechanisms. For better evaluations, monodimensional ϵ_i distributions are used. ϵ_i is the

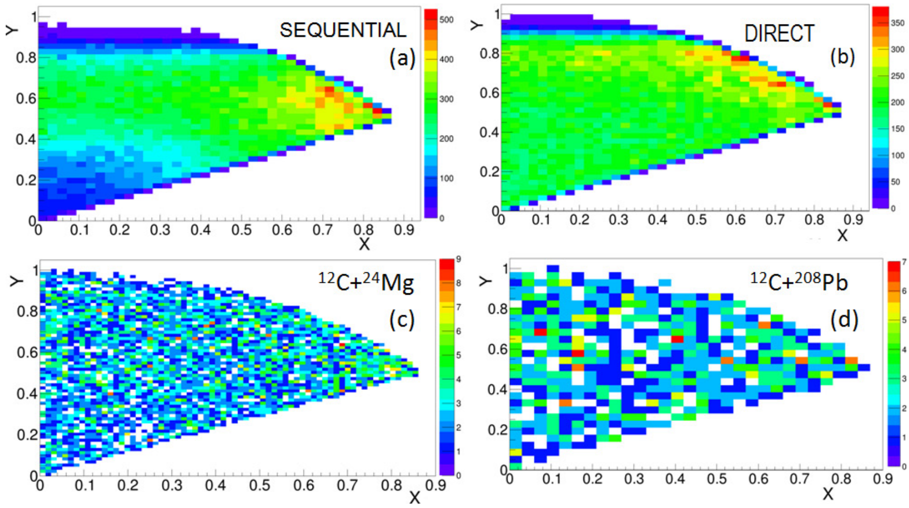

Figure 3: Panels (a) and (b): Dalitz plots of simulated events for sequential ($^{12}C^* \rightarrow ^8 Be_{gs} + \alpha \rightarrow 3\alpha$) and direct ($^{12}C^* \rightarrow 3\alpha$) decay of Hoyle state. Panels (c) and (d): Dalitz plot constructed with experimental data collected in ^{12}C+^{24}Mg and $^{12}C + ^{208}$Pb reactions.

highest normalized energy among those of the 3α particles decaying from the Hoyle state; in the case of sequential mechanism it should have a peak around 0.5 because the first decay α particle takes away two thirds of the released energy. On the other hand, in the direct processes, it should range between 1/3 and 2/3. On Fig. 4 the experimental distributions (pink lines), constructed using the data collected in ^{12}C+^{24}Mg and ^{12}C+^{208}Pb reactions, are shown on the left and right panel, respectively. They are compared with simulated events for sequential (blue lines) and direct (green lines) decays of Hoyle state. The experimental ϵ_i distributions show a peak typical of a sequential mechanism, but they have also the tails similar to the case of direct processes. These results, in both reactions, suggest a strong contribution of direct decay, a mechanism already observed in in Ref. [7] for ^{40}Ca+^{12}C at 25 $AMeV$.

3 Conclusions and perspectives

Multi-particle correlations are under study to explore the decay of excited states in peripheral ^{12}C+^{24}Mg and ^{12}C+^{208}Pb collisions at 35 $AMeV$. As a first physical system, we focus on α decay mechanisms of Hoyle state by

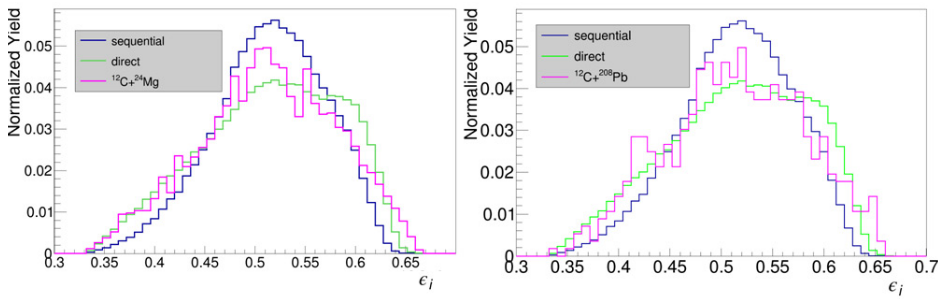

Figure 4: ϵ_i distributions for ^{12}C+^{24}Mg (left panel) and ^{12}C+^{208}Pb (right panel) reactions, compared with simulated data. Blue and green lines refer to simulated events for sequential and direct decays of Hoyle state, respectively, while pink lines represent experimental ϵ_i distributions.

using Dalitz plots. The comparison with Monte-Carlo simulations evidences the contribution of a direct mechanism component, in agreement with results reported in the literature [2,7]. Similar contributions of sequential and direct decays exist for the state at 9.64 MeV in ^{12}C. This and other resonances are under study to understand if differences in decay mechanisms are observed in different reaction systems (^{12}C+^{24}Mg, ^{208}Pb), or in data collected in other experiments with heavy-ion collisions. Among the aim of present study we plan to explore the possible existence of in-medium effects in nuclear structure properties.

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