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Study of resonances produced in Heavy Ion Collisions

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Abstract. At Laboratori Nazionali del Sud of Catania an experiment has been carried out in order to investigate the correlations between particles produced in ^{12}C+^{24}Mg reaction at 35 AMeV incident energy. Two α correlation has been explored because provide information about temperature of ^{8}Be nuclei produced in the reaction, while three α correaltion has been studied in order to evaluate the competition between sequential and direct decay mode of resonances produced in ^{12}C quasi-projectiles.

1. Introduction

In the framework of heavy ion collisions two- and multi-particles correlations are a powerful tool to probe the properties of emitting sources produced and thus involved dynamics [1] but also to explore certain structure properties of unbound states such as the spins [2]. Correlations between light particles can also be used to study the population of unbound states of decaying parent nuclei [3, 4]. Population probability of two internal states, Y_1 and Y_2, separated by an energy ΔE, is determined by the temperature T of the system according to Boltzmann factor $e^{(\Delta E/T)}$ [5]. If these states decay into specific particle pairs, they can be isolated by means of the two-particle coincidence spectra and their population can be estimated and linked to emission temperature of the decaying system. But these techniques have been also used in experiment performed with 4π detectors in order to disentangle direct and sequential decay modes of the produced resonances and to estimate their relative contribution to the decay width. For example three-α correlation has been explored to study the decay mechanisms of ^{12}C excited states [6, 7]. With the aim to investigate dynamics and also to extract nuclear structure properties of produced resonances in heavy ion collisions, correlations between two-and multi-particle emitted in peripheral ^{12}C+^{24}Mg reaction at 35 AMeV incident energy have been analyzed.

2. Experimental results

The studied experiment has been carried out at Laboratori Nazionali del Sud of Catania; detection and identification of charged reaction products have been possible using the forward part of CHIMERA 4π multi-detector [8]. The two particle correlation function, $1 + R(x_1, x_2)$, can be defined as:

$$1 + R(x_1, x_2) = C_{12}\ \frac{Y_{12}(x_1, x_2)}{Y_1(x_1) \cdot Y_2(x_2)}, \tag{1}$$

where $Y_{12}(x_1, x_2)$ is the two-particle coincidence yield, while $Y_1(x_1) \cdot Y_2(x_2)$ is the product of the single particle yields and C_{12} is a normalization constant. In Eq. 1 x_1 and x_2 represent generic variables chosen to express the two bodies correlation. Traditionally, for correlation between two particles, momentum of relative motion, q_{rel}, is used. In Fig. 1 α-α correlation function is reported in term of relative momentum (q_{rel}). The $Y_{12}(x_1, x_2)$ coincidence yield has been obtained using all α-α couples detected in coincidence in the same event while the denominator of Eq. 1, $Y_1(x_1) \cdot Y_2(x_2)$, has often been approximated with the uncorrelated two-particle yields $Y_{12}^{unco}(x_1, x_2)$ and may be constructed using different techniques. In this work the emission of uncorrelated α-α pairs are simulated by extracting randomly their energy, polar (θ) and azimuthal (Φ) angles, from single particle yield spectra. In this way it is possible to construct the relative momentum of uncorrelated α-α pairs.

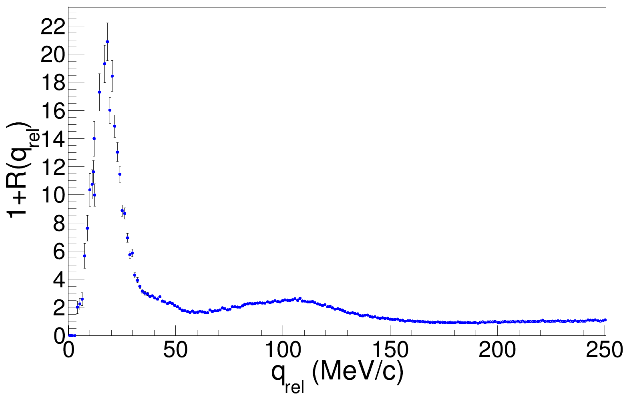

Figure 1. Experimental α-α correlation function versus momentum of relative motion, q_{rel}, measured in ^{12}C+^{24}Mg reaction at 35 AMeV.

The correlation function on Fig. 1 shows a pronounced peak centered around q_{rel} $\approx$18.5 MeV/c corresponding to decay of the unstable ground state of ^{8}Be (J^π=0^+, Γ=6.8 MeV). The second broader peak at q_{rel} $\approx$105 MeV/c corresponds to the decay of its first excited state at E_{ex}(^{8}Be)=3.04 MeV (J^π=2+, Γ=1.5 MeV). This α-α correlation function can be used to extract information about the emission temperature of ^{8}Be nuclei produced in ^{12}C+^{24}Mg reaction. Instead according to the thermal model the primary relative population of particle unstable states (i, j; E_i<E_j) is strictly related to the temperature T of the system, according to Boltzmann factor, $e^{-\Delta E/T}$ [9]:

$$R_{i,j} = \frac{Y_i}{Y_j} = \frac{(2J_i + 1)}{(2J_j + 1)} e^{-\Delta E/T}. \tag{2}$$

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With the aim of estimating the temperature associated to the decay of ^{8}Be nuclei, experimental α-α coincidence yield is compared to results of Monte-Carlo simulations.

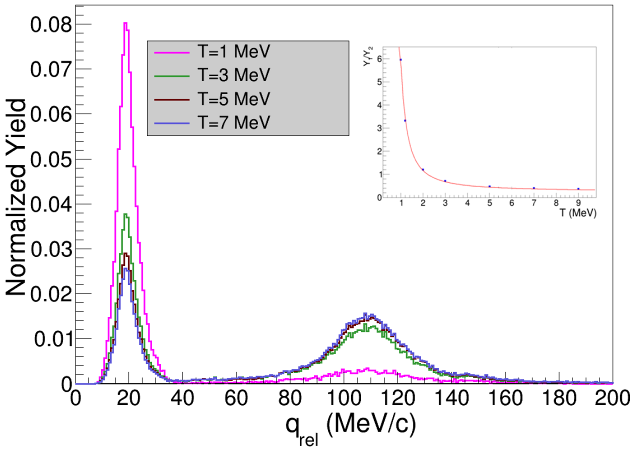

Figure 2. Simulated α-α coincidence yields as a function of relative momentum q_{rel} obtained using different temperatures. The relative population of the two states has been simulated according to Eq. 2. The insert shows Y_1/Y_2 predicted by simulations as a function of temperature.

The decay ^{8}Be$\rightarrow 2\alpha$ has been simulated taking into account the temperature dependence of relative population of parent nucleus states shown in Eq. 2. Fig 2 reports simulated α-α coincidence spectra as a function of q_{rel} at different temperatures (1, 3, 5, 7 MeV). Simulated data have been filtered through the geometry and detector response of CHIMERA. Yield ratio Y_1/Y_2 predicted by Monte Carlo simulations as a function of temperature is reported in the insert of Fig. 2 where Y_1 and Y_2 denote integrated yields of ^{8}Be at lower and higher excitation energy, respectively. The populations of ^{8}Be unstable states are extracted by integrating the experimental α-α coincidence yield over the range of energies dominated by the corresponding resonances. The comparison with simulated events suggests a value of temperature of about 5 MeV. Such value is in reasonable agreement with emission temperature measurements at similar beam energies.

Similarly to two-particle correlation function, correlation of three or more particles can be constructed in heavy ion reactions. In the present work three-α correlations have been explored with the aim of studying the competition between different decay processes of resonances produced in ^{12}C. In order to isolate α particles resulting from decay of excited ^{12}C quasi-projectiles, a selection based on the velocities of fragments has been applied. In particular the parallel velocity reconstructed from the center of mass of three α particles detected in the same event, has been required to be greater than 80% of the beam velocity (8 cm/ns). This criterion has been suggested by comparison with results of simulations performed with HIPSE model calculations [10]. The 3 α correlation function is shown on Fig. 3 and it is reported as a function of excitation energy E$_{ex}$=E$_{tot} - Q$, where E$_{tot}$ is the total kinetic energy of the three α particles in the 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 MeV, corresponds to the Hoyle state (E$_{th}$=7.65 MeV, Γ=8.5 eV); the second one, centered at E$_{ex}$=9.8 MeV, arises from the overlap of states at E$_{ex}$=9.64 MeV (3^-), E$_{ex}$=10.3 MeV (0^-) and possibly at E$_{ex}$=9.7 MeV (2^+).

The uncorrelated background has been built with a similar procedure used to construct two-

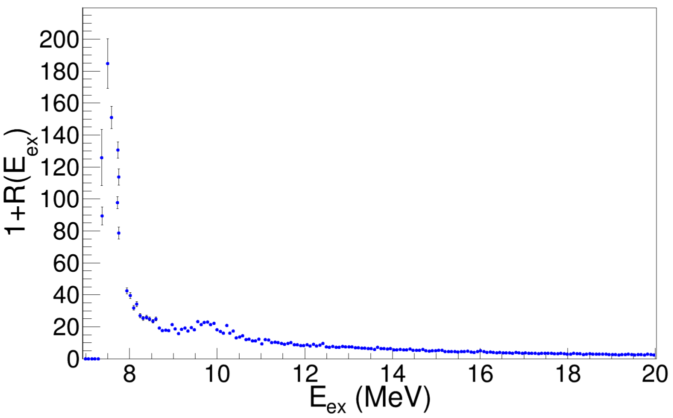

Figure 3. 3 α correlation function versus excitation energy of ^{12}C obtained in $^{12}C+^{24}Mg$ reaction at 35 AMeV.

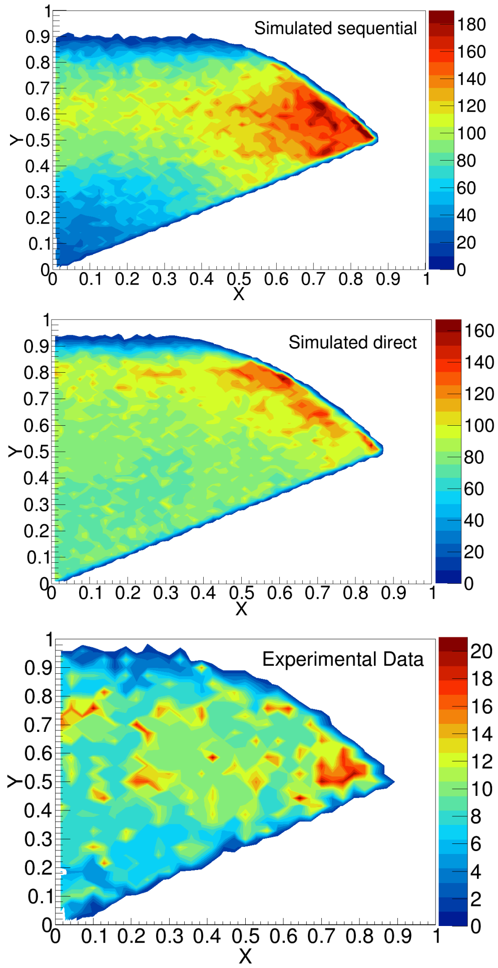

Figure 4. Dalitz plots of simulated events for sequential (top panel) and direct phase-space (central panel) decay of Hoyle state. Bottom panel: Dalitz plot, corresponding to decay from Hoyle state region, constructed with experimental data collected in $^{12}C+\,^{24}Mg$ reaction.

particle one, described above; in particular α particles have been chosen randomly by single-particle spectra. In order to study decay mechanisms of the observed resonances, possibly disentangling sequential decays from direct three-body ones, a procedure based on construction of Dalitz plots has been developed. There are several couples of variables (x,y) used to construct this kind of plot; here the following coordinates have been used [11]:

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

where $\epsilon_{i,j,k} = \mathrm{E}_{i,j,k} / (\mathrm{E}_i + \mathrm{E}_j + \mathrm{E}_k)$ are the energies of particles in the center of mass reference frame, normalized to total decay energy. In order to interpretate experimental results, dedicated Montecarlo simulations in which ^{12}C decays in 3 α particles directly ($^{12}\mathrm{C} \rightarrow \alpha-\alpha-\alpha$) or passing through the ground state of ^{8}Be ($^{12}\mathrm{C} \rightarrow {}^{8}\mathrm{Be}\text{-}\alpha \rightarrow 3\alpha$) have been performed. Simulated data have been processed by a filter that take into account all effects induced by the used apparatus.

Fig. 4 shows Dalitz plots for simulated events corresponding to sequential mechanism (top panel) and direct 3 α decay according to phase-space equiprobability DDΦ (central panel) of the Hoyle state. As it emerges from simulated events, DDΦ results in a flat distribution, while in the case of sequential decay (SD) the events are distributed in a narrow horizontal band of uniform intensity. The plot constructed with experimental data, reported on bottom panel of Fig. 4, exhibits 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 highest normalized energy among those of the 3 α particles emitted from the region around the Hoyle state, and it gives information about decay processes [13].

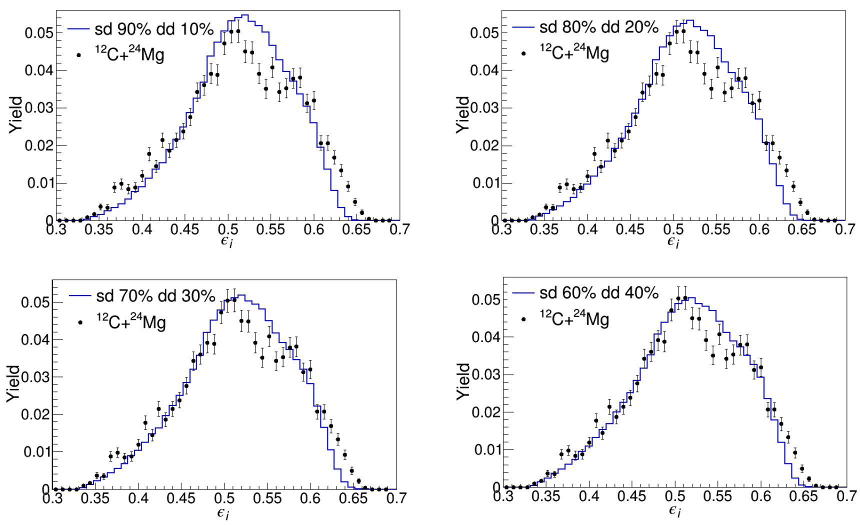

Figure 5. ϵ_i distribution constructed with data collected in ^{12}C+^{24}Mg reaction fitted with four combinations of percentages related to sequential and direct decay mechanisms.

In the case of sequential mechanism, ϵ_i distribution should have a peak around 0.5 while in direct processes ϵ_i should range between 1/3 and 2/3, corresponding to the case of three α particles with an equal energy, and the case in which α particle is emitted in a direction opposite to that of the other two, respectively. In order to obtain a quantitative estimation for the probability of each individual sequential and direct decay mechanism, experimental distributions have been compared to simulated events in which different percentages of direct and sequential decays have been introduced. Fig. 5 shows the results of such comparison of calculations to experimental data in ^{12}C+ ^{24}Mg reaction. As clear from the fits, agreement between simulated and experimental data improves when increasing the percentage of direct decay component. It is very difficult to extract the percentage of direct and sequential components from this comparison because of limited energy and angular resolution. Nevertheless the results reported in Fig. 5 evidence the presence of an important direct decay component that seems lower than 60% but also larger than 20% of the total decay width.

3. Conclusions

In the present work a study of two- and multi-particle correlations in ^{12}C+^{24}Mg reaction has been carried out using CHIMERA 4π multi-detector. A method to extract the emission temperature of excited systems from two-particle coincidence spectra has been discussed. This analysis has provided an emission temperature of ^{8}Be nuclei that is compatible with values obtained in this kind of reactions. Instead three α correlation has been investigated to study the decay processes of Hoyle state produced in ^{12}C quasi-projectiles. From the comparison between experimental and simulated data the contribution of a direct mechanism component emerge in the decay of this analyzed resonance according to other works performed with heavy ion reactions [6, 7]. The quantitative contributions of various 3α decay mechanisms of the Hoyle state have been determined in many works. A large part of these studies, performed with direct reactions [15, 14, 16] or inelastic scattering [13] evidence a very low direct contribution in the decay of this state. These discrepancies could be due to different mechanisms that dominate these reactions. It is possible that the observed effects are influenced by the medium in which the resonance is originated and decays; infact heavy ion collisions are characterized by more dissipative mechanisms and by longer interaction times compared to direct reactions. In order to clarify this intriguing topic it will be necessary to perform new experiments with different reaction systems at various dissipation degrees.

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