Decay modes of $^{10}$C nuclei unbound state

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Abstract

Unbound states of $^{10}$C nuclei produced as quasi-projectiles in $^{12}$C+$^{24}$Mg collisions at E/A = 53 and 95 MeV are studied with the Indra detector array. Multi-particle correlation function analyses provide experimental evidence of sequential de-excitation mechanisms through the production of intermediate $^9$B, $^6$Be and $^8$Be unbound nuclei. The relative contributions of different decay sequences to the total decay width of the explored states is estimated semi-quantitatively. The obtained results show that heavy-ion collisions can be used as a tool to access spectroscopic information about exotic nuclei.

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Energetic heavy-ion collisions have been extensively studied to extract information about the properties of nuclear matter under extreme conditions [1]. These studies have also shown that a large variety of isotopes is produced during the dynamical evolution of the reaction. Some of these isotopes, being far from the valley of stability, live temporarily and decay by particle emission. Their internal particle unbound states can then be isolated and studied by means of correlation function techniques [2, 3, 4, 5]. As an example, proton-$^7$Be correlation functions have been recently measured [5] in central Xe+Au collisions at E/A=50 MeV to determine the spin of internal unbound states of the astrophysically important $^8$B nucleus.

In this respect, a collision between two heavy ions can be viewed not only as a tool to study nuclear dynamics but also as a laboratory to produce several nuclear species in one single experiment and study their spectroscopic properties. This aspect of heavy-ion collision experiments certainly represents an important perspective to access information about the properties of very exotic nuclei.

Among all exotic nuclear species that can be produced in nuclear reactions, $^{10}$C can be considered as an especially interesting system. Antisymmetrized Molecular Dynamics calculations (AMD) predict a molecular structure for the ground state of $^{10}$C [6]. Exotic features, such as molecular states and clustering [7, 8, 9, 10, 11, 12, 13, 14, 15], have indeed attracted the interest of a large community and particle correlation analyses have been used to access such features experimentally [9, 10, 11, 12, 13, 14, 15]. However, previous studies of $^{10}$C nuclei have hardly been capable of reconstructing those states lying above the particle emission threshold of 3.73 MeV [16] and decaying into a single final configuration constituted by two alpha particles and two protons (2α+2p). All intermediate states that can be formed starting from the decay of $^{10}$C nuclei into charged particle emission (i.e. $^2$H, $^8$Be, $^5$Li, $^6$Be, $^9$B) are unstable. Reconstructing the decay paths of $^{10}$C states therefore requires detection capabilities with high energy and angular resolution over a large solid angle.

In this article we access highly lying states in $^{10}$C nuclei produced as excited quasi-projectiles in $^{12}$C+$^{24}$Mg peripheral collisions at E/A=53 and 95 MeV. By means of three- and four-particle correlation functions we provide experimental evidence of sequential decay modes for these states through the production of intermediate unbound $^9$B, $^6$Be and $^8$Be nuclei. Exploring the relative contributions of these sequential decay processes to the total decay widths of $^{10}$C states provides important spectroscopic information that is relevant to access branching ratios and spins.
A 2 mg/cm$^2$-thick $^{24}$Mg target was bombarded with $^{12}$C beams at E/A=53 and 95 MeV, with an intensity of a few $10^7$ pps, produced by the GANIL cyclotrons. The data presented in this work were collected with the Indra detector array \cite{17, 18} and one of the forward rings of the Chimera 4π detector \cite{19}. In peripheral collisions, $^{10}$C quasi-projectiles are largely produced. We reconstructed their internal unbound states by selecting those peripheral events where two alpha particles and two protons were detected in the forward part of the detector setup. The longitudinal velocities, $v/\lambda$, of these four particles were peaked around beam velocity, $v_{\text{beam}}$. Therefore, we used the condition $v/\lambda > v_{\text{beam}}/2$ to select those events where $2\alpha + 2p$ particles can be unambiguously associated to the decay of primary $^{10}$C quasi-projectiles. More details about isolating $^{10}$C projectile decays can be found on Refs. \cite{20} and \cite{21}.

In order to illustrate our analysis techniques, we first study the most peripheral events where excited $^{12}$C quasi-projectiles are produced and are reconstructed by detecting three alpha particles with $v/\lambda > v_{\text{beam}}/2$. Similarly to previous works \cite{22, 23}, we constructed the three-alpha particle (3α) correlation function:

$$1 + R(E_k) = \frac{Y_{\text{corr}}(E_k)}{Y_{\text{uncorr}}(E_k)}$$  \hspace{1cm} (1)$$

In this equation, the correlated yield spectrum, $Y_{\text{corr}}(E_k)$, is constructed with 3 α particles detected in the same event. This spectrum is sorted with respect to the quantity $E_k = \sum_{i=1}^{3} e_{ki}$, with $e_{ki}$ being the kinetic energy of the $i$-th alpha particle calculated in the center of mass of the three-body system. When a $^{12}$C quasi-projectile is produced at an excitation energy $E^*$, it decays into the three alpha particles detected in coincidence. Then it follows that $E_k = E^* + Q$, where $Q$ is the mass-difference in the $^{12}$C $\rightarrow$ 3α channel. The uncorrelated yield spectrum, $Y_{\text{uncorr}}(E_k)$, is constructed with 3 α particles detected in three different events, by using the so-called event mixing technique \cite{24, 25}. The full dots on Fig. II show the obtained 3α correlation function in $^{12}$C+$^{24}$Mg collisions at E/A=53 MeV. This correlation function allows one to explore the internal states of $^{12}$C. The Q-value for the 3α decay of $^{12}$C is -7.27 MeV. The first peak observed at $E_k \simeq 0.5$ MeV corresponds to the 7.65 MeV state in $^{12}$C. The second peak, centered at $E_k \simeq 2.2$ MeV, can be associated to the 9.65 MeV state, while the third bump at $E_k \simeq 6$ MeV results from the overlap of highly lying closely packed states. The width of the observed resonances is affected by the finite angular resolution of the apparatus. Stimulated by the analysis technique described in Ref. \cite{22}, we
modified the definition of the uncorrelated three particle yields used in the denominator of
Eq. 1 by using a partial event mixing (PEM) technique. In particular, the open symbols in
Fig. 1 correspond to the correlation function obtained when the denominator is constructed
with two $\alpha$ particles taken from the same event and the third one from a different event. The
resonant peaks are still observed in the correlation function but with a reduced magnitude.
This reduction can be partly attributed to the presence of 2-body correlations associated to
sequential decays of $^{12}$C. Indeed, the decay of certain internal $^{12}$C states can proceed via the
emission of $^{8}$Be+$\alpha$ pairs, with the very loosely bound $^{8}$Be nucleus subsequently decaying into
two $\alpha$ particles. These second chance $^{8}$Be decays are included in the numerator of Eq.1 but
not in the denominator, if the latter is evaluated with the standard event mixing technique.
In contrast, when the PEM technique is used, two $\alpha$ particles in the denominator are still
taken from the same event. Thus, some $\alpha$ – $\alpha$ correlations due to secondary $^{8}$Be decays
are kept in the denominator of Eq. 1 Then, the $^{8}$Be decay contributions contained in the
numerator of Eq. 1 are partially cancelled out by calculating the ratio, $Y_{corr}/Y_{uncorr}$, and
the magnitude of the correlation function peaks is reduced. In this respect, the attenuation
observed in the height of the correlation peaks demonstrates the existence of $^{12}$C sequential
decay modes.

We now turn to the study of $^{10}$C states by selecting those projectile breakup events where
$2\alpha+2p$ are detected in coincidence. Fig[2] shows the four-particle $2\alpha-2p$ correlation function,
$1+R(E_k)$, constructed by using both the standard (closed symbols) and partial event mixing
techniques described for the case of $3\alpha$ correlation functions. The top (bottom) panel refers
to $E/A=53$ MeV ($E/A=95$ MeV) incident energy. The $2\alpha-2p$ correlation functions on Fig. 2
show two broad peaks. The Q-value of the $2p+2\alpha$ decay of $^{10}$C is -3.7 MeV. The first peak
at $E_k \approx 1.5$ MeV can be associated to an overlap of $^{10}$C states at $E^* \approx 5.2-5.4$ MeV. The
second peak at $E_k \approx 5-5.5$ MeV corresponds to unknown states around $E^* \approx 9$ MeV [26].
The location of these peaks is independent of the beam energy, indicating that our access to
intrinsic properties of the $^{10}$C system is not affected by possible artifacts induced by reaction
dynamics.

Regardless of the limited angular resolution of the INDRA detector, we attempt to ex-
tract information about the decay modes corresponding to the intense peak at $E_k \approx 1.5$ MeV.
We search for signatures of sequential decays of $^{10}$C passing through the formation of its
loosely bound subsystems $^9$B, $^6$Be and $^8$Be. In particular, we explore the following decays se-
quences: A) $^{10}\text{C}\rightarrow ^9\text{B}_{g.s.}+p$ with the $^9\text{B}_{g.s.}$ nucleus further undergoing a decay $^9\text{B}\rightarrow \alpha+\alpha+p$; B) $^{10}\text{C}\rightarrow ^6\text{Be}_{g.s.}+\alpha$ with the $^6\text{Be}_{g.s.}$ nucleus further decaying into $\alpha+p+p$; C) $^{10}\text{C}\rightarrow ^8\text{Be}+p+p$ with the $^8\text{Be}_{g.s.}$ nucleus further decaying into $\alpha+\alpha$.

In order to search for contributions coming from the decay sequence A, we construct the denominator of Eq. 1 with a PEM technique where two $\alpha$ particles and one proton ($2\alpha+p$) are taken from the same event and the remaining fourth particle ($p$) is taken from a different event, obtaining the correlation functions shown as open crosses on Fig. 2. The magnitude of the first peak at $E_k \approx 1.5$ MeV is strongly reduced to about 2% with respect to the case of complete event mixing (full dots). In line with what we have already discussed in the case of $^{12}\text{C}$, this result indicates that a strong contribution to the first peak can be attributed to a decay of $^{10}\text{C}$ proceeding through the unbound $^9\text{B}_{g.s.}$ nucleus. The decay sequence B, going through the formation of intermediate $^6\text{Be}_{g.s.}$ nuclei is investigated using the PEM technique with one $\alpha$ particle and two protons from the same event ($\alpha+2p$) and the second $\alpha$ particle from a different event. In this case, the observed reduction of the peak magnitude (about 20% of the original peak height) is less pronounced than the one observed in case A. Finally, by selecting two $\alpha$ particles from the same event ($\alpha-\alpha$) and the two protons from different events, one explores the decay sequences of type C passing through the formation of $^8\text{Be}_{g.s.}$ nuclei (open circles on Fig. 2). The first peak is reduced to about 11% of the original peak height, indicating that the decay through $^8\text{Be}_{g.s.}$ is more likely than the decay sequence B but less important than decay sequence A. The stronger attenuation of the correlation peak height obtained with the PEM technique with $2\alpha+p$ taken from the same event suggests a preference for the $^{10}\text{C}$ states at $E^*=5.2-5.4$ MeV to decay through the intermediate formation of $^9\text{B}_{g.s.}$ nuclei, as compared to the decays through the formation of $^8\text{Be}_{g.s.}$ or $^6\text{Be}_{g.s.}$ nuclei. In particular, it seems that the decay sequence A is more likely than decay sequence B by a factor 10 and more likely than decay sequence C by a factor 5.

In the case of the states of $^{10}\text{C}$ corresponding to the peak observed at $E_k \approx 5-5.5$ MeV, the attenuation of its magnitude observed when using the PEM techniques A, B and C is less pronounced as compared to the case of the lower lying state. This observation suggests that direct four body decays ($2p+2\alpha$) without passing through any intermediate unbound state are more likely for the states around $E^* \approx 9$ MeV than the state for $E^* \approx 5.2-5.4$ MeV. Among the studied sequential decay modes, sequence A is the most likely as it induces a peak magnitude attenuation of the order of 30% of its original value (see open crosses). Decay
sequences B and C seem to provide comparable contributions to the decay of the studied 
$^{10}$C state, within statistical uncertainties, reducing the peak magnitude to about 35-40% 
of its original value. A slight systematic preference for B with respect to C is observed. 
In general, for both the first and the second peak we observe a preference of $^{10}$C to decay 
through the production of $^{9}$B$_{g.s.}$ nuclei rather than through the $^{8}$Be and $^{6}$Be systems.

In order to confirm the $^{10}$C sequential decay modes, we study three-particle coincidence 
spectra for those events with $1\text{ MeV} \leq E_k \leq 3.5\text{ MeV}$, corresponding to the first peak on 
Fig. 2. On Fig. 3 we show $\alpha - \alpha - p_1$ and $\alpha - \alpha - p_2$ kinetic energy spectra (top panels), 
$N(E_k)$, where the kinetic energy, $E_k$, is calculated in the three-body reference frame. In 
particular, we choose the slowest ($p_1$) or the fastest ($p_2$) proton in the $^{10}$C reference frame. 
Similar spectra are constructed using the $\alpha_1 - p - p$ and $\alpha_2 - p - p$ coincidences (bottom 
panels on Fig. 3), where $\alpha_1$ and $\alpha_2$ particles are chosen using the same criteria as for $p_1$ 
and $p_2$. These spectra of Fig. 3 are expected to contain information about intermediate 
states in $^{9}$B and $^{6}$Be nuclei eventually produced during the $^{10}$C decay sequences A and B 
described above. If $^{10}$C$^*$ did not decay through a definite sequence, the $N(E_k)$ distributions 
would show no signatures of nuclear resonant decays. In contrast, we observe a peak at 
$E_k \approx 0.2\text{ MeV}$ in the $\alpha - \alpha - p_1$ spectrum, corresponding to the decay of $^{9}$B$_{g.s.}$ in the decay 
sequence A, and a peak at $E_k \approx 1.4\text{ MeV}$ in the $\alpha_1 - p - p$ spectrum, corresponding to 
the decay of $^{6}$Be$_{g.s.}$ in decay sequence B. In the spectra $\alpha - \alpha - p_2$ and $\alpha_2 - p - p$ (right 
panels on Fig. 3) we observe broad peaks possibly associated to the decay of higher $^{9}$B 
and $^{6}$Be excited states. These observations confirm our conclusions deduced from the PEM 
analysis shown on Fig. 2, providing a first experimental evidence of sequential decay modes 
by unbound states of $^{10}$C exotic nuclei. More details about the analysis can be found in 
Ref. [20] and [21]. Our estimates of contributions from different sequential decay modes 
have been recently confirmed by a dedicated experiment performed with a high resolution 
detector array and by using a different analysis technique aimed at exploring two-proton 
emission [27].

The results shown in the present work provide new insights about spectroscopic properties 
of $^{10}$C states. In particular, the existence of sequential decay modes and a semi-quantitative 
estimate of their contributions to the total width of $^{10}$C unbound states provide relevant 
information in order to determine their branching ratios and spins. Our results also show that 
heavy-ion collisions at intermediate energies can be used as a standard spectroscopic tool to
access simultaneously important properties of several unstable nuclei that can be produced in one single reaction. This conclusion opens promising perspectives in collisions induced by radioactive beams where more exotic nuclear species are expected to be abundantly produced.

In summary, we have used peripheral C+Mg collisions at intermediate energies to produce unbound $^{10}$C nuclei. By means of multi-particle correlation functions we access excited states in $^{10}$C and explore their decay modes. For the first time, an experimental evidence of sequential decays of $^{10}$C proceeding though the production of the intermediate loosely bound $^{6}$Be, $^{8}$Be and $^{9}$B nuclei is found. The used analysis techniques allow one to semi-quantitatively estimate the relative contributions of different sequential modes to the total width of the investigated states. A preference for a decay path producing unbound $^{9}$B nuclei is found.

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FIG. 1: Three-α correlation function. Full dots: 1+R(q) constructed with standard event mixing technique. Open symbols: 1+R(q) constructed with the partial event mixing technique (see text). An expanded view of the correlation function for $E_k \leq 5$ MeV is shown in the inset.
FIG. 2: 2α-2p correlation functions at E/A = 53 MeV (top panel) and 95 MeV (bottom panel). Solid symbols: standard event mixing technique. Open symbols: PEM techniques with two α’s (circles), two α’s and one proton (crosses) and one α and two protons (squares) taken from the same event (see text for details). Expanded views of the correlation functions for $E_k \leq 5$ MeV are shown in the inset.
FIG. 3: Top panels: $\alpha - \alpha - p$ kinetic energy spectra constructed with the slowest ($p_1$, left panel) and the fastest ($p_2$, right panel) proton. Bottom panel: $\alpha - p - p$ kinetic energy spectra constructed with the slowest ($\alpha_1$, left panel) and the fastest ($\alpha_2$, right panel) $\alpha$ particle. The data correspond to an incident energy of $E/A=53$ MeV.