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PAPER

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The $^{12}\text{C}^*$ Hoyle state in the inelastic $^{12}\text{C} + ^{12}\text{C}$ reaction and in $^{24}\text{Mg}^*$ decay

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Abstract

The reaction $^{12}\text{C} + ^{12}\text{C}$ at 95 MeV has been studied at the Legnaro Laboratories of INFN with the GARFIELD + RCo apparatus. Data have been analyzed in order to investigate the decay of the Hoyle state of $^{12}\text{C}^*$. Two different data selections have been made. The first one corresponds to peripheral binary collisions where the quasi-projectile is excited to the Hoyle state and the target has been left in the ground state. The second selection allows for studying central events with the formation of a $^{24}\text{Mg}^*$ and the Hoyle state is obtained as a step of the decay chain. The characteristics of the Hoyle state decay are very similar in the two samples and point to a mainly sequential decay through the population of an intermediate $^8\text{Be}_{\text{gs}}$, with a small contribution ($\sim 1.1\%$) from simultaneous three α -particle processes.

Keywords: nuclear reactions, $^{12}\text{C}^*$ excited states, Hoyle state decay

(Some figures may appear in colour only in the online journal)

1. Introduction

The low-lying ^{12}C excited states, and especially the Hoyle state at 7.65 MeV excitation energy [1], play a very important role in different issues of nuclear structure and nuclear astrophysics. In particular, the properties of the Hoyle state are of crucial importance to determine the triple- α reaction rate in the stellar medium. In turn, this latter determines the relative abundance of ^{12}C in the first generation of stars and in the late stages of stellar evolution, and has an important catalytic role in various explosive stellar phenomena. The standard modeling of the reaction rate assumes that the breakup of the Hoyle state into three α particles proceeds exclusively as a sequential two-step process via the ground state of ^8Be . The possible presence of other decay mechanisms, with a non-negligible branching ratio, would have important consequences for a number of astrophysical processes at low temperature, where the triple- α reaction occurs [2–4], as well as for our understanding of the structure of α -clustered excited states [5, 6].

Different experimental studies have been performed in recent years to reveal the features and decay properties of the Hoyle state [7–13]. A review of the experimental results (together with implication on nuclear forces, structure and astrophysics) has been recently published [5]. Most studies have confirmed the presence of a doorway ^8Be state [7–11]. Model comparisons indicate a nearly complete agreement with a sequential decay with a very small (less than 0.2% [11]) contribution from a direct process. However other studies report a sizeable amount ($17 \pm 5\%$) of instantaneous three α -particle decay [12, 13]. This shows that the subject deserves further analysis. In particular, it is important to elucidate if a selectivity of the reaction mechanism exists concerning the branching ratios of the different decay modes.

We have studied the reaction $^{12}\text{C} + ^{12}\text{C}$ with a 95 MeV carbon beam using an apparatus (GARFIELD + RCo) that covers approximately 80% of 4π [14]. The collected data have been analyzed with the aim of selecting compound nucleus reactions and compared with a dedicated Hauser–Feshbach sequential evaporation model (HF ℓ) that includes all known discrete excited states of light nuclei.

A detailed description of the HF ℓ model, as well as the values chosen for the input parameters of the calculation (level density, transmission coefficients), is given in [15, 16]. No further modification was done for the HF ℓ predictions presented in this paper.

Experimental results, published in [15–17], show a substantial agreement with theoretical predictions except for some discrepancies for even- Z residues, showing contamination from direct reactions or clustering issues.

In this paper we will first concentrate on the analysis of semiperipheral $^{12}\text{C} + ^{12}\text{C}$ collisions and in particular reactions where the projectile interacts with the target, leaving it in the ground state, and decays in three α -particles.

We will compare the experimental results with the prediction of HF ℓ for the decay of an excited $^{12}\text{C}^*$ at 7.65 MeV and angular momentum $J = 0 \hbar$. The boost energy and angular distribution (deduced from the data) corresponding to this specific reaction have been first added to HF ℓ predictions; then the outcome has been filtered with the detector response in order to make it comparable with experimental data. In this way we properly took into account the geometry and angular resolution, as well as the energy thresholds and resolution of the individual detectors. Data have also been compared with filtered simple model calculations for simultaneous decay modes: DDE (direct decay with equal energies) i.e. three α -particles simultaneously emitted from the excited carbon with equal energies and relative angles of 120° and DDL (direct decay in linear chain), i.e. two α -particles emitted back to back with the third α -particle at rest in the ^{12}C frame. Another decay mode has been

Figure 1. Vertical cross section of the GARFIELD + RCo apparatus, azimuthally symmetric around the beam axis.

considered in previous measurements [8–11], i.e. the direct decay (DD) with uniform population of the phase space (DD Φ).

Since data compatible with an appreciable amount of non-sequential decay have only been obtained in reactions involving heavy ions [12, 13] we have also investigated the Hoyle state obtained in the decay of the hot source formed in central collisions. In particular we have analyzed events with six α -particles and compared the data with HF ℓ calculations for the α -decay chain of the compound nucleus ^{24}Mg at $E^*/A_{\text{CN}} = 2.6$ MeV issued in case of complete fusion, and with an angular momentum distribution taken from the systematics of fusion cross sections [16].

In section 2 we will briefly describe the experiment and discuss the selection both for peripheral and central events. Section 3.1 is devoted to the observables which can characterize the decay of the Hoyle state in peripheral collisions. Section 3.2 deals with the properties of the Hoyle state in the decay chain of $^{24}\text{Mg}^*$ in central collisions. Finally some conclusions and perspectives are drawn.

2. The experiment and data selection

A 95 MeV ^{12}C beam, delivered by the TANDEM accelerator of the *INFN Laboratori Nazionali di Legnaro*, impinged on a thin ^{12}C target ($\sim 85 \mu\text{g cm}^{-2}$). The apparatus (see figure 1) has been extensively described in [14] and here we recall only the main aspects.

The apparatus has 488 detecting cells with a geometrical coverage of the order of 80% of 4π . The forward polar angles ($7^\circ \div 17^\circ$) are covered by a three stage device ‘Ring Counter’ (RCo), consisting of a ionization chamber (IC) (filled with CF_4 gas at a pressure of 50 mbar) divided in eight azimuthal sectors, each one followed by a eight-strip 300 μm thick silicon detector (Si) and 6 CsI(Tl) scintillators. This allows for an angular resolution of about 0.7° for the polar angle and 11° for the azimuthal one. Particle and fragment identification is obtained through ΔE – E technique in IC-Si or Si-CsI(Tl) and/or with CsI(Tl) scintillator fast-slow pulse shape analysis (PSA) [18]. Particles and fragments are identified in charge with energy thresholds as low as $0.8 \div 1$ A MeV. Reaction products with $1 \leq Z \leq 12$ that reach the CsI scintillator can be identified also in mass with an energy threshold of ~ 6 A MeV. The RCo allows us to obtain energy determination with percent accuracy.

Figure 2. Total energy spectrum for ‘true’ α -particles (a) and for $Z = 2$ products (b). From right to left the peaks correspond to the ground and excited states of the recoil ^{12}C nucleus. For the analysis presented in this work, only the breakup of the ^{12}C projectile has been taken into account and the ^{12}C target has been selected in the ground state. With this condition, the lower panels present the excitation energy spectra of the $^{12}\text{C}^*$ quasi projectile for the ‘true’ α -particles (c) and for $Z = 2$ products (d).

Larger polar angles are covered by two drift chambers (GARFIELD) filled with CF_4 gas at a pressure of 50 mbar. Each chamber consists of a two stage combination of IC—CsI(Tl) scintillator. Both chambers are divided in subsectors covering 7.5° each in azimuthal angle and in four polar angle regions defined by four CsI(Tl) scintillators covering approximately 14° in ϑ . For both chambers the $\Delta E-E$ technique allows charge identification of particles and fragments. Light particles (up to $Z = 3$) are identified in both charge and mass thanks to the PSA of CsI(Tl) signals. The energy of particles and fragments is determined with an accuracy of the order of few percent with a $0.8 \div 1$ A MeV threshold.

2.1. Selection of peripheral events

Since we are interested in the decay of the $^{12}\text{C}^*$ quasi-projectile, we have selected events where three α -particles are detected in the forward cone (RCo) and no other charged product is detected in the rest of the solid angle. If we want to unambiguously identify α -particles (hereafter called ‘true’) we have a threshold of about 6 A MeV, due to the energy loss for passing through the silicon detector, and consequently the kinetic energy of the ^{12}C nucleus emitting three α -particles is relatively high. The recoil ^{12}C nucleus is therefore very slow and its energy (less than 0.8 A MeV) is not sufficient to be detected, even with a very thin target. To increase the number of events corresponding to the ^{12}C quasi-projectile decay one can consider all the $Z = 2$ particles, i.e. all the particles identified in charge exploiting the $\Delta E-E$ technique either in IC-Si or in Si-CsI(Tl), together with the CsI(Tl) PSA. The mean kinetic

energy of the quasi-projectile is therefore lower than the one obtained with the previous selection and the kinetic energy of the quasi-target can be sufficiently higher so that it, or its decay products, can be detected. This second selection of course includes more events since it lowers the threshold (0.8 A MeV), at the price of a small contamination of a few percent ^3He ions [15].

In figure 2(a) the total energy spectrum is shown, as calculated from the sum of the laboratory energies of the three ‘true’ α -particles (E_i):

$$E_{\text{tot}} = \sum_{i=1}^3 E_i + E_{\text{rec}}, \quad (1)$$

where E_{rec} is the kinetic energy of the ^{12}C quasi-target, calculated from momentum conservation. Most of the events correspond to a negligible recoil energy and therefore a $^{12}\text{C}_{\text{g.s.}}$ quasi-target, nearly at rest in the laboratory frame. The total kinetic energy, obtained by subtracting from the beam energy (95 MeV) the decay energy threshold ($E_{\text{th}} = 7.27$ MeV) for the decay of ^{12}C in three α -particles, is peaked at ≈ 88 MeV. A small peak is present at about 84 MeV, corresponding to the $^{12}\text{C}^*$ quasi-target at about 4.4 MeV excitation energy, the first $^{12}\text{C}^*$ excited level. As previously mentioned, the same analysis has been performed considering all the $Z = 2$ products detected in the $7^\circ \div 17^\circ$ angular range with a lower (0.8 A MeV) threshold. The results are shown in figure 2(b). The energy spectrum shows that the ^{12}C quasi-target can be excited not only to the first 4.4 MeV, but also to the 9.64 MeV state with a peak at about 78 MeV, obtained subtracting 9.64 MeV and E_{th} from the beam energy. A long tail to lower energies is also present.

The excitation energy of the ^{12}C quasi-projectile can be calculated as:

$$E^* = \sum_{i=1}^3 E_i - T_C + E_{\text{th}}, \quad (2)$$

where $T_C = \frac{1}{2}m_C v_C^2$ is the laboratory kinetic energy of the $^{12}\text{C}^*$ reconstructed from the three measured α -particles.

A further selection has been made considering only the events corresponding to the ^{12}C quasi-target in the ground state, i.e. selecting the rightmost peak of the upper panels in figure 2. The results for ‘true’ α -particles are presented in figure 2(c). Three excited $^{12}\text{C}^*$ quasi-projectile levels are evident, whereas for $Z = 2$ also higher excitation energies are present (see figure 2(d)). Similar results have been obtained selecting also the first $^{12}\text{C}^*$ excited state for the target. In the following analysis, in order to have the kinematics under control, we select only events corresponding to the ground state of the ^{12}C quasi-target ($E_{\text{tot}} > 86.5$ MeV).

As previously mentioned, in figure 2(c) three ^{12}C excited state are evident. The lower one located at 7.65 MeV, corresponds to the 0^+ Hoyle state, while the middle one at 9.64 MeV corresponds to the next 3^- level. The smaller peak at higher energy is around 10.8 MeV and corresponds to a convolution of ^{12}C levels around this energy. If we restrict ourselves to these first excited states, the results are not very different selecting ‘true’ α -particles or $Z = 2$ products. The comparison of figures 2(c) and (d) shows that only the relative population of the excited states is slightly different with the two selections. In the following we will analyze ‘true’ α -particles, since the results with the $Z = 2$ particles have a larger background. We have indeed evaluated that the peak to background ratio for ‘true’ α -particles is 70, whereas for $Z = 2$ products we get 30. We have in any case checked that the selection ($Z = 2$) gives results compatible with those obtained for the ‘true’ α -particles and presented in the following.

Figure 3. Q_{kin} distribution for the six α -particle events (a). The vertical lines indicate the events kept for the analysis. The arrow indicates the expected value for six α -particles in the final state. Reconstructed $^{12}\text{C}^*$ excitation energy from the three α -particles in central collisions (b). For more detail see text. Laboratory velocity of the center of mass of three α -particles coming from the Hoyle state (c). Lines are drawn to guide the eye. All distributions are normalized to the unitary area.

It has to be noted that ^{12}C levels are narrow resonances (3.5 eV and 34 keV for 7.65 and 9.64 MeV), while the experimental distributions result much wider, i.e. 240 and 400 keV, respectively. This is mainly due to the finite angular resolution of the apparatus, as pointed out in [19], which preserves the correct mean values, but enlarges the widths. This enlargement is well reproduced by the filter applied to the $\text{HF}\ell$ predictions. The model has the correct tabulated widths for the 7.65 and 9.64 MeV levels, but the output of the filtering procedure gives 200 keV for the Hoyle state and 360 keV for the 9.64 state, in good agreement with experiment.

2.2. Selection of central events

The first selection of central events was performed in [17], looking for six α -particles events all detected by the apparatus, obtaining a complete reconstruction ($Z_{\text{tot}} = 12$) of the $^{24}\text{Mg}^*$ decay. We used $Z = 2$ selection in order to have the same threshold over the whole solid angle. This first study showed compatibility with a sequence of α -particle emissions in a decay chain of a $^{24}\text{Mg}^*$. However, the statistics is not high enough to perform further investigations. Therefore here we have analyzed also events where only five α -particles have been detected, deducing the properties of the sixth α -particle from momentum and energy conservation.

To exclude events of channels different from the six α -particles (for instance events in which a neutron can be emitted) and to cut down the background, we have reconstructed the energy dissipated by the quantity Q_{kin} defined in [17] as $Q_{\text{kin}} = \sum_{i=1}^6 E_i - E_{\text{beam}}$. In figure 3(a) the Q_{kin} distribution is shown, together with the cut used for the analysis presented here.

We have considered all the combinations of three (out of six) α -particles, calculated the excitation energy similarly to (2), and chosen the three α -particles with the minimum excitation energy of a reconstructed $^{12}\text{C}^*$. This is shown in figure 3(b). The two lowest $^{12}\text{C}^*$ excited states are evident.

The velocity of the reconstructed $^{12}\text{C}^*$ in the Hoyle state is peaked at the value of the $^{24}\text{Mg}^*$ velocity (2.0 cm ns $^{-1}$ —see figure 3(c)). The same occurs for the velocity of the center

Figure 4. Laboratory energy (a) and angular (b) distributions of the six α -particles. Laboratory energy (c) and angular (d) distributions of the three α -particles coming from the Hoyle state. Lines are HF ℓ calculations. All distributions are normalized to the unitary area.

of mass of the remaining three α -particles. The laboratory energy and angular distributions of α -particles are very well reproduced by HF ℓ calculations for sequential α emissions from the hot $^{24}\text{Mg}^*$ (see figures 4(a) and (b)). A comparable good reproduction is obtained also if one selects just the Hoyle state, i.e. events where the $^{12}\text{C}^*$ is excited in its Hoyle state and further sequentially decays in three α -particles (see figures 4(c) and (d)). These findings indicate that the selected events with six α -particles events correspond mainly to central events.

3. The Hoyle state

The lowest energy peak in figure 2(c) for peripheral events, in figure 3(b) for central collisions correspond to the very well known Hoyle state, which has been extensively studied in past years [7–13]. The main debate consists in the interpretation of the decay of this state, whether it is purely sequential via the $^8\text{Be}_{\text{gs}}$ formation, or if there is a sizeable amount of instantaneous breakup. In the following we will analyze in detail the properties of the Hoyle state and compare the experimental data with the HF ℓ model and DDE and DDL prescriptions. Central events will be analyzed to check if differences exist when the decay of the Hoyle state happens during the decay of a compound $^{24}\text{Mg}^*$ nucleus.

3.1. Peripheral collisions

With the selections shown in section 2.1 one can build observables useful to investigate the decay of the Hoyle state. Some of them have been introduced in [7–12].

First of all there is the minimum relative energy between any two α -particles (see figure 5(a)). If the Hoyle state decays through $^8\text{Be}_{\text{gs}}$, the aforementioned distribution has to

Figure 5. Minimum α - α relative energy (a). Minimum (b), intermediate (c) and maximum (d) α -particle energies, normalized to their sum. The lines correspond to simulations filtered by the detector response for the following decay scenarios: sequential HF ℓ (solid), equal energy DDE (dotted) and linear chain DDL (dashed). All distributions are normalized to the unitary area.

show a peak at 92 keV whereas an equal energy sharing among the three α -particles (DDE) would peak at ≈ 188 keV [10]. Indeed in the case of equal energy sharing, the kinetic energy E_α of each α -particle in the ^{12}C rest frame, is one third of the total available energy in that frame ($E_{\text{cm}} = 7650 - 7272 = 375$ KeV). The relative energy between two α -particles with equal velocities at 120° relative angle is then given by $E_{\text{rel}} = \frac{3}{2} E_{\text{cm}}/3 = 188$ keV.

A lower relative energy distribution is expected for the DDL mechanism: infact the two α -particles moving in opposite directions have $E_\alpha = E_{\text{cm}}/2$; therefore the minimum relative-energy (with respect to the α -particle at rest) is $E_{\text{cm}}/4$.

Figure 5(a) shows the minimum α - α relative energy. A clear peak at about 92 keV is present, indicating that the reaction mainly proceeds through a $^8\text{Be}_{\text{gs}}$. The results are similar to the data of [10], but the distribution slightly extends to higher values. The width of the $^8\text{Be}_{\text{gs}}$ results experimentally larger than expected, i.e. 56 keV, instead of 5.5 eV (to be compared with 46 keV for HF ℓ filtered events) again due to the finite angular resolution of the apparatus, as discussed in section 2.1. The distribution for DDE peaks below 188 keV because the widening caused by the experimental resolutions tends to give minimum values smaller than the average ones.

We have also extracted the energies of the three α -particles in the $^{12}\text{C}^*$ rest frame. In particular we plot, normalized to their total energy, the minimum energy e_{min} in figure 5(b), the intermediate energy e_{int} in figure 5(c) and the maximum energy e_{max} , recently proposed in [11], in figure 5(d). In a sequential decay mechanism, these normalized energies are expected to be $e_{\text{max}} = 0.506$, where e_{min} and e_{int} are distributed in a wide range. This expectation comes from momentum conservation arguments. Indeed in a α - ^8Be event, the energy of the α -particle must be equal to two third of the total energy E_{cm} (after subtraction of the ^8Be Q -value), thus leading to $e_{\text{max}} = 0.506$.

The DDE prediction should have three equal energies, peaked at 0.33, whereas the DDL mechanism should give about 0.5 for e_{int} and e_{max} , while e_{min} should be close to zero. This is shown in figures 5(b)-(d) where all the calculated distributions are plotted after the filtering procedure. For all the observables presented in figure 5 the corresponding predicted HF ℓ distributions agree with the data and only very small components of DDE and DDL could contribute to the observables.

Other observables proposed for the analysis of the data are the mean center-of-mass energy $\langle E_\alpha \rangle$ and the deviation from the average energy, defined as $E_{\text{rms}} = \sqrt{\langle E_\alpha^2 \rangle - \langle E_\alpha \rangle^2}$. E_α

Figure 6. Experimental two dimensional plot of E_{rms} versus the mean α energy (a). The same plot for $\text{HF}\ell$ predictions (b). The same plot for DDE (blue contours) and DDL (green contours) calculations, superimposed on $\text{HF}\ell$ predictions (c). For more details see text.

Figure 7. Left panel: experimental energy Dalitz plot. Middle panel: $\text{HF}\ell$ Dalitz plot. Right panel: results obtained with DDE (blue squares) and DDL (green squares), superimposed onto $\text{HF}\ell$ predictions.

represents the energy of the α -particles in the ^{12}C rest frame and the average is over the three α -particles in each event. The average $\langle E_\alpha \rangle$ corresponds to $1/3$ of the Q -value for the Hoyle-state decay into three α -particles (127 keV). In figure 6(a) we show the experimental plot of E_{rms} versus the mean α -particle energy $\langle E_\alpha \rangle$. In figure 6(b) the $\text{HF}\ell$ predictions are shown: the sequential mechanisms of the $\text{HF}\ell$ is compatible with the data. The simultaneous DDE decay, which would occur at very low E_{rms} values and at mean α energy of 127 keV is absent in our data, in contrast with the results of [12]. In figure 6(c) the DDE and DDL calculations, superimposed on the $\text{HF}\ell$ predictions, show peculiar correlations, not evident in our data.

One can also evaluate the Dalitz-plot [20] from the α -particle energies in the ^{12}C frame, normalized to the total energy. The two coordinates of the Dalitz-plot are defined as $x_d = \sqrt{3}(e_i - e_j)$ and $y_d = 2e_k - e_i - e_j$, where $e_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$ are the normalized α -particle energies in the ^{12}C frame. The results are shown in figure 7 (left panel). One would expect that the simultaneous DDE decay should result in an enhancement of the central part of the plot, which is not the case for our data. In contrast, the data show enhancement in the regions where the energy of two α -particles are close to one another and the third α -energy is relatively far from the previous two. This can be considered as an

Figure 8. Radial projection of Dalitz plot. Full points: data. Continuous line: HF ℓ calculations. Dotted, dashed, dotted–dashed lines: DDE, DDL and DD Φ predictions, respectively. All distributions are normalized to the unitary area.

additional signal of the predominance of the sequential decay, as confirmed by the comparison with HF ℓ predictions (see figure 7 middle panel). Indeed an equal energy decay DDE and a linear configuration DDL would appear as the plot shown in figure 7 (right panel). With the DDE decay only the central region of the Dalitz-plot appears to be populated, whereas the DDL populates the extreme regions; both regions are not particularly populated in the data.

The technique of the radial projection of the Dalitz plot should give further insight into the decay mechanism. The radial coordinate ρ can be expressed as $(3\rho)^2 = x_d^2 + y_d^2$. The distribution of the radial projection is shown in figure 8 where we have also introduced the filtered DD Φ predictions. The data are very well reproduced by HF ℓ calculations, while DDE, DDL and DD Φ predictions would give bumps at the extremes of the distribution.

In conclusion all these observables seem to indicate that in the considered peripheral reaction the decay of the $^{12}\text{C}^*$ Hoyle state proceeds in a sequential way through the formation of an intermediate ^8Be ground state, in this way confirming most of the previous results, but not the results shown in [12, 13]. This conclusion is qualitative and therefore we have performed a fitting procedure of five observables, i.e. the minimum α – α relative energy, the minimum, intermediate and maximum α -particle energies ($e_{\min}$, e_{int} , $e_{\max}$) normalized to the total energy and the radial projection of the Dalitz plot 3ρ . For this first fit we have used as free parameters the percentages of DDE and DDL, being the complement to unity the percentage of sequential decay. The results, within 95% confidence level, give $1.1\% \pm 0.8\%$ for DDL and a value consistent with zero with an error of 0.02% for DDE, giving $1.1\% \pm 0.8\%$ for the total DD.

Even if the DD Φ contribution in previous papers [8–11] seems to result negligible (see table 1), we have checked the modifications introduced by DD Φ in our DDE and DDL contributions. We therefore fitted the 3ρ variable, which carries the maximum amount of information, as suggested by [9], with all the possible components, i.e. HF ℓ , DDE, DDL and DD Φ . We have obtained the same values for DDE and DDL percentages of our previous fit, with a contribution of DD Φ compatible with 0 with an error of 0.4%. The total amount of DD is therefore confirmed.

3.2. Central collisions

With the selection described in section 2.2 we repeated the same analysis performed for peripheral collisions, with the aim of investigating agreements or disagreements in the decay mechanism of the Hoyle state. The first observable is the minimum relative energy of two of

Figure 9. Central collisions. Minimum α - α relative energy (a). Minimum (b), intermediate (c) and maximum (d) α -particle energies, normalized to their sum. The lines correspond to simulations filtered by the detector response for the sequential HF ℓ . All distributions are normalized to the unitary area.

Figure 10. Central collisions. Left panel: experimental energy Dalitz plot. Right panel: HF ℓ Dalitz plot.

the three α -particles assigned by the procedure to an excited $^{12}\text{C}^*$ produced in the $^{24}\text{Mg}^*$ decay chain. Also in this case the width of the distribution is larger (80 keV) than the theoretical value, for the same reason discussed in section 2.1. Together with the minimum α - α relative energy (figure 9(a)), we present the other observables shown in figure 5 for peripheral collisions, i.e. the minimum (figure 9(b)), intermediate (figure 9(c)) and maximum (figure 9(d)) α -particle energies, normalized to their total energy. Despite the low statistics, the results are compatible, like those obtained for peripheral collisions, with the HF ℓ simulations of a sequential mechanism, indicating that the decay mainly proceeds through the intermediate formation of a $^8\text{Be}_{\text{gs}}$.

The Dalitz plot of normalized energies (see figure 10) and the radial projection of the Dalitz plot, 3ρ are reported, for central collisions, in figures 10 and 11 respectively and compared with the HF ℓ predictions.

All the experimental data appear in very good agreement with the HF ℓ predictions. Therefore no indication for a different decay configuration has been found, if one considers the decay of the Hoyle state in peripheral reactions or when it is populated in the decay chain of $^{24}\text{Mg}^*$. The low statistics of central collisions prevents a quantitative analysis such as the one performed with a fitting procedure for peripheral collisions. New experimental data are therefore needed for a quantitative analysis also of central collisions.

Figure 11. Radial projection of Dalitz plot. Full points: data. Continuous line: HFℓ calculations. The distribution is normalized to the unitary area.

Table 1. Comparison of experimental results on the decay of the Hoyle state.

Experiment	DDE (%)	DDΦ (%)	DDL (%)	DD (%)	C.L. (%)
[7]	...	...	...	<4	99.5
[12]	7.5 ± 4	...	9.5 ± 4	17.0 ± 5.0	...
[8]	<0.45	1.3 ± 0.9 (<3.9)	...	...	99.75
[9]	<0.09	<0.5	<0.09	<0.5	95
[10]	0.3 ± 0.1	0.60 ± 0.09	<0.1	0.91 ± 0.14	99.75
[11]	<0.08	<0.2	...	<0.2	95
Present I	<0.02	...	1.1 ± 0.8	1.1 ± 0.8	95
Present II	<0.05	<0.4	1.1 ± 0.2	1.1 ± 0.4	95

4. Conclusions and perspectives

In this paper we have discussed the decay properties of the $^{12}\text{C}^*$ Hoyle state populated in peripheral and in central collisions via the $^{12}\text{C} + ^{12}\text{C}$ reaction at 95 MeV bombarding energy. It has been debated whether the decay mechanism is sequential, through $^8\text{Be}_{\text{gs}}$ formation, or if a sizeable amount (few percent) of simultaneous decay in three α -particles could be present.

All the results obtained in inelastic channels in several reactions at various energies [7–11] indicate a sequential decay, with a very low limit to a possible contribution of simultaneous processes, of the order of the per mill. On the other side reactions involving more complex systems with heavier ions at higher energies seem to be compatible with a simultaneous decay of some percent [12, 13].

Our results, obtained comparing peripheral and central reactions with the formation of $^{12}\text{C}^*$ Hoyle state in the decay chain of $^{24}\text{Mg}^*$, give no indications of appreciable deviations from the sequential decay mechanism. In particular the fitting procedure for the peripheral case gives the values 1.1% (error 0.8%) for DDL and an upper limit of 0.02% for DDE. As far as the central collisions are concerned, the fitting procedure is difficult due to the low statistics, but qualitatively we can infer a similar contribution.

In table 1 we compare the results of the present work with those obtained in previous experiments. In the last but one row, we present values obtained in the fit of five variables with the contributions of HFℓ, DDE and DDL as free parameters. The last row refers to the fit performed only on the 3ρ variable, when HFℓ, DDE, DDL and DDΦ are all included.

Further measurements with more statistics are needed, possibly also increasing the energy and the number of nucleons involved in order to investigate if *in medium* effects may affect the decay of the Hoyle state.

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