High-Precision Probe of the Fully Sequential Decay Width of the Hoyle State in ^{12}C

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The decay path of the Hoyle state in ^{12}C ($E_x = 7.654$ MeV) has been studied with the ^{14}N$(d, \alpha_2)^{12}$C(7.654) reaction induced at 10.5 MeV. High resolution invariant mass spectroscopy techniques have allowed us to unambiguously disentangle direct and sequential decays of the state passing through the ground state of ^{8}Be. Thanks to the almost total absence of background and the attained resolution, a fully sequential decay contribution to the width of the state has been observed. The direct decay width is negligible, with an upper limit of 0.043% (95% C.L.). The precision of this result is about a factor 5 higher than previous studies. This has significant implications on nuclear structure, as it provides constraints to 3α cluster model calculations, where higher precision limits are needed.

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Exploring the structure of ^{12}C is extremely fascinating, since it is strongly linked to the existence of α clusters in atomic nuclei and to the interplay between nuclear structure and astrophysics. Furthermore, ^{12}C is one of the major constituents of living beings and ourselves. Our present knowledge traces the origin of ^{12}C to the so-called 3α process in stellar nucleosynthesis environments. The 3α process, which occurs in the He-burning stage of stellar nucleosynthesis, proceeds via the initial fusion of two α particles followed by the fusion with a third one [1,2] and the subsequent radiative deexcitation of the so formed excited carbon-12 nucleus, ^{12}C*. The short lifetime of the ^{8}Be unbound nucleus (of the order of 10^{-16} s), formed in the intermediate stage, acts as a bottleneck for the whole process. Consequently, the observed abundance of carbon in the universe cannot be explained by considering a nonresonant two-step process. This fact led Fred Hoyle, in 1953, to the formulation of his hypothesis [3,4]: the second step of the 3α process, $\alpha +^8 \mathrm{Be} \rightarrow^{12} \mathrm{C} + \gamma$, has to proceed through a resonant $J^\pi = 0^+$ state in ^{12}C, close to the $\alpha +^8$ Be emission threshold. The existence of such a state was then soon confirmed [5] at an excitation energy of 7.654 MeV. This state was then named as the *Hoyle state* of ^{12}C [6].

The decay properties of this state strongly affect the creation of carbon and heavier elements in helium burning [7], as well as the evolution itself of stars [8,9]. At typical stellar temperatures of $T \approx 10^8$–10^9 K, this reaction proceeds exclusively via a *sequential* process consisting of the $\alpha + \alpha$ s-wave fusion to the ground state of ^{8}Be, followed by the s-wave radiative capture of a third α to the Hoyle state. However, in astrophysical scenarios that burn helium at lower temperatures, like for instance helium-accreting white dwarfs or neutron stars with a small accretion rate, another decay mode of the Hoyle state completely dominates the reaction rate: the nonresonant, or *direct*, α decay [10–12], where the two α's bypass the formation of ^{8}Be via the 92 keV resonance. Recent theoretical calculations show that, at temperatures below 0.07 GK, the reaction rate of the direct process is largely enhanced with respect to the one calculated by assuming only the sequential scenario [13]; as an example, for temperatures around 0.02 GK such enhancement is predicted to be 7–20 orders of magnitude [7,10,14–16].

In nuclear structure, the Hoyle state is crucial to understand clustering in nuclei [17–19]. Theoretical calculations show different hypotheses regarding its spatial configuration. Recent *ab initio* calculations describe it as a gaslike diluted state [18,19], where the constituent α clusters are only weakly interacting. The possible appearance of Bose-Einstein condensates of α particles have been also proposed [20–22], as well as molecularlike structures with three α particles forming a linear chain, an obtuse triangle, or a bent-arm configuration [18,19,23–25]. Between several observables, some of these models are able to predict the sequential-to-direct decay branching ratio (BR) of the Hoyle state [26]. Accurate knowledge of the experimental value of such a branching ratio has therefore the capital importance to serve as a benchmark of theoretical models attempting to describe α clustering in ^{12}C.

Recently, a quite large number of experiments have been carried out to probe the structure and decay properties of the Hoyle state in ^{12}C [27–32]. The most commonly adopted strategy is to explore how the Hoyle state decays via 3α emission, i.e., what is the *direct* decay rate relative to the *sequential* one. An upper limit to the direct decay branch was first given by Freer *et al.* in 1994 [27]. In their work they suggested that the BR of the Hoyle state decay bypassing the ^{8}Be ground state was lower than 4%, i.e., $(\Gamma_\alpha - \Gamma_{\alpha_0})/\Gamma_\alpha < 0.04$. Here Γ_α indicates the global α decay width and Γ_{α_0} is the partial width of the α emission leading to the ground state of ^{8}Be. More recently, Raduta *et al.* [28] reported a result in strong contradiction with the previous one, finding a rather high value (17% $\pm$ 5%) of the direct BR. Such contrasting results stimulated a series of new experiments aimed at determining the actual value of the direct decay BR of the Hoyle state. A new upper limit of 0.5% (95% C.L.) was obtained by Kirsebom *et al.* by using the kinematic fitting method [30]. Two more recent experiments by Rana *et al.* [31] and Morelli *et al.* [33] suggested nonzero values of the direct decay BR, respectively, of $(\Gamma_\alpha - \Gamma_{\alpha_0})/\Gamma_\alpha = 0.91\% \pm 0.14\%$ and $1.1\% \pm 0.4\%$. Finally, thanks to a high statistics experiment, Itoh *et al.* [32] determined an improved upper limit of the direct BR of 0.2% (95% C.L.). It is important to underline that, as discussed in Refs. [27,32], the use of strip detectors introduces the presence of a nonvanishing background, that reduces the sensitivity to the direct decay BR signal. Taking into account the importance of fully understanding α clustering effects in the nuclear structure of ^{12}C, it is mandatory to improve our knowledge of the direct-to-sequential decay BR of the Hoyle state, since theoretical estimations of this quantity are given at the 0.1% level, i.e., well below the most recent upper limit reported in the literature [32,34].

In this Letter we report on the result of a new high precision experiment specifically designed to isolate, if any, 3α direct decays of the Hoyle state in ^{12}C. For the first time we succeeded in having almost *zero background*, which is a requirement in order to unambiguously disentangle sequential and direct decays. To populate ^{12}C nuclei in the Hoyle state we used the ^{14}N$(d,\alpha)^{12}$C nuclear reaction. A 10.5 MeV deuteron beam was provided by the 15 MV tandem accelerator of the INFN-LNS (Catania, Italy). As a detection apparatus we used the combination of a ΔE-E telescope and a high granularity hodoscope detector. The adopted experimental method is the invariant mass analysis of 3α disintegrations of the Hoyle state. We completely reconstruct the kinematics of the reaction by simultaneously detecting the four α particles emitted in the final state,

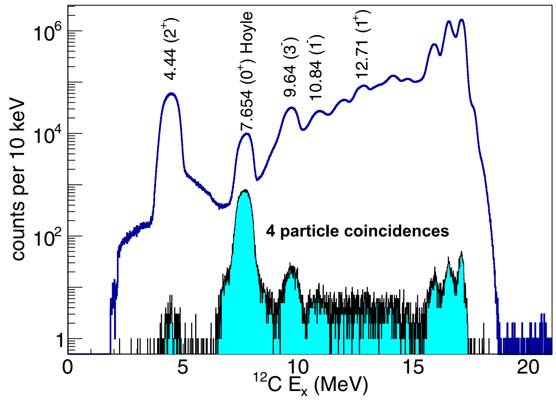

FIG. 1. ^{12}C excitation energy spectrum reconstructed from the measured momentum of particles detected by the $\Delta E - E$ anticoincidence telescope (blue line). Labels are used to indicate the energy and spins of well-known states of ^{12}C. (filled histogram) Same spectrum obtained by selecting four-particle coincidences.

namely, the α ejectile, used to tag the excitation of the ^{12}C residue at its Hoyle state ($E^* = 7.654$ MeV), and the three α particles fed by the Hoyle state decay.

The hodoscope detector was specifically designed to ensure the detection of the three α particles coming from the Hoyle state decay with the highest possible efficiency and to avoid the artificial introduction of background. It is constituted of 8×8 independent silicon pads (1 cm^2, 300 μm thick), and it is placed in such a way that its center is aligned with the axis of the ^{12}C(7.654) three-α emission cone, when the corresponding α tagging ejectile is detected by the ΔE-E telescope.

The ^{12}C excitation energy spectrum, reconstructed from the measurement of kinetic energy and emission direction of the particles detected in the ΔE-E telescope, is shown on Fig. 1 by the blue line. Only particles stopping in the first detection stage are selected, allowing us to strongly reduce contaminations from (d,d) and (d,p) reactions on the target constituents. Details on this technique can be found, e.g., in Ref. [35]. The excitation energy spectrum reduces to the filled one if we select events with four particles in coincidence, i.e., by selecting events where three particles are detected in coincidence by the hodoscope. This spectrum exhibits a pronounced peak at $E_x = 7.654$ MeV, corresponding to the energy position of the Hoyle state, while background as well as other peaks are strongly suppressed, demonstrating the good sensitivity of our detection system to the α decays of the Hoyle state and a very low background level. For the subsequent analysis, events are selected by gating on the Hoyle peak and on the corresponding four-particle total energy spectrum, which unambiguously identifies the reaction channel of interest.

In Fig. 2 we report (full dots) the ^{12}C excitation energy spectrum obtained by an invariant mass analysis of ternary coincidences inside the hodoscope, assuming that they are

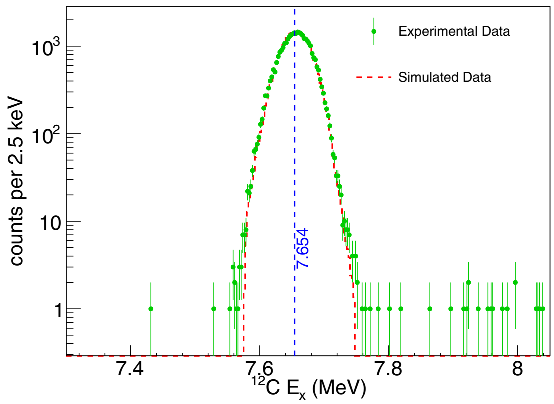

FIG. 2. Three-particle invariant mass spectrum (^{12}C E_x) gated on the Hoyle peak of Fig. 1. Experimental points are compared with the result of a Monte Carlo simulation of the $^{14}N(d,\alpha_2)^{12}C(7.654)$, details are explained in the text. Events under the peak centered at 7.654 MeV are due to the decay of the Hoyle state. The evaluated background level is about 0.036%.

α particles. The red dashed line is the result of a complete Monte Carlo simulation of the effect of the detection system on the reconstruction of the three α particles resulting from the in-flight decay of the Hoyle state. To produce this result we consider four-α-particle fully reconstructed events from $^{14}N(d,\alpha_2)^{12}C(7.654)$ reaction simulated data. In our simulation we have taken into account both the profile of the beam on the target and the angular distribution of the emitted α ejectile, as reported in Ref. [36] at the same incident energy. The geometry of the detectors and their energy resolution are also taken into account in the simulation. The result of the simulation is in excellent agreement with the experimental data, confirming the unambiguous reconstruction of this physical process.

The invariant mass of the Hoyle state is determined with a resolution of about 47 keV (FWHM), while the center of the distribution is in agreement with the position of the Hoyle state within an indetermination smaller than 1 keV. Four-α-particle fully detected events are thus selected by means of a further cut on the peak of Fig. 2. In such a way we obtain a number of about 28 000 decay events of the Hoyle state, an amount well higher than any other previous investigation. The background level, due to spurious coincidences, is extremely low thanks to the stringent constraints on the data, the sensitivity of the apparatus to the physical process, and the unambiguous particle track identification achieved by the use of a hodoscope. It can be evaluated by inspecting the right and left sides of the spectrum; it amounts to about 0.036% of the total integral of the peak.

Details about the three-α-particle decay mechanisms of the Hoyle state can be studied by using the symmetric Dalitz plot [37]. This technique is particularly suited to geometrically visualize the decay pattern into three equal mass particles. Cartesian coordinates to construct the Dalitz plot can be obtained as follows:

$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k),\; y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k, \tag{1}$$

where $\epsilon_{i,j,k} = E_{i,j,k}/(E_i + Ej + E_k)$ are the kinetic energies of each particle, in the reference frame where the emitting source is at rest, normalized to the total energy of the decay. $E_{i,j,k}$ are selected so that $E_i \geq E_j \geq E_k$ and, consequently, $\varepsilon_i \geq \varepsilon_j \geq \varepsilon_k$. In Fig. 3 we show the Dalitz plot obtained from the experimental data selected with the above discussed procedure (a) compared with the analogous plot constructed with simulated 100% sequential decay (SD) data (b) and the 100% DDΦ data (direct decay to the available phase space) (c). Simulated data have been obtained with the same prescription used to construct Fig. 2. In this Dalitz plot representation, a SD mechanism would populate a uniform horizontal narrow band, while a spread of events along the whole plot region would be observed in the case of DDΦ. The plots of Figs. 3(b) and 3(c) are particularly useful to characterize the expected distortion introduced by the experimental apparatus on the analysis to discriminate the decay mechanism. In particular, two significant conclusions can be extracted from these plots. First, the effect of the detection device on the three-alpha-particle reconstruction results only in a broadening of the SD band, without introducing a significant background contamination in the region outside the band. This result demonstrates that we are able to distinguish between the two mechanisms with an exceptionally low background level. In previous investigations [32], the Dalitz plot constructed with

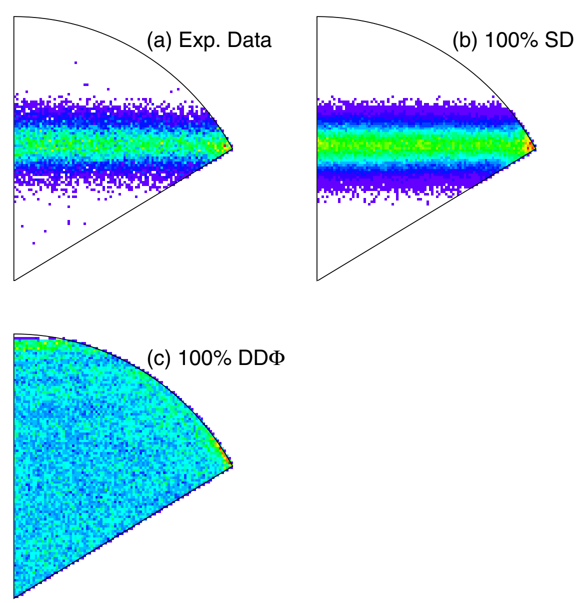

FIG. 3. Experimental symmetric Dalitz plot (a) compared with Monte Carlo simulations of (b) 100% SD and (c) 100% DDΦ. Further details on the simulation procedure are explained in the text. Simulated SD events result in a horizontal band and the effect of our experimental apparatus is expected to not introduce any significant contamination outside this band, as instead observed in previous works [27,32].

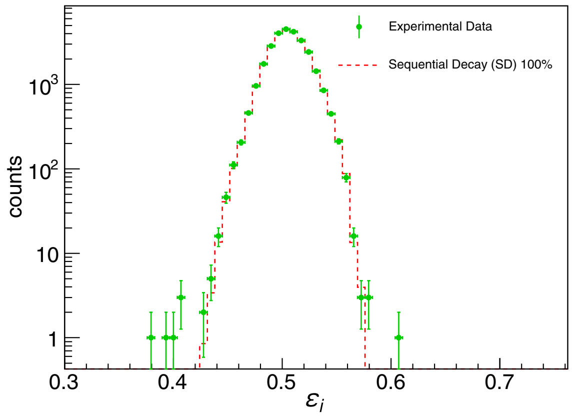

FIG. 4. ϵ_i distribution, i.e., the largest energy among the normalized decay energy of the three α particles in their emitting reference frame. Experimental data (green circles) are compared with the result of a Monte Carlo simulation (red dashed line) where we assumed a 100% sequential decay (SD).

simulated sequential decays shows the presence of data points outside the above mentioned horizontal band, thus containing ambiguities and leading to a reduced sensitivity on direct decay contributions. These difficulties arise from the misassignment of particle tracks inside the strip detectors used in their experiment, as the authors of Ref. [32] state. Our experiment is free from such problems thanks to the use of a hodoscope made of indepenent detectors free of pixel assignment ambiguities. A second, very important, conclusion can be deduced by comparing the behavior of the experimental Dalitz plot of Fig. 3(a) with the simulated ones. An excellent agreement with the simulated SD horizontal band is clearly seen, while only few counts populate the region outside the SD band.

A more quantitative analysis can be achieved by inspecting the ϵ_i distribution, i.e., the distribution of the largest energy among the $\epsilon_{i,j,k}$ normalized energies [32]. The ϵ_i distribution is shown by the green points of Fig. 4. These values are expected to lie, in the case of a DDΦ, between 0.33 (when particles share an equal amount of the energy decay) and 0.67 (when one α is emitted in the opposite direction of the other two). In contrast, a value of about 0.506 is expected for a SD mechanism. In order to estimate the BR of direct decays contributing to the width of the Hoyle state, we have compared the experimental data with the result of a Monte Carlo simulation assuming 100% of SD (red dashed line on Fig. 4). From an analysis of this spectrum, it is possible to identify an extremely small amount of counts not reproduced by the SD simulation. They correspond to background events falling into the selection of Fig. 2 (the total estimated background level is about 0.036%, as previously discussed) and, eventually, to a *signal* of DD.

Starting from the observed experimental data, we can determine the *lower* and *upper* limits of the DD BR, by assuming that both the DD and background counts are regulated by the Poisson statistics [38]. In doing this evaluation, we follow the Feldman and Cousin's approach to the analysis of small signals described in Ref. [39], and we carefully take into account the different expected detection efficiencies for DD and SD, as determined with Monte Carlo simulations. The lower limit is found to be compatible with *zero*. Therefore, we quote an upper limit on the BR of the direct three-α-particle decay of 0.043% (95% C.L.). This value is about a factor 5 lower than the state of the art experiment [32].

To summarize, we have studied the α decay from the Hoyle state (7.654, 0^+) in ^{12}C by simultaneously detecting the four α particles emitted from the reaction $^{14}\mathrm{N}(d,\alpha_2)^{12}\mathrm{C}(7.654)$ at an incident energy of 10.5 MeV. To quantitatively estimate the possible contribution of nonresonant (direct) decays bypassing the ground state of ^{8}Be, we inspect the distribution of the highest normalized energy in the 3α decay, ε_i. A complete Monte Carlo simulation, assuming exclusively the sequential decay pattern, fully reproduces the experimental data. The possible presence of any direct decay is found to be statistically insignificant, and an upper limit of 0.043% (C.L. 95%) to the corresponding branching ratio is estimated. This finding is in agreement with the previous results by Freer *et al.* [27], Kirsebom *et al.* [30], and Itoh *et al.* [32], introducing an improvement of about a factor 5 with respect to the previous most statistically significant work [32]. These results provide important information about the α cluster structure of the ^{12}C Hoyle state and have to be carefully taken into account in theoretical models attempting to reproduce the outgoing α particles and the structure of the Hoyle state. They have also very significant astrophysical impact. Indeed, the further reduction of the upper limit of direct decay implies that calculations of the triple-α stellar reaction rate at temperatures lower than 10^8 K have to be correspondingly revised [7,11].

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