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A new measurement of the direct alpha-decay width of the Hoyle state in ^{12}C

D. Dell'Aquila[1,a)], I. Lombardo[3], G. Verde[3], M. Vigilante[2,1], L. Acosta[4], C. Agodi[5], F. Cappuzzello[6,5], D. Carbone[5], M. Cavallaro[5], S. Cherubini[5,6], A. Cvetinovic[5], G. D'Agata[5,6], L. Francalanza[1], G.L. Guardo[5], M. Gulino[7,5], I. Indelicato[5], M. La Cognata[5], L. Lamia[6], A. Ordine[1], R.G. Pizzone[5], S.M.R. Puglia[5], G.G. Rapisarda[5], S. Romano[5], G. Santagati[5], R. Spartà[5], G. Spadaccini[2,1], C. Spitaleri[6,5] and A. Tumino[7,5]

[1]*INFN-Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy.*
[2]*Dip. di Fisica "E. Pancini", Università di Napoli Federico II, I-80126 Napoli, Italy.*
[3]*INFN - Sezione di Catania, Via S. Sofia, I-95125 Catania, Italy.*
[4]*Universidad Nacional Autónoma de México, A.P. 20-364, Cd.Mx, D.F. 01000 México.*
[5]*INFN - Laboratori Nazionali del Sud, Via S. Sofia, I-95125 Catania, Italy.*
[6]*Dip. di Fisica e Astronomia, Università di Catania, Via S. Sofia, I-95125 Catania, Italy.*
[7]*Facoltà di Ingegneria ed Architettura, Università Kore, I-94100 Enna, Italy.*

[a)]Corresponding author: dellaquila.daniele@gmail.com

Abstract.
The so-called Hoyle state in ^{12}C (7.654 MeV, 0^+) is an excited state of ^{12}C characterized by a well-pronounced 3α cluster nature. Many possible cluster configurations, such as a linear-chain arrangement of 3α particles, bent-arm, triangular or gas-like structures were theoretically conjectured within the previous decades, but, also due to the existence of ambiguities in experimental data, it is still impossible to draw a firm conclusion. Its direct α-decay partial width is accurately predicted by models but requires better experimental constraints. We performed a high-precision and high-selectivity investigation of its α-decay by using the ^{14}N(d,α_2)^{12}C* reaction at 10.5 MeV incident energy with the aim of distinguishing between sequential and direct decay patterns. We are able to significantly improve the state of the art upper limit for direct 3α decays by placing the new limit at 0.043%. Such a low limit allows to give fundamental constraints to theoretical models attempting to describe the structure of the Hoyle state.

INTRODUCTION

One of the most interesting questions of modern nuclear physics originates from the understanding of clustering phenomena in nuclei, which is a fascinating effect of the Pauli principle. Such phenomena are shown to dominate in excited states of light nuclear systems and their study is crucial to address fundamental questions related to the *quantal* properties of nuclei [1]. The Hoyle state in ^{12}C (E_x = 7.654 MeV, $J^\pi = 0^+$) is a particularly relevant example [2]. The existence of this state was theoretically predicted by Fred Hoyle [3, 4] during the early 1950's, as a solution of the problem of the elemental abundance of carbon in the universe. The main reaction responsible for the nucleosynthesis of carbon in our universe is indeed the so-called 3α process, which consists in the transmutation of three α-particles into a ^{12}C. The 3α process is a sequential process that involves the capture of two αs into a ^{8}Be and the subsequent capture of a third α to form ^{12}C. Due to the extremely limited lifetime of the unbound ^{8}Be ($\tau \approx 10^{-16}$ s), formed in the intermediate stage, the quantity of ^{8}Be at the equilibrium in the stellar plasma is extremely small and does not support the formation of ^{12}C via a non-resonant capture as the main mechanism [5]. Hoyle argued that such process should

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have predominately proceeded via a resonant *s*-wave $\alpha +^8$ Be capture, and, therefore, an excited state of ^{12}C close to the $\alpha +^8$ Be emission threshold (7.367 MeV), characterized by $J^\pi = 0^+$, existed. The existence of this state, with the same properties predicted by Hoyle, was experimentally confirmed only a few years later by Cook and collaborators [6], lying at an excitation energy of 7.654MeV and being nowadays known as the *Hoyle state* of ^{12}C [2]. For its pronounced α-cluster nature, this state is the perfect candidate to be formed in a process involving 3α particles. The role of this state in the 3α process can be understood more in detail by considering the following equation for the 3α reaction rate [2]:

$$< \sigma v > \propto \frac{\Gamma_\alpha \Gamma_{rad}}{\Gamma} e^{-\frac{E_R}{k_B T}} \tag{1}$$

Here E_R indicates the resonance energy of the Hoyle state, T is the temperature of the astrophysical site where the reaction takes place and $\Gamma = \Gamma_\alpha + \Gamma_{rad}$ is the total width of the state. The latter is the sum of the decay partial widths Γ_α, which relates to the decay via α-particle emission, and Γ_{rad}, which represents the partial width for the *radiative* decay. The total width Γ of the Hoyle state is strongly dominated by the α width, $\Gamma \approx \Gamma_\alpha$. The quantity of carbon that is produced in such a process depends therefore on the small fraction of ^{12}C* that undergoes in a *radiative* decay, that is affected by the detailed structure properties of the Hoyle state via its partial decay widths [7, 8]. Equation 1, given by the *sequential* picture of NACRE [8], is anyway valid only at high temperatures $T > 10^8$ K, where the process is dominated by a resonant behavior. When the temperature of the helium plasma is lower, mechanisms for which ^{12}C is formed by-passing intermediate stage resonances are expected to dominate the rate [9, 10] and the possible existence of a non-vanishing *direct* decay of the Hoyle state, i.e. a one-step α decay without ^{8}Be formation, might affect the efficiency of the process [11].

The structural properties of the Hoyle state are not only important in nuclear astrophysics for their role in the nucleosynthesis of carbon, but also in the effort of understanding clustered states in nuclei [2]. The Hoyle state presents indeed intricate geometrical properties and its investigation is key for the development of nuclear structure models and our understanding of the properties of few body nuclear systems [12]. Immediately after its experimental discovery, with a pioneering theoretical work, Morinaga has conjectured that the Hoyle state could be constituted by a linear one-dimensional arrangement of three α-particles. In this innovative hypothesis for the time, the Hoyle state could have been the *band-head* of a rotational band that, for the large deformation, should have had 2^+ and 4^+ members respectively at 9.61 MeV and 14.16 MeV [13]. After half a century, only recently this hypothesis was ruled out experimentally, with the identification of the 2^+ excitation of the predicted band [14]. Many progresses have been done also in theoretical models within the past decades, allowing a more accurate description of such properties in terms of fully microscopic approaches with realistic interactions [15]. A seminal work based on the THSR method has successfully described the properties of the Hoyle state in terms of a diluted gas structure of 3α-particles, suggesting the possible appearance of Bose-Einstein condensation (BEC) phenomena [16], an extremely challenging hypothesis in nuclear physics. An interesting description in terms of an equilateral triangle or *bent-arm* arrangement of the three cluster centers has been provided in [17] by using a 3α microscopic model. This model provides a description of the decay path of the Hoyle state, indicating that the corresponding direct decay should result strongly suppressed with respect to the sequential one. Anyway, for a correct refinement of these models, firm experimental results are required. This is not the case for the direct decay width of the Hoyle state. While theoretical models set an upper limit of direct decays at around 0.1% of the total decay width [18], experimental results provide a quite confusing picture [19, 20, 21, 11, 22, 23], setting an upper limit at 0.2% in the most recent experiment [23].

Due to the large degree of discrepancy among the published experiments aiming at measuring the direct decay width of the Hoyle state, and since this information is required by theoretical models attempting to describe clustered states in nuclei, we have performed a new high-precision experiment to shed light on the possible existence of such a rare decay. By using the ^{14}N(d,α_2)^{12}C* reaction at 10.5 MeV and a new generation hodoscope detector to detect the disintegration in 3α particles of the Hoyle state, we are able to increase of a factor 5 the sensitivity to direct decays, placing a new upper limit at 0.043% (95% C.L.). In the proceeding, we describe some details of the experiment and the data analysis.

EXPERIMENTAL DETAILS

The experiment has been performed at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) of Catania (Italy). Highly accurate deuteron beams were delivered by the 15MV Tandem accelerator at an energy of 10.5 MeV on a $\approx 40\mu$g/cm^2 melamine ($C_3H_6N_6$) target deposed on a $\approx 10\mu$g/cm^2 carbon backing [24]. A

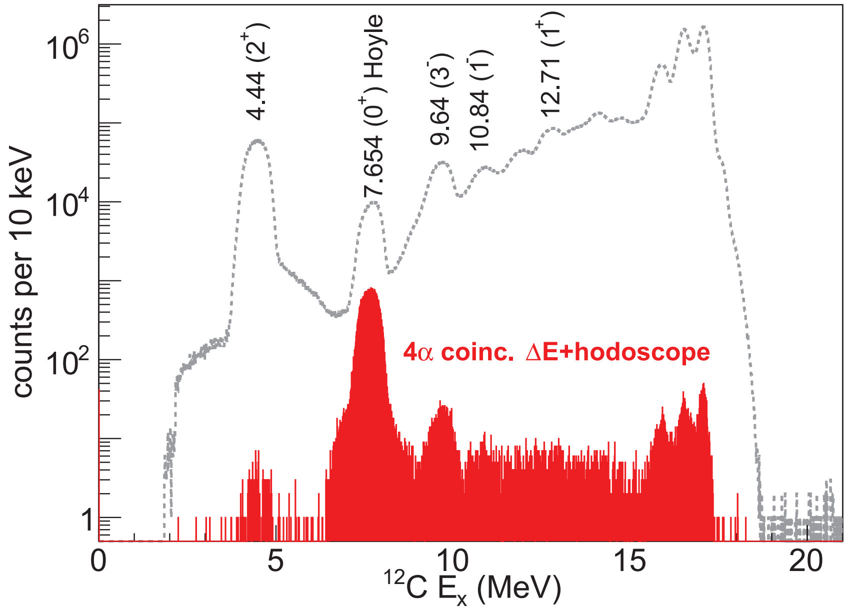

FIGURE 1. Single particle energy spectrum obtained from particles detected in the backward telescope shown as excitation energy of the residual ^{12}C, assuming that the particle is an α from the ^{14}N(d,α)^{12}C reaction (dashed spectrum). The red filled spectrum is the same spectrum but obtained under the condition that three additional particles are detected by the hodoscope.

telescope based on two high-resolution silicon detectors was placed at backward angles, with respect to the incident beam, to detect the ejectiles from ^{14}N(d,α)^{12}C reactions. To rule out contaminants due to (d,d) scatterings and (d,p) reactions on the various elements of the target we used the technique of the *anti-telescope*, as described in Ref. [25]. By measuring energy and emission angle of the α ejectile, we are able to reconstruct emission direction and excitation energy of recoiling ^{12}C nuclei. The reconstructed ^{12}C excitation energy spectrum, obtained from the measurement of a single particle with the backward telescope, and assuming that it is an α, is shown in Fig. 1 with the dashed spectrum. This spectrum shows the appearance of many peaks which are mainly associated to states in ^{12}C, including the Hoyle state. In kinematical coincidence with α particles leaving the Hoyle state as the residual (the ^{14}N(d,α_2)^{12}C* reaction), we placed a new generation hodoscope of high-resolution independent cells [26]. This detector introduces a crucial advantage with respect to previous experiments, since, being constituted by independent detection units, it allows to strongly reduce the background due to particle directions misassigned [23]. By requesting that three particles are detected in the hodoscope, in coincidence with a backward particle, the dashed single-particle spectrum of Fig. 1 collapses into the red one. Here the peaks result suppressed, but the ratio between the Hoyle peak and the others is strongly enhanced, testifying the high selectivity of our apparatus to the decay of the Hoyle state. The small number of leftover counts still present in correspondence of the 4.44 MeV state of ^{12}C is compatible with a minimum percentage of spurious coincidences of particles within the experiment gate, as testified by their strong reduction when a coincidence time gate is applied. The high degree of sensitivity of such a geometrical configuration allows to assume that those particles are αs and to select 3-body decays of the Hoyle state in ^{12}C by using cuts on the single particle spectrum observed in Fig. 1. The analysis of the three particles detected by the hodoscope, assuming that they are αs, allows then to study the decay pattern of the Hoyle state. By collecting 4α particles fully reconstructed events with the above described procedure, a first quantitative analysis of triple-α coincidences can be done by using invariant mass techniques, see for example [27, 28]. The result is shown in Fig. 2 in terms of ^{12}C excitation energy. A sharp peak, with a FWHM of around 40 keV is obtained, centered at the excitation energy of the Hoyle state. This spectrum is particularly significant, not only because it provides an insight into the resolution of our detection system, but also because it allows a quantitative measurement of the degree of background expected. This can be inferred by studying the counts distribution at the right and left side of the peak. A further selection on this peak allows to produce a set of well reconstructed Hoyle decay events, with an extremely low background level, equal to 0.03% of the total number

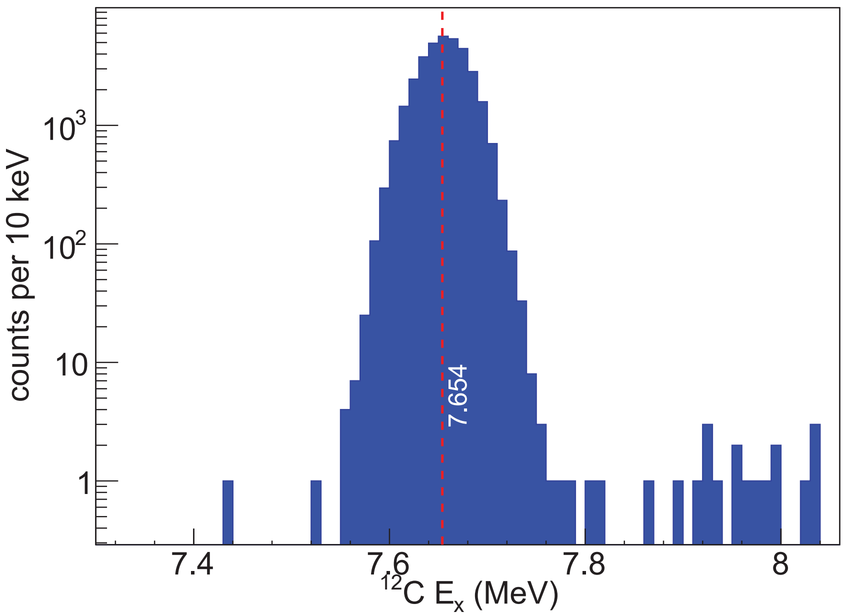

FIGURE 2. ^{12}C excitation energy spectrum obtained via invariant mass analysis of ternary particles, assuming that they are αs, in coincidence with a cut on the Hoyle peak of Fig. 1.

of counts.

DATA ANALYSIS AND RESULTS

The decay pattern in three α particles of the Hoyle state can be studied by analyzing the phase space distribution of the final particles. In particular, the aim of the present analysis is to distinguish between *sequential* decays (SD), which involve the initial emission of an α-particle with the other two αs emitted in the opposite direction to form a ^{8}Be, from possible *direct* decays (DD), where the three α are emitted simultaneously. A particularly powerful method to geometrically visualize such decays is using the so-called symmetric Dalitz plot [29, 30]. This plot can be constructed in cartesian coordinates by using the following set of equations [23]:

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

where $\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$ are the so-called *normalized* energies, sorted such as $\varepsilon_i > \varepsilon_j > \varepsilon_k$. They represent the energies of each of the three particles in their emission center of mass frame $E_{i,j,k}$ normalized to the total energy of the decay $(E_i + E_j + E_k)$. In such a plot, data collapse into a region like the ones shown in Fig. 3 delimited by a red line. The locus occupied by sequential events manifests in a narrow horizontal line in this plot, while a uniform fill of the entire region is expected for events associated to DD, spanning uniformly the available phase space. We performed a detailed Monte Carlo simulation, as described in [31], taking into account the spot of the beam on the target, the interaction of beam with the target, the reaction angular distribution and the geometry of our experimental apparatus in order to explore the possibility to distinguish between SD and DD and to study their corresponding efficiency. As an example, Fig. 3, right hand side, shows the result obtained by simulating Hoyle state decay events with 100% SD as detected by our device. We observe the appearance, as expected, of an horizontal line, and no counts lie in the region outside of the line. This not only probes the capability of our device to distinguish between the two decay patterns, but represents a significant improvement in these kind of investigations if compared to the state of the art experiments [23, 11], that were instead affected by significant contributions lying outside of the SD band even in the

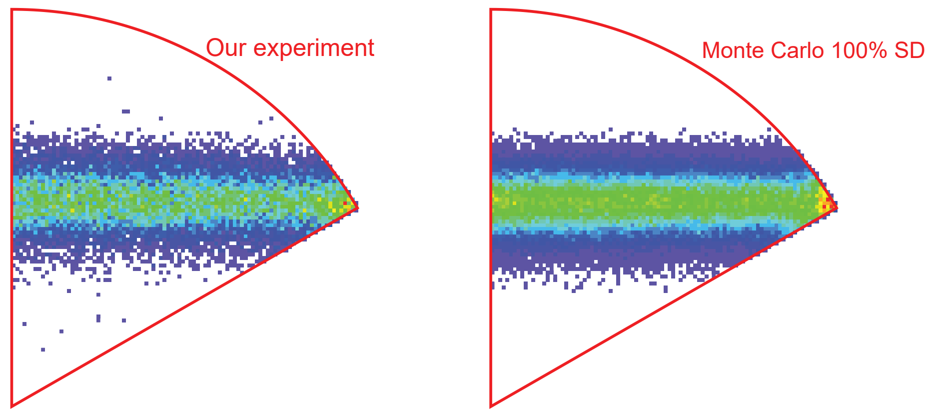

FIGURE 3. Symmetric Dalitz plot obtained experimentally, left side, and by means of a detailed Monte Carlo simulation of SD only. In both cases, a narrow horizontal band is present, with an extremely low background level.

presence of only SD events. The previous observed background, as stated in Ref.[23], originated by a certain amount of misassigned particle tracks in silicon strip detectors, that are here avoided by means of the use of independent silicon cell detectors. The same plot obtained with our experimental data is shown in the left side of Fig. 3. The plot is qualitatively in agreement with the simulated one obtained in the case of a pure SD mechanism. The extremely low level of background observed in Fig. 2 allows to use such experimental data to infer even an extremely small percentage of DD events. Quantitative information regarding signal of DD can be obtained by analyzing the radial projection of the Dalitz plot shown in Fig. 3, as discussed in [31]. By applying the Feldman and Cousin's approach for small signals in the presence of small background levels, we found DD signals to be statistically not significant. We place a new upper limit to DD of 0.043% with a confidence limit (C.L.) of 95%.

CONCLUSIONS AND FUTURE PERSPECTIVES

The investigation of nuclear structure properties, and specifically the properties of clustered states, has a wide importance in nuclear physics, not only for the astrophysical relevance [2, 32, 33, 34, 35], but also for our understanding of the properties of nuclear forces in few body interacting systems [36, 37]. The Hoyle state in ^{12}C represents a particularly relevant case for its unique structural properties [2]. We have carried out a high-precision experimental investigation of the direct α-decay width of the Hoyle state by using the ^{14}N(d,α_2)^{12}C* reaction with a 10.5 MeV deuteron beam delivered by the 15MV Tandem accelerator of INFN-LNS. A high-resolution hodoscope was used to select, with extremely high-sensitivity, three-body decays. They were studied by using the symmetric Dalitz plot technique. Our almost-zero background measurement allows us to obtain a new upper limit for the DD branch of 0.043% (95% C.L.) [31], which is about a factor 5 lower than the present state of the art [23]. This result is in extremely good agreement with another recent experiment from the Birmingham group [38]. It is worth mentioning that new interesting theoretical calculations have been carried out more recently, [39, 40], showing the importance of Coulomb effects in the decay of the Hoyle state. In order to benchmark this hypothesis, further experiments involving the decay of the Hoyle state have to be performed.

Finally, efforts to improve the radiative partial width of the Hoyle state were made by the CHIMERA group of LNS. In their experiment, they used the combination of a large acceptance detector [41] and a high-resolution array to measure charged particles [42]. A better constraint on our knowledge of the radiative decay partial width, with the present refined knowledge of the DD branch, will definitely help to improve our understanding not only of the Hoyle state of ^{12}C but also of clustered states in nuclei.

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