The α-decay of the Hoyle state in ^{12}C: a new high-precision investigation

D. Dell'Aquila[1,2,⋆], *I.* Lombardo[4], *G.* Verde[4], *M.* Vigilante[1,2], *L.* Acosta[5], *C.* Agodi[6], *F.* Cappuzzello[7,6], *D.* Carbone[6], *M.* Cavallaro[6], *S.* Cherubini[6,7], *A.* Cvetinovic[6], *G.* D'Agata[7,6], *L.* Francalanza[2], *G.L.* Guardo[6], *M.* Gulino[8,6], *I.* Indelicato[6], *M.* La Cognata[6], *L.* Lamia[7], *A.* Ordine[2], *R.G.* Pizzone[6], *S.M.R.* Puglia[6], *G.G.* Rapisarda[6], *S.* Romano[6], *G.* Santagati[6], *R.* Spartà[6], *G.* Spadaccini[1,2], *C.* Spitaleri[7,6], and *A.* Tumino[8,6]

[1] *Dip. di Fisica "E. Pancini", Università di Napoli Federico II, I-80126 Napoli, Italy*
[2] *INFN-Sezione di Napoli, I-80126 Napoli, Italy*
[3] *Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France*
[4] *INFN - Sezione di Catania, Via S. Sofia, I-95125 Catania, Italy*
[5] *Universidad Nacional Autónoma de México, A.P. 20-364, Cd.Mx, D.F. 01000 México*
[6] *INFN - Laboratori Nazionali del Sud, Via S. Sofia, I-95125 Catania, Italy*
[7] *Dip. di Fisica e Astronomia, Università di Catania, Via S. Sofia, I-95125 Catania, Italy*
[8] *Facoltà di Ingegneria ed Architettura, Università Kore, I-94100 Enna, Italy*

Abstract. The α-decay path of the Hoyle state in ^{12}C (E_x = 7.654MeV) represents one of the most challenging questions of modern nuclear physics. Its knowledge can help in the understanding of cluster configurations in light nuclei and the possible existence of Bose-Einstein condensates in nuclei. In stars, it is involved in the so-called 3α process, where the ^{12}C nucleosynthesis occurs. We studied the ^{14}N(d, α_2)^{12}C(7.654) reaction at 10.5MeV incident energy to probe its direct decay component. We found, with a precision higher of a factor 5 than any other previous experiment, an almost total absence of direct decays by-passing the ground state of ^{8}Be. From our analysis, a new upper limit of such decay is found at 0.043% (95% C.L.). Astrophysical 3α process reaction rate calculations have to be accordingly revised.

1 Introduction

The majority of the constituents of our universe are produced in stars by means of nuclear reactions, whose efficiency is regulated by the structure properties of the nuclei involved [1]. Studying nuclear reactions at low energy and the spectroscopy of nuclei is therefore important to understand how and to what extent elements are produced in stars [2–6]. A fundamental question in nuclear astrophysics is certainly how the production of carbon, one of the major constituents of the universe and human beings, could occur [7]. Such question has attracted the interest of nuclear physicists and astrophysicists since very long time. When a star leaves the main sequence, after the proton burning, it is mainly constituted by helium nuclei. In such a scenario, the way for the nucleosynthesis to proceed towards

⋆e-mail: dellaquila@na.infn.it

heavier nuclei consists in the so-called *helium burning* [1], where nuclei of helium are first transmuted into carbon and then in heavier elements via subsequent radiative captures. The first part of the process, i.e. the trasmutation of 3 α particles into a ^{12}C ($3\alpha \rightarrow ^{12}$C), is anything but trivial. This process proceeds via the initial fusion of two α particles into the ^{8}Be, followed by the radiative capture of a third α, $\alpha+^{8}$Be$\rightarrow^{12}$C$+\gamma$ [8, 9]. Anyway, due to the extremely short lifetime of the unbound ^{8}Be (formed in the intermediate stage and having a lifetime of the order of 10^{-16} s), the efficiency of the whole process is limited and, by simply assuming a non-resonant capture of the third α, it is not possible to explain the carbon to oxygen abundance ratio observed in the universe [10]. This apparent contradiction was solved by Fred Hoyle with an interesting hypothesis formulated in 1953: the radiative capture of the third α takes place via a resonant process through a $J^{\pi} = 0^{+}$ state of ^{12}C located close to the α emission threshold of ^{12}C($\approx$ 7.4 MeV) [11, 12]. The existence of this state was then confirmed, a few years later, by Cook and collaborators [13], lying at an excitation energy of 7.654MeV. This state is nowadays known as the *Hoyle state* of ^{12}C [7].

The production rate of carbon in such a *sequential* process can be calculated from the competition between radiative decays and the α-decay of the Hoyle state. This clearly depends on the structure properties of the Hoyle state, and the following empirical equation determines it [7]:

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

where E_R is the Hoyle state energy of resonance, k_B the Boltzmann constant and Γ the total level width. The latter is fully dominated by the α decay width, i.e. $\Gamma = \Gamma_{\alpha} + \Gamma_{rad} \approx \Gamma_{\alpha}$, and so it results in a dynamical equilibrium ^{4}He + ^{8}Be $\leftrightarrows$ ^{12}C* only broken by the small leakage to the ^{12}C ground state given by the radiative decays.

The knowledge of the properties of the Hoyle state allows then to determine the reaction rate of the 3α process [14]. However, while in stars that burn helium at temperature grater than 10^{8} K it is dominated by the resonant process (called sequential), for lower temperatures another mechanism could be present and dominate the reaction rate: the so-called *direct* (non-resonant) process. The first of the two mechanisms is fully dominated by the Hoyle state process and by its *sequential decay* (SD) width, while in the second the 3α do not have energetically access to the intermediate resonances. Anyway, in the presence of a non-vanishing *direct decay* (DD) width of the Hoyle state, the second process may also occur through the low energy tail of the Hoyle state [15, 16], being the corresponding rate significantly enhanced with respect to the commonly adopted low energy extrapolation reported in NACRE [17]. In order to fully understand these processes, and the validity of the NACRE empirical rate formula, a precise knowledge of the decay pattern of the Hoyle state has to be experimentally achieved.

On the theoretical point of view, several refined microscopic calculations have been developed to describe the 3α process, improving the simple empirical description reported by NACRE. Ogata and co-workers [14] showed an enhancement of the 3α reaction rate at low temperatures of several orders of magnitude with respect to the NACRE assumption (26 orders of magnitude at $T = 0.01GK$), as an effect of the direct processes. Following this work, different calculations with other quantum three-body approaches have been performed [16, 18–20] but the resulting picture remained quite puzzling and far from a firm conclusion. More recently, Akahori and collaborators developed an imaginary-time formalism approach to the problem of the 3α reaction rate, producing values in good agreement with the NACRE rate [21].

In nuclear structure, the Hoyle state in ^{12}C is crucial to better understand clustering phenomena and the structure of light nuclei. Given the bosonic nature of the α-particles, the inter-cluster separation of the 3α system could be large enough that their internal structure can become no longer important. Under this peculiar condition one can expect the appearance of a Bose-Einstein condensate [22, 23],

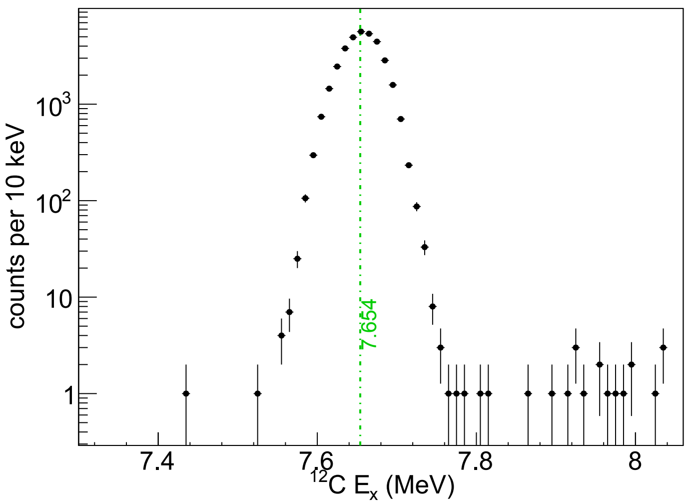

Figure 1. ^{12}C excitation energy spectrum obtained by means of invariant mass techniques on the 3α detected in the hodoscope. A line indicates the expected position of the Hoyle peak. The counts outside the peak region are associated to background events.

a very extreme case due to the limited size of the system. Such possibility could be linked to the possible presence of a non-vanishing direct decay width, as discussed in [24].

Recently, a quite large number of experiments have been performed in order to measure the direct decay (DD) width of the Hoyle state to the sequential (SD) one [24–29]. Anyway, no definitive conclusions can be drawn regarding the possible existence of a non-vanishing DD width and the precision of the state of art experiments, see [29] for example, was limited by the presence of a not negligible background level.

For these reasons, we performed a new high-precision experiment with the aim of solving the present ambiguities in the experimental knowledge of the DD width of the Hoyle state in ^{12}C with an unprecedented ultra-low background level.

2 Experimental results

Our experiment was performed at the 15 MV Tandem accelerator of INFN-Laboratori Nazionali del Sud (Catania). A highly collimated deuteron beam was accelerated at 10.5 MeV and delivered to a Melamine ($C_3N_6H_6$) target, with intensities not exceeding 4 nA to minimize possible background events due to spurious coincidences on the detectors. The ^{14}N(d,α) reaction was used to populate the Hoyle state in the residual ^{12}C. We used a two-stage telescope, placed at backward angles, and the anti-coincidence technique, see more details in Refs. [30, 31], to detect the backward recoiling α ejectile. In such a way, we are free from light ejectile contaminants coming from elastic scattering or transfer reactions induced by deuterons. The measured ejectile energy spectra, thanks to the presence of two bodies in the reaction exit channel, can be easily translated in excitation energy of the ^{12}C residual by using momentum and energy conservation laws. This apparatus allows us to tag, by means of energy cuts in the backward emitted ejectile spectrum, excitation energy and recoling direction of the residual

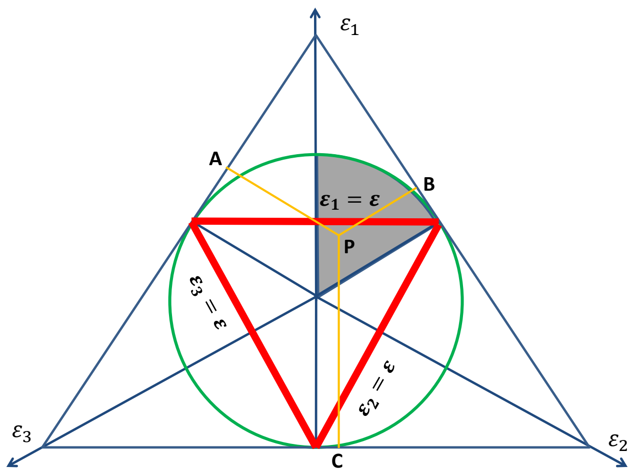

Figure 2. Representation of *normalized energy* coordinates ($\varepsilon i, j, k$) to build a symmetric Dalitz plot. By selecting $\varepsilon_i > \varepsilon_j > \varepsilon_k$ data collapse into the shadowed region. The red horizontal band indicates, schematically, the region where sequential decays should lie.

^{12}C nucleus, with extremely low background level. In kinematical coincidence with the ^{12}C*(7.654) residuals we placed an hodoscope of 64 independent silicon cells, with the aim of detecting the three α-paticles resulting from the α-decay of the Hoyle state. The telescope is constituted by 4 square blocks of 4×4 silicon detectors, each of them analogous to the second detection stage of one module of the OSCAR hodoscope (see Ref. [32] for details).

To analyze data, we restricted the events to the ones where 4 particles are detected. Such condition implements a further selectivity on the decays of the Hoyle state. As a confirmation of this, when selecting 4-particles events, the energy spectrum obtained with the backward telescope shows a strong reduction of the background under the peak associated to the Hoyle state, as shown in Ref. [33]. Invariant mass techniques, as described for example in [34], were used to unveil the decay path of the Hoyle state. Fig. 1 reports the excitation energy spectrum obtained from the invariant mass of the three particles, assuming that they are α-particles. Black points with error bars represent the experimental data and a green dashed line indicates the expected position of the Hoyle state. As clearly visible, a peak is observed centered at the correct value of energy. We obtain a precision of 1 keV in the position of the peak and the distribution has a FWHM of the order of 47 keV, indicating the high-precision level of our apparatus in invariant mass reconstruction. The contributions that lie outside of the peak region are useful to estimate the background level under the peak. It amounts at about 0.036% of the whole peak integral.

A very useful method to geometrically visualize the decay in 3α is using the so-called symmetric Dalitz plot [35]. A symmetric Dalitz plot can be constructed by using the kinetic energy of the three particles in the reference frame where the emitting nucleus is at rest. Calling $E_{i,j,k}$ these values, one can define the Dalitz plot coordinates by using the *normalized decay energies* $\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$. Since the sum of each of the coordinates is a constant, experimental points, corresponding to $(\varepsilon_i, \varepsilon_j, \varepsilon_k)$ energy coordinates, are localized within an equilateral triangle (see figure 2). Moreover, being $\varepsilon_{i,j,k}$ constrained by the energy conservation law in the decay, i.e. $\varepsilon_i + \varepsilon_j + \varepsilon_k = 1$, not every combination of

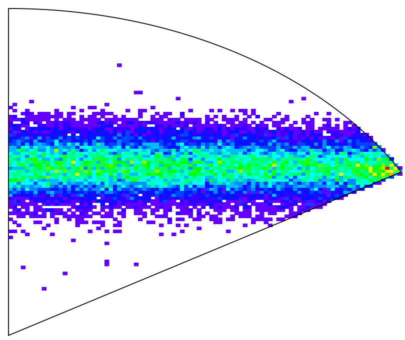

Figure 3. Experimental Dalitz plot of the 3α decay from the Hoyle state. A straight horizontal line is observed and associated to SD events. The counts outside this region are topologically compatible either with background events or signals of DD. Their amount is significantly lower than previous works.

these values is permitted and, as a result of this, data is confined within the green circle in figure 2. The distribution of experimental points in such a graph allows to distinguish different decay paths. In the case of a direct decay to the phase space, for example, energy can be shared with any of the possible combinations $\varepsilon_{i,j,k}$, and the circle is almost uniformly filled. For the case of sequential decays, instead, the energies of the decay have to obey to more restrictive constraints, resulting in the red bands shown in figure. A similar plot can be generated in cartesian coordinates by using the following equations:

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

Finally, by selecting $\varepsilon_i > \varepsilon_j > \varepsilon_k$ the data collapse into the shaded region of Figure 2, where the red horizontal band is associated to sequential decay processes, while the remaining part of the sector will be populated by direct events.

In figure 3, we present our experimental Dalitz plot. Compared to the ones observed in the state of art experiments [27, 29], the amount of counts outside the horizontal band is much reduced. It can be associated either to DD events or to background. This confirms the low-background of our finding.

To quantitatively estimate the DD contribution we used the radial projection of the symmetric Dalitz plot. It corresponds to the highest decay energy of the three particles measured in the decay center of mass, and it is usually indicated in the literature as ε_i [29]. It is shown in the Fig. 4 from the data of the present experiment. Here, a peak at about 0.5 represents SD decays, while a distribution from about 0.33 to 0.67 is expected in the case of DD. We performed a detailed simulation to take into account the effect introduced by the experimental apparatus and the whole reaction mechanism. The result of our simulation is shown in the figure as a dashed line for the case of 100% SD. We identify a number of counts not compatible with a fully SD mechanism. Taking into account the background level, and by using 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

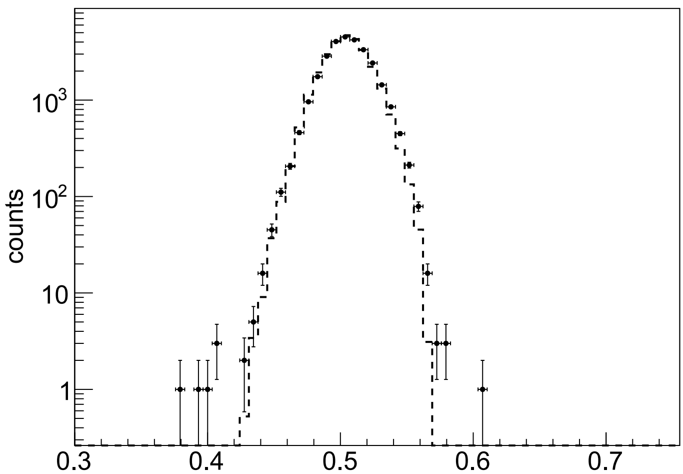

Figure 4. Distribution of the largest normalized energy ε_i in the decays of the Hoyle state. They are studied by means of invariant mass technique on experimental Hoyle state decay data measured in the hodoscope.

to DD of 0.043% with a confidence limit (C.L.) of 95% [36]. This result is about a factor 5 lower than the present state of art experiment.

3 Conclusions

The DD of the Hoyle state in ^{12}C was measured by means of a new high-precision and low background experiment. We produced ^{12}C recoils excited in their Hoyle state by means of the ^{14}N(d, α_2)^{12}C(7.654) reaction at 10.5MeV incident energy. To tag excitation energy of the ^{12}C recoiling nuclei, we used a backward angle anti-coincidence telescope. The decay of such ^{12}C is then studied via invariant mass techniques of the 3α decay, detected by means of a hodoscope detector.The use of a hodoscope made by 64 silicon independent cells allows us to avoid the background typical of the use of a single strip detector. With this experiment, we are able to place an improved upper limit for direct decay branches of the Hoyle state of 0.043% (95% C.L.). This result was recently published in [36] and has a precision of about a factor 5 better than any other previous investigations. Analogous results were accomplished by a recent experiment performed by the group of Birmingham [37]. Our results do not support a revision of the fully sequential NACRE 3α reaction rate [17] at high and intermediate temperatures ($T > 0.028$ GK). In the lower temperature region, where the 3α process is dominated by the non-resonant capture involving three α particles [21], the present results may instead give some constraints to microscopic models that assume possible contributions from 0^+ continuum states [16].

Very recently, the CHIMERA group of LNS has designed and carried out an experiment to increase the precision in the knowledge of the γ decay width of the Hoyle state. In this experiment, they benefited of a large acceptance detector [38, 39] and a high-granularity array for charged particles [40, 41]. Further attempts to better constraint the experimental knowledge of the radiative decay width of the Hoyle state, together with the present improved limit of the DD width, are particularly important in the effort of understanding clustering phenomena in light nuclei and the role of the Hoyle state in stars that burn helium at low temperatures.

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