Radiative Decay Branching Ratio of the Hoyle State in ^{12}C via Charged Particle Coincidence Techniques

D. Dell'Aquila[1,2,*], *I.* Lombardo[3,4], *L.* Redigolo[3,4], *M.* Vigilante[1,2], *F.* Angelini[6,7], *L.* Baldesi[8,9], *S.* Barlini[8,9], *A.* Best[1,2], *A.* Camaiani[8,9], *G.* Casini[9], *C.* Ciampi[8,9], *M.* Cicerchia[6,7], *M.* D'Andrea[4], *J.* Diklić[11], *D.* Fabris[7], *B.* Gongora Servin[5], *A.* Gottardo[5], *F.* Gramegna[5], *G.* Imbriani[1,2], *T.* Marchi[5], *A.* Massara[10], *D.* Mengoni[6,7], *A.* Ordine[2], *L.* Palada[11], *G.* Pasquali[8,9], *S.* Piantelli[9], *E.* Pilotto[6,7], *D.* Rapagnani[1,2], *M.* Sigmund[11], *A.* Stefanini[8,9], *D.* Stramaccioni[6,7], *D.* Tagnani[12], *I.* Tišma[11], *S.* Valdré[9], *G.* Verde[4], and *N.* Vukman[11]

[1]Dipartimento di Fisica "Ettore Pancini", University of Napoli "Federico II", Napoli, Italy
[2]INFN - Sezione di Napoli, Napoli, Italy
[3]Dipartimento di Fisica e Astronomia "Ettore Majorana", University of Catania, Catania, Italy
[4]INFN - Sezione di Catania, Catania, Italy
[5]INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
[6]Dipartimento di Fisica, University of Padova, Padova, Italy
[7]INFN - Sezione di Padova, Padova, Italy
[8]Dipartimento di Fisica e Astronomia, University of Firenze, Sesto Fiorentino, Italy
[9]INFN - Sezione di Firenze, Sesto Fiorentino, Italy
[10]INFN - Laboratori Nazionali del Sud, Catania, Italy
[11]Zavod za eksperimentalnu fiziku, Rudjer Bošković Institute, Zagreb, Croatia
[12]INFN - Sezione di Roma Tre, Roma, Italy

Abstract. The properties of the Hoyle state in ^{12}C (7.654 MeV, 0^+) affect the rate at which carbon, one of the most abundant elements in the Universe, is forged in stars. Recent experiments reported values of its radiative decay branching ratio that are in tension, posing major implications especially in the astrophysical domain. This work reports on an almost background-free measurement of the radiative decay branching ratio of the Hoyle state that exploits charged particle coincidence techniques. The experiment adopts several methodologies to minimize the background and identify the rare signal associated with the radiative decay. Large care is devoted to having under full control two of the major sources of systematic errors in particle-coincidence experiments: the coincidence efficiency and the spurious coincidence rate. We find a radiative decay branching ratio of $\Gamma_{rad}/\Gamma_{tot} = 4.2(6) \cdot 10^{-4}$. The new finding helps to resolve the tension between recent data published in the literature.

1 Introduction

The community of nuclear clustering has put special attention, over the past decades, to the investigation of the Hoyle state in ^{12}C (7.654 MeV, 0^+) [1, 2]. This nuclear state is of paramount importance for the understanding of clusters in light nuclear systems [3], and is particularly famous also for its relevance in the astrophysical domain, where it is crucial to describe the rate at which carbon is produced in stars through the so-called triple-alpha process [4]. The latter is directly affected by the competition between its α-decay and its rare radiative decay. However, while the first has been the subject of numerous experimental and theoretical investigations (see, e.g., [5–12]) that seem to have drawn a fully conclusive picture, recent experiments have reported contrasting results for its radiative decay branching ratio, which enters in the determination of the radiative decay partial width, a fundamental ingredient to constrain the triple-alpha process [13].

The radiative decay branching ratio of the Hoyle state $\Gamma_{rad}/\Gamma_{tot}$ is presently known from numerous experimental investigations, exploiting gamma-particle [14, 15] and particle-particle coincidence techniques [16–21], which date back to the 60s and 70s of the past century. From a weighted average of the previously published values, excluding the outlier published in Ref. [16], the recommended value is $4.19(11) \cdot 10^{-4}$ [1].

This value has been seriously questioned by a recent high-resolution gamma-particle coincidence experiment [22][1], published after almost half a century from the last gamma-particle investigation of the Hoyle state [15], and with an improved technique. The new experiment adopted a fully rigorous treatment of the spurious coincidence rate and identified and corrected an inconsistency previously

*e-mail: daniele.dellaquila@unina.it

[1]A recent re-investigation of the Hoyle state radiative decay at the same facility reported a radiative branching ratio $\Gamma_{rad}/\Gamma = 4.1(4) \cdot 10^{-4}$ [23], contradicting the former result of Ref. [22]. From the new analysis, the source of the discrepancy remains unclear, demanding for further studies.

reported in Ref. [15]. With this improved experiment, the newly recommended value for the radiative decay branching ratio was $6.2(6) \cdot 10^{-4}$, which would support an increase of about 34% of the carbon production rate in red giant stars. Such a tremendous increase would strongly impact not only models for stellar evolution and nucleosynthesis, but also other astrophysical problems, such as the pair-instability mass gap the formation of black holes [13]. The latter is a crucial problem, given the recent LIGO obervations [24, 25], whose resolution requires a detailed knowledge of both the Hoyle state mechanism and the key ^{12}C(α,γ)^{16}O reaction in red giants.

The publication of Ref. [22] triggered a series of new high-resolution experiments attempting to measure the radiative decay branching ratio of the Hoyle state. The first work of this *new era* of experiments, published by Tsumura and collaborators [26], was primarily focused on the determination of the radiative branching ratio of the 9.63 MeV state, but obtained information on the Hoyle state decay as a byproduct. The result by Tsumura and co-workers contradicted the value suggested by Kibédi et al. [22], even if their value was compatible within two-sigmas. The situation became even more complicated after the publication of Ref. [27]. This work, again primarily focused on the 9.63 MeV state, is the only work published so far that achieved a complete measurement of all reaction products, with a four-fold coincidence method made possible by the use of a large acceptance multi-detector. The reported $\Gamma_{rad}/\Gamma_{tot}$ value turned out to be even larger than the result of Ref. [22], but was affected by a much larger uncertainty. Finally, even more recently, Luo et al. [28] used particle-particle coincidence techniques and a magnetic spectrometer to investigate the radiative decay branching ratio of the Hoyle state. The value reported by Luo and collaborators is in agreement with the state-of-the-art established with elder works, and contradicts the result by Kibédi [22].

In the framework described above, given the high relevance of the topic, it is clearly mandatory to make further experimental efforts to definitely clarify the radiative decay branching ratio of the Hoyle state in ^{12}C. To contribute clarifying the situation, we performed a new high-resolution experiment using the ^{14}N(d,α)^{12}C reaction at 2.7 MeV bombarding energy. This reaction is highly selective for the population of the Hoyle state in ^{12}C [5], and allows to isolate physics events in which the Hoyle state is produced with low background due to competing reactions. In our experiment, for the first time in a similar particle-coincidence experiment, we performed a topological study of the coincidence efficiency in two-dimensions, allowing to reach unitary efficiency.

This manuscript describes the main ideas and results of our experiment, which was recently published in Ref. [29].

2 The Experiment

The experiment was performed at the CN accelerator of the INFN - Laboratori Nazionali di Legnaro (INFN-LNL), Legnaro, Italy, in two runs from 2021 to 2023. A 2.7 MeV

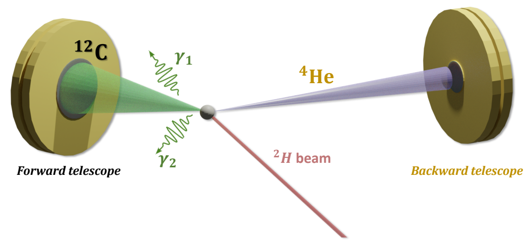

Figure 1. Schematic drawing illustrating the physical principle of the experiment.

deuteron beam was delivered to the *zero-degree* scattering chamber at an intensity of ≈ 10-40 nA. The entire beamline was suitably aligned using a combination of laser and traditional optical positioning systems. This allowed to have the beam axis intercepting the experimental target at its center when the beam is delivered along the axis of the focusing magnets of the beamline. In order for the beam emittance on target to be fully reproducible, a crucial point in particle-particle coincidence measurements [20], the beam passed through a series of six circular tantalum collimators, with diameters ranging from 1 mm to 3 mm, placed before and after the scattering chamber. The beam current on the collimators was constantly monitored in order to correct for small drifts of the beam direction; in addition, a Faraday cup placed at the end of the beamline constanty recorded the beam current passing through the collimators: the ratio between the current at the collimators and at the Faraday cup gives a further feedback for the beam emittance on target.

The beam impinged on a thin melamine target ($C_3H_6N_6$, ≈ 50 μg/cm^2 thick), deposited on an ultra-thin carbon backing (≈ 10 μg/cm^2). A tiny gold deposition (≈ 1.5 nm) on the melamine helped to maintain the target stability under bombardment. The target lied at the center of the scattering chamber. Two silicon telescopes were used as the detection system: a *backward* telescope (93 μm/500 μm thick), centered at a polar angle $\theta = 90°$ in the laboratory frame, and a *forward* telescope (17 μm/500 μm thick), placed in the forward hemisphere and mounted on a micro-positioning device. Both telescopes are internally used as anti-coincidence telescopes as described more in details in Refs. [5, 29][2]. The physical principle of the experiment is schematically illustrated in Fig. 1: when the ^{14}N(d,α)^{12}C reaction occurs in the nitrogen element present in the target, we detect the α ejectile with the backward telescope. This defines the kinematic cone in which the recoiling ^{12}C is emitted and its excitation energy. If the recoil is populated in its Hoyle state, i.e. if the (d,α_2) re-

[2] The term *anti-coincidence* refers here as a logic condition between first and second detection layer of a given telescope. In this experiment, we discard events in which the coincidence between first and second layer occurred. These events are associated with lighter particles coming, for example, from the contaminant (d,d) and (d,p) reactions. This helps to reduce sources of background.

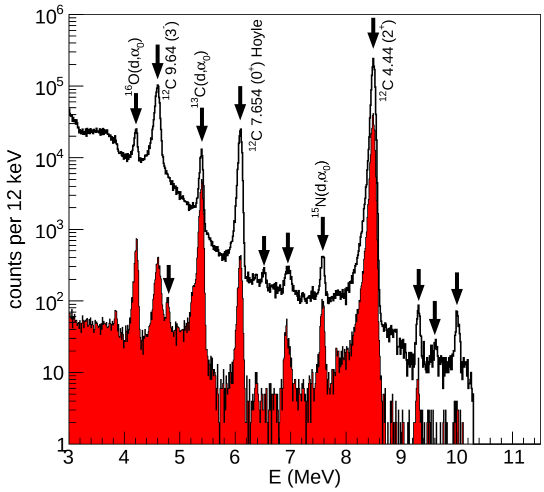

Figure 2. Backward telescope energy spectrum without further conditions (black line) and backward telescope energy spectrum when a time-coincidence is recorded a the forward detector, when this is placed in the α_2-^{12}C coincidence position (red-filled spectrum). Black arrows indicate the energy position of the Hoyle state peak, (d,α_2) reaction, alongside those associated with the most frequent contaminant reactions.

action occurs, then its kinematic emission cone is centered at the direction of the forward telescope. After radiative decay, which is schematically depicted in the drawing as a cascade of two gammas, the kinematic cone is on average still centered at the same direction and the residual ^{12}C can be detected by the forward detector. If unitary efficiency is reached, i.e. if, being α_2 detected by the backward telescope, the residual ^{12}C after radiative decay falls in the coverage of the forward detector, then $\Gamma_{rad}/\Gamma_{tot}$ can be deduced as the ratio between the α_2-^{12}C coincidence rate and the α_2 rate at the backward telescope. In our experiment, given the low beam intensity and the thin target, the spurious coincidence rate between the two detectors is estimated to be lower than 10^{-6} Hz, allowing to safely neglect spurious coincidences within the events of interest elucidated in the following paragraphs.

In Fig. 2, we report the backward detector energy spectrum obtained considering only particles that are fully stopped by its first detection layer. The black line represents the spectrum optained without further conditions, while the red-filled spectrum is obtained requiring a time-coincident detection at the forward telescope. In the figure, black arrows indicate the energy position of peaks associated with the most frequent reactions taking place in the target. As it is possible to observe, the Hoyle state peak due to the detection of the α_2 ejectile emitted from the ^{14}N(d,α_2) reaction is well visible, and separated by nearby contaminant peaks. A prominent peak is due to the ^{14}N(d,α_1) reaction, where the residual ^{12}C is left in its first excited state (4.44 MeV, 2^+). The latter is crucial for the geometry calibration of the experiment.

As pointed out above, the geometry of the forward telescope should allow to fully contain the ^{12}C emission cone, after radiative decay from the Hoyle state, in coincidence with the α_2 ejectile at the backward telescope. A crucial aspect of the present experiment is therefore the geometrical positioning of the forward telescope. This has been done with the procedure carefully discussed in Ref. [29], and involved the use of the micro-positioning device on which detector was mounted and a rotating plate on which the entire forward detector sat. The movable device allowed to move the detector along the vertical axis with a precision better than 1 μm, with a remote control, while the rotating plate allowed to vary its polar angle with a precision of 0.1°. The combined use of these two systems allowed to experimentally find the center of the ^{12}C emission cone exploiting the ^{12}C-α_1 coincidence from the more frequent ^{14}N(d,α_1) reaction, taking advantage of the unitary radiative branching ratio of the first ^{12}C excited state. These events were selected using the backward energy spectrum of Fig. 2. After the ^{12}C emission cone is determined from ^{12}C-α_1 coincidences, the forward detector is just rotated to the ^{12}C-α_2 coincidence position. Given the two-body nature of these reactions, the tilt angle is uniquely determined.

After we safely reached the unitary coincidence efficiency, data from the backward telescope and coincidence data from both telescopes were recorded. During the entire experiment, the ^{12}C-α_1 coincidence rate was constantly inspected and used as a *standard candle* for monitoring the efficiency. This is possible because the solid angle covered by the forward detector is sufficiently large to catch part of the ^{12}C-α_1 emission cone even when the forward detector is placed in the ^{12}C-α_2 position. In addition, the bidimensional calibration of the coincidence efficiency was repeated every about 24 hours of beam time.

3 Data Analysis and Results

The data analysis was restricted to events in which the energy recorded by the backward detector was in the proximity of the Hoyle state peak of Fig. 2. Coincidence events were obtained by requiring a time-coincidence (usually in a narrow coincidence window of a few nanoseconds) between both detectors. Once the time coincidence is applied to the data, the backward energy spectrum collapses into the red-filled one of Fig. 2. In this spectrum, the background is strongly reduced, and additional peaks, due to other two-body reactions, become visible.

The forward detector coincidence spectrum under the Hoyle peak of Fig. 2 is shown in Fig. 3 with the black circles. This spectrum exhibits a few contributions: a low energy continuum, a broad peak in the energy region expected for the ^{12}C recoil, and other higher energy contributions. The first is fully compatible with α-α_2 coincidence events, in which the recoiling ^{12}C in its Hoyle state undergoes α-emission and one of the three alphas is detected by the forward telescope. The expected contribution of such events is shown by the red line, which is the result of a fully rigorous Monte Carlo simulation performed according to the prescriptions of Ref. [29]. At higher energies, we observe two possible contributions: one compatible with ^{8}Be-α_2 coincidence events, in which two of the

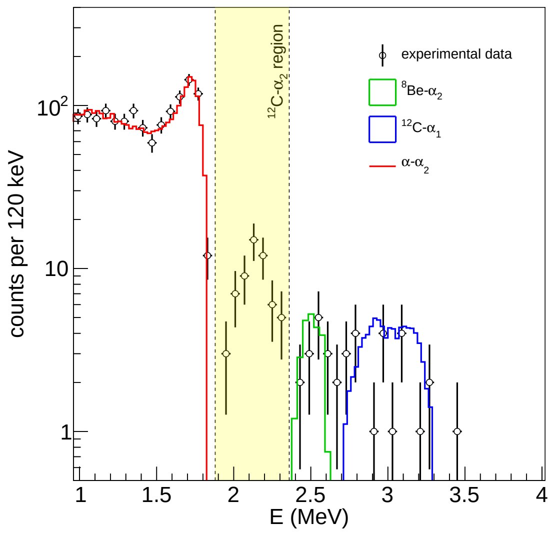

Figure 3. Forward energy spectrum in coincidence with the α_2 region of Fig. 2. The shadowed area highlights the energy region where the ^{12}C-α_2 contribution is expected. Solid lines are the result of Monte Carlo simulations.

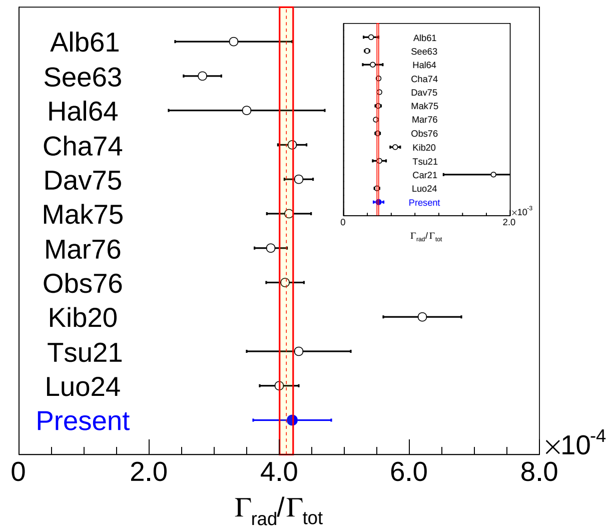

Figure 4. Summary of experimental $\Gamma_{rad}/\Gamma_{tot}$ values published in the literature up to date for the Hoyle state in ^{12}C from particle-coincidence experiments [28] (Luo24), [26] (Tsu21), [21] (Mar76), [20] (Mak75), [19] (Dav75), [18] (Cha74), [17] (Hal64), [16] (See63), and γ-particle coincidence experiments [22] (Kib20), [15] (Obs76), [14] (Alb61). The result of (Car21) [27] ($\Gamma_{2\gamma}/\Gamma_{tot}$ = 1.8 ± 0.6 · 10^{-3}) is shown only in the insert for clarity reasons. The result of Ref. [28] is also affected by a systematic uncertainty of ±0.16 · 10^{-4}, not shown in the figure. The yellow band represents the weighted average of all the values, excluding the values from [16], [22], and [27].

three α emitted by the recoiling Hoyle state fall simultaneously in the forward detector due to the sequential ^{8}Be decay, and the other compatible with ^{12}C-α_1 events, due to the tail of α_1 events under the α_2 peak in Fig. 2. These contributions are well reproduced by Monte Carlo simulations, shown, respectively, with the green and blue lines. In the present case, due to energy loss effects in the target, both such contributions are separated from the region of interest (shadowed area), making it possible to deduce the ^{12}C-α_2 coincidence rate by simply performing an energy cut in the spectrum of Fig. 3. Similar contributions were also previously observed, for example, in Ref. [20].

The ^{12}C-α_2 coincidence rate is finally deduced from the integral of the above mentioned contribution and the integral of the Hoyle peak selected in the spectrum of Fig. 2. In both cases, we subtracted the small background with the procedure discussed in Ref. [29]. In the present experiment, we obtained 125190 α_2 counts tagged by the backward telescope without coincidence and 57 coincidence events. The deduced radiative branching ratio, corrected fo the background, turns out to be $\Gamma_{rad}/\Gamma_{tot}$ = 4.2(6) · 10^{-4}. This value is fully compatible with the recent work of Ref. [28] and with the previous state-of-the-art, as shown in Fig. 4, where we summarize all the experimental $\Gamma_{rad}/\Gamma_{tot}$ values published in the literature so far. The value recently proposed in [22] (6.2(6) · 10^{-4}) is more than 3σ higher the present measurement: we recommend, therefore, to exclude it from the weighted average procedures for the determination of the Hoyle state radiative decay branching ratio. Excluding the outlier values of Refs. [16, 22, 27] from the systematics, the new recommended value for radiative branching ratio of the Hoyle state is finally $\Gamma_{rad}/\Gamma_{tot}$ = 4.11(10) · 10^{-4}.

4 Conclusions and Perspectives

The determination of the radiative decay branching ratio of the Hoyle state in ^{12}C is a fascinating problem that has relevance in nuclear structure and astrophysics. This manuscript describes a novel experiment for its direct experimental determination using advanced high-resolution particle-coincidence techniques, with the aim to contribute resolving the tension generated by *modern* experiments.

We obtain $\Gamma_{rad}/\Gamma_{tot}$ = 4.2(6) · 10^{-4}, which do not support any significant revision of the triple-alpha reaction rate with respect to the state-of-the-art obtained in elder experiments. Clarifying the tension on the $\Gamma_{rad}/\Gamma_{tot}$ determination has deep implication in astrophysics: a modification of the rate of the triple-alpha process has been in fact proposed as one of the possible solutions to the problem of the pair-instability mass gap for black holes, which was raised by recent gravitational waves observations. The present findings suggest that a possible solution to the puzzle on the pair-instability gap boundaries should be explored *outside* the nuclear structure domain.

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