A new high-precision upper limit of direct α-decays from the Hoyle state in ^{12}C

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Abstract. The Hoyle state in ^{12}C ($E_x = 7.654$MeV) is characterized by a pronounced 3α cluster configuration. It is involved in the so-called 3α process in stars, that is responsible of ^{12}C nucleosynthesis. We studied the decay path of the Hoyle state by using the ^{14}N(d, α_2)^{12}C(7.654) reaction at 10.5MeV incident energy. 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. A new upper limit of such a decay width is placed at 0.043% (95% C.L.). Astrophysical 3α process reaction rate calculations have to be consequently revised.

1 Introduction

The origin of elements in our universe, as well as the evolution of stars, reflect the properties of nuclei which are involved in the reactions taking place in stellar environments [1]. Studying nuclear reactions at low energy is therefore important to understand how and to what extent elements are produced in stars [2–5]. A particularly remarkable case is the 3α process, which occurs during the helium burning stage of stellar evolution. This process is responsible of the creation of one of the major constituent of the universe and human being: the carbon. The 3α process proceed with the initial fusion of two α particles into the ^{8}Be, followed by the radiative capture of a third α, α+^{8}Be→^{12}C+γ [6, 7]. Anyway, the lifetime of the intermediate ^{8}Be, formed in the initial fusion, is extremely short ($\tau \approx 10^{-16} s$) and the corresponding reaction rate is therefore limited by the almost instantaneous decay of the unbound

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^{8}Be. To explain the ratio of carbon and oxygen abundances observed in our universe, which amounts at about 0.6 [8]), Fred Hoyle formulated in 1953 an interesting hypothesis: the radiative capture of the third α takes place via a resonant process through a $J^\pi = 0^+$ state of ^{12}C [9, 10]. This state should be close to the α-threshold of ^{12}C in a way to introduce a strong enhancement in the reaction cross section. The existence of this state was then confirmed, a few years later, by Cook and collaborators [11], lying at an excitation energy of 7.654MeV, and it is now named as the *Hoyle state* of ^{12}C [12]. The amount of carbon produced in such a process so depend on the competition between the Hoyle state radiative decays and the α-ones. This can be calculated, for an environment of temperature higher than 10^8 K, as follows [12]:

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

where E_R is the resonance energy of the Hoyle state, 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 reaction rate of the 3α process is therefore strongly affected by the decay properties of the Hoyle state [13]. However, while for star temperatures greater than 10^8 K it is dominated by the *sequential* (resonant) process through the ground state of ^{8}Be, for lower temperatures another mechanism plays a role in the reaction rate determination: the so-called *direct* (non-resonant) process, where the formation of the Hoyle state happens by-passing the ^{8}Be ground state level. While the first process is affected by the *sequential decay* (SD) width of the Hoyle state, the second one is determined by the *direct decay* (DD) one. As an example, for a temperature of $T = 0.02$GK the 3α reaction rate associated to the direct process is found to be 7-20 orders of magnitude greater than the one calculated via a resonant process [14, 15].

Recently, a quite large number of experiments have been performed in order to measure the DD width of the Hoyle state [16–21]. Anyway, the picture resulting from these experiments is quite complicated, see Ref. [21], and no definitive conclusions can be drawn regarding the possible existence of a non-vanishing DD width.

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.

2 Experimental results

The experiment was performed at the INFN-Laboratori Nazionali del Sud (LNS) of Catania, Italy. A 10.5 MeV deuteron beam was delivered to the scattering chamber on a $C_3N_6H_6$ (40 μg/cm^2) composite target, deposed on a C backing ($\approx$ 10 μg/cm^2). To produce ^{12}C*(Hoyle) we used the ^{14}N(d,α) reaction. A ΔE-E silicon telescope is placed at an angle $\theta_{lab} = 125°$ to detect the ejectiles from the reaction of interest. A strong reduction of the background due to contaminant reactions is achieved by using the anti-coincidence telescope technique, as described in Ref. [22], where a detailed sketch of the present experimental apparatus is presented. By measuring energy and directions of the α ejectiles we are able to detect the recoiling direction of the emitted ^{12}C residuals and their excitation energy. A ^{12}C excitation energy spectrum obtained from the anti-coincidence spectrum measured in the backward telescope is shown in figure 1 (black spectrum). States populated in ^{12}C are indicated by labels. A peak corresponding to the energy of the Hoyle state is clearly observed. It can be used to tag the recoiling ^{12}C*(Hoyle). In kinematical coincidence with these recoils we placed a hodoscope of 64 silicon independent cells [23], in order to detect the three-body disintegration of the produced and

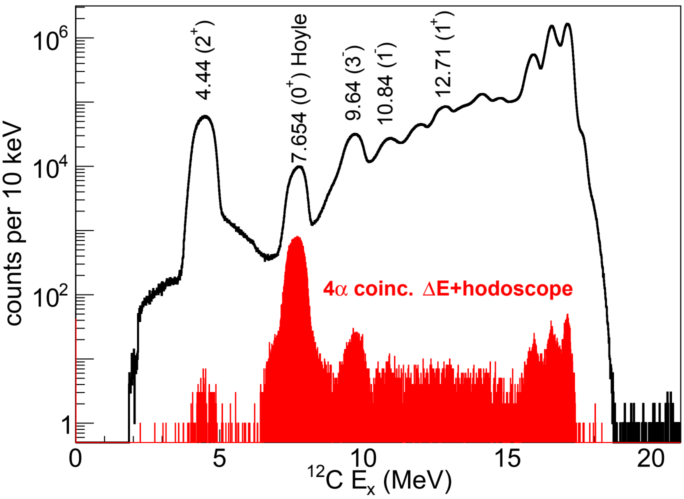

Figure 1. ^{12}C excitation energy spectrum obtained from the single-particle spectrum measured by the ΔE-E anti-telescope (black spectrum). It collapses into the filled one by including only 4-particles fully reconstructed events

tagged $^{12}C^{\star}$(Hoyle). Such an apparatus is extremely sensitive to the disintegration of the Hoyle state. Indeed, if one requires that 3 particle are detected in the hodoscope in coincidence with the backward detected ejectile, the spectrum collapses into the filled one of figure 1. Here contributions due to ^{12}C states different from the Hoyle state are almost totally suppressed, while the peak associated to the Hoyle state is prominent.

Invariant mass reconstruction (see for example [24, 25]) of the 3α particles detected by the hodoscope allow to study the decay pattern of the Hoyle state. The total energy of the Hoyle state decay is normally shared among the three α-particles. If one calls with E_1, E_2 amd E_3 these values, so the normalized energy of the decay are defined as $\varepsilon_{1,2,3} = E_{1,2,3}/(E_1 + E_2 + E_3)$. It is obvious that $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 1$. In the case of a sequential decay, the first α particle is emitted with the maximum energy in the center of mass. In other words, as discussed more in detail for example in [19, 21], in order for the total momentum to be conserved, the first α-particle should bring an amount of kinetic energy almost equal to the half of the total energy of the $^{12}C^{\star} \rightarrow 3\alpha$ decay. Indicating with i the first emitted α-particle, one should observe $\epsilon_i \approx 0.5$ for a SD, while any value from 0.33 to 0.67 is possible, according to the available phase space, in the presence of a DD.

Figure 2 shows the experimental distribution of ε_i, i.e. the largest normalized energy in the decay, obtained in the present experiment. A peak is present at around 0.5 which represents events associated to a SD. A dashed line is the result of a detailed simulation of the experiment which assumed a full SD path of the Hoyle state. Only a few events fall outside of the SD region, and they are not reproduced by our simulation. By using the Feldman and Cousin's method for evaluating small signal in the presence of small background, we are able to indicate that such amount of counts is statistically non-significant. The corresponding upper limit of DD is placed at 0.043% with a confidence limit (C.L.) of 95%.

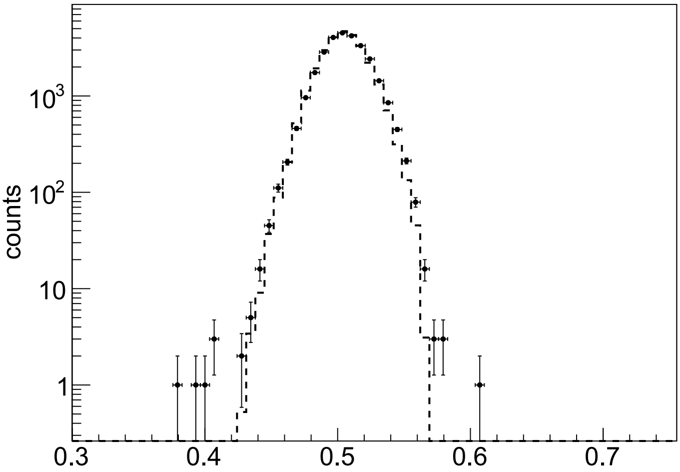

Figure 2. Distribution of the largest normalized energy ε_i in the decays of the Hoyle state. They are obtained by means of invariant mass technique on experimental Hoyle state decay data measured in the hodoscope.

3 Conclusions

We have measured the DD of the Hoyle state in ^{12}C by means of a high-precision experiment. We used the ^{14}N(d, α_2)^{12}C(7.654) reaction at 10.5MeV incident energy to tag ^{12}C nuclei, whose decay is studied via invariant mass techniques of the 3α decay. To measure the three particles of the decay we used a hodoscope of 64 silicon independent cells, thus avoiding background typical of the use of a single strip detectors. We do not evidence any DD contribution, placing a upper limit for direct decay branches of the Hoyle state of 0.043% (95% C.L.). This result, recently published in [26], has a precision of about a factor 5 better than any other previous investigation. An analogous result has been also obtained by a very recent experiment performed by the group of Birmingham [27].

In the next future, an experiment will be performed by the CHIMERA group of LNS to increase the precision in the knowledge of the γ decay width of the Hoyle state. The experiment will benefit of the coupling of a large acceptance detector [28] and a high-granularity array [29]. A more accurate knowledge of the radiative decay width of the Hoyle state, together with the present improved limit of the DD width will help in better understanding the structure of the Hoyle state and the rate of the 3α process in low temperature stars.

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