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Investigation of the Hoyle state in ^{12}C with a new hodoscope detector

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Abstract. The 0_2^+ state in ^{12}C (7.654MeV, the Hoyle state) is important for the understanding of clustering phenomena in nuclei. The pronounced cluster nature of this state allows the triple-α process in stars with a reaction rate regulated by its structure properties. To precisely estimate the direct component in the 3α decay mechanism of the Hoyle state, we developed a new experiment using the ^{14}N(d,α)^{12}C reaction at 10.5MeV. An anti-coincidence telescope was used to identify the α ejectiles leading the residual ^{12}C in the Hoyle state, while its decays in 3α were studied by means of a new hodoscope of silicon detectors, superOSCAR, placed in kinematical coincidence to fully reconstruct the events. Details of the experiment and preliminary results are discussed in the text.

1. Introduction

Carbon isotopes represent a unique opportunity to characterize the properties of clustering phenomena as a function of their neutron-richness [1–9]. Indeed, several excited states based on molecular chains of α particles can be predicted in carbon neutron-rich isotopes starting from the assumption of a pronounced cluster nature for the Hoyle state in ^{12}C [10, 11].

The Hoyle state (7.654MeV, 0^+) is a well known cluster state of the self-conjugated ^{12}C isotope. Its pronounced cluster nature plays a fundamental role in Astrophysics, where it is involved in the so-called 3α process. This stellar process, which occurs in the helium-burning stage, regulates the nucleo-synthesis of carbon and heavier elements in the Universe. In 1952, it was indeed proposed by Salpeter [12] and Opik [13] that the synthesis of carbon in the red giant stars would proceed in a two-steps process, with the non-resonant radiative capture of an α particle by the unbound ground state of ^{8}Be, produced in a previous α-α fusion reaction. Anyway, the short life time of ^{8}Be ($\approx 10^{-16}s$) limited the reaction rate of this process, making not possible to explain the amount of carbon and heavier elements present in the Universe. In 1953, Hoyle suggested that the presence of an s-wave resonance in the α+^{8}Be capture process, close to the corresponding separation energy, would increase the reaction rate of the production of ^{12}C [14], introducing what we now know as the *Hoyle state*. The structure of the Hoyle state is quite unusual and represents one of the most important unanswered questions in Nuclear Physics. Inelastic scattering experiments have pointed out a relatively large radius or this state, compared to the ground state of ^{12}C [15]. On a theoretical point of view, different hypothesis were formulated. As an example, while microscopic cluster model calculations describe the Hoyle state as a gas-like diluted structure [16], it appears as a bent-arm structure from *ab initio* calculations [17, 18] and a possible linear chain configuration was also predicted [15, 16]. All these properties are crucial in the determination of the 3α reaction rate, since it is strongly related to the corresponding decay partial widths.

The 3α reaction rate can be calculated by knowing the radiative and α decay widths of the Hoyle state. Radiative decay branching ratios are known to be a small amount of the total width ($\Gamma_{rad}/\Gamma = 4.12(11) \times 10^{-4}$ [19]), while, in good approximation, it is considered $\Gamma \approx \Gamma_{\alpha_0}$, where Γ_{α_0} represents the decay through α+^{8}Be (sequential decay), without contribution due to the corresponding direct decay in 3α ($\Gamma_{3\alpha}$). This assumption is well supported by [20], where an upper limit of $\Gamma_{3\alpha}/\Gamma < 4\%$ was given. Anyway, in recent times, after the results of Raduta et al. [21], that suggested a significantly larger value of this decay width ($\Gamma_{3\alpha}/\Gamma = 17.0\% \pm 5.0\%$), a number of high precision experiments were performed. All these experiments contradict the results of [21], but are not able to converge on a definitive conclusion. More in detail, while Kirsebom et al. [22] and Itoh et al. [23] do not evidence any direct component in the decay of Hoyle state, giving, respectively, the two upper limits $\Gamma_{3\alpha}/\Gamma < 0.5\%$ (C.L. 0.95) and $\Gamma_{3\alpha}/\Gamma < 0.2\%$ (C.L. 0.95), Rana et al. [24] and Morelli et al. [25] estimated a non-zero value of this branch ($\Gamma_{3\alpha}/\Gamma = 0.91\% \pm 0.14\%$ and $\Gamma_{3\alpha}/\Gamma = 1.1\% \pm 0.4\%$). The possible existence of a direct component in the 3α decay of Hoyle would result in a sizable modification of the triple-alpha reaction rate, especially in low temperature regions ($T_9 < 0.1$) of red giant stars, where the s-wave 2-step process does not dominate and possible direct processes could occur, increasing, as a consequence, the expected reaction rate [26, 27].

We report preliminary results on a new measurement of the 3α decay of the Hoyle state. We used the ^{14}N(d,α)^{12}C reaction at 10.5MeV with a backward anti-coincidence telescope, as discussed in [28], placed at $\theta_{lab} = 125°$, to identify α particles from the (d,α_2) reaction. The corresponding recoil is thus a ^{12}C excited in the Hoyle state, whose decay into 3α is studied with a new hodoscope of silicon detectors, superOSCAR. This paper is organized as follows: in the Section 2 details of the experiment are discussed, the Section 3 is dedicated to a preliminary description of the data analysis, while conclusions and future perspectives will be discussed in the Section 4.

2. Experimental details: the HOYLE experiment

The HOYLE (Hodoscope Oriented Yield Loader Experiment) experiment at INFN-Laboratori Nazionali del Sud (LNS, Catania, Italy) was developed with the aim of shedding light on the direct decay of the Hoyle state with large statistics and low background levels. The basic idea of this experiment is to use of the ^{14}N(d,α)^{12}C reaction to produce carbon recoils excited in the Hoyle state, and to fully reconstruct the 3α decays using an hodoscope of silicon detectors, superOSCAR. A 10.5MeV deuteron beam was provided by the 15MV tandem accelerator of the INFN-LNS with intensities not exceeding 4enA to avoid spurious coincidences. Deuterons induced reactions on a melamine target (40μg/cm^2, $C_3H_6N_6$) deposited on a carbon backing (10μg/cm^2). We used an anti-coincidence backward telescope to give the trigger for the

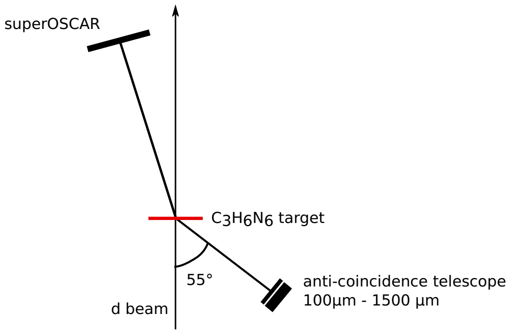

Figure 1. A scheme of the experimental device used in the HOYLE experiment. The anti-coincidence telescope is placed at 125° respect to the beam axis, while the superOSCAR hodoscope is at forward angles (≈ 30°).

experiment. The logic was the same as seen in [28]: a first stage is dimensioned to stop the α particles from the (d,α) groups, while the more energetic elastic deuterons and protons from (d,p) reactions, which appear as contaminants in the spectrum, punch through the first stage and give signal in the second stage. These particles can be removed from the trigger by using a fast anti-coincidence circuit between signals from the first and second stage. In other words, the anti-telescope gives a trigger to the experiment only if a particle is detected in the first stage without any signal in the second stage. With this technique it is possible to strongly reduce the contribution of contaminants to the experiment trigger. The used telescope detector is a two stages silicon 100μm-1500μm detector as indicated in Figure 1. The superOSCAR hodoscope is placed in kinematical coincidence with the center at 30° respect to the beam axis. It is constituted by 64 independent silicon pads (300μm thick), with energy resolutions of the order of 0.3% and active area of 1cm × 1cm, placed in 8 × 8 configuration. They are connected, with short SCI-SCI cables, to 4 pre-amplifier NPA-16FE, manufactured by the NeT Instruments and then to 4×16 channels NIM amplifiers. The advantage of using hodoscope detectors is that they provide better energy resolution than strip detectors and that they avoid the problem of tracks identification typical of the use of strips, as discussed in [23]. With this features we expect to strongly reduce the background level observed in previous works, where strips are used.

The energy released by the detected particles in the first stage of the backward telescope, which gives the trigger to the experiment, can be used in order to tag the excitation energy of the corresponding recoiling nucleus. The energy spectrum taken at 125° is reported with the blue line in the Figure 2, using a logarithmic scale. Peaks are well visible and they correspond to excited states populated in the ^{12}C residual nucleus or to deuteron-induced reactions on contaminants. The three high energy peaks correspond, respectively, to α particles leading the ^{12}C in the 9.63MeV, 7.654MeV and 4.44MeV excitation energy states. A continuous background is present under the identified peaks. Interestingly, by selecting only events for which we are able to reconstruct three particles inside superOSCAR, the blue spectrum becomes the green filled one (of Figure 2). This spectrum has a reduced statistics compared to the single particle spectrum, because of the geometrical efficiency of superOSCAR in the reconstruction of three particles, but the background results strongly reduced and almost vanishing in correspondence to the tails of the Hoyle peak. The green spectrum represents the backward spectrum obtained in case of fully reconstructed events, and, therefore, can be used to identify the class of events for which we will perform the analysis. In the following, only fully reconstructed events under the Hoyle peak of Figure 2 will be considered.

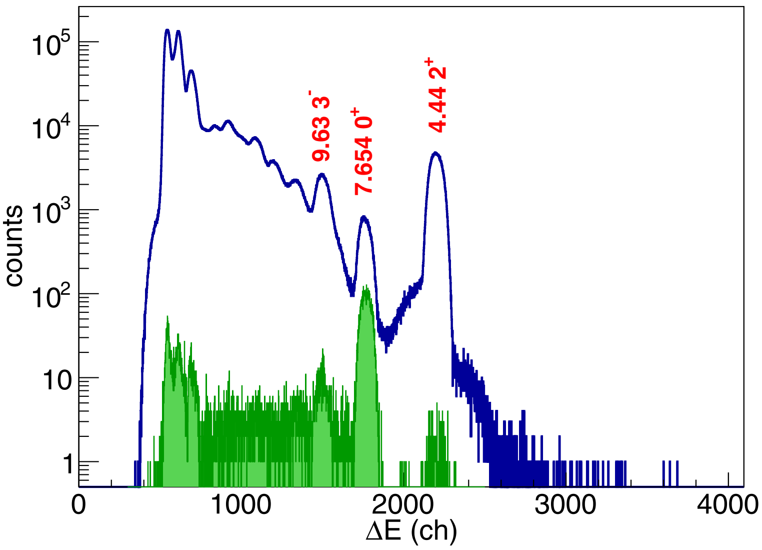

Figure 2. (Blue spectrum) Energy spectrum of particles detected with the anti-telescope technique at $\theta_{lab} = 125°$. States of the recoiling carbon close to the one of our interest are indicated by labels. (Green spectrum) energy spectrum obtained for fully reconstructed events. Only a part of the statistics was used to produce this Figure.

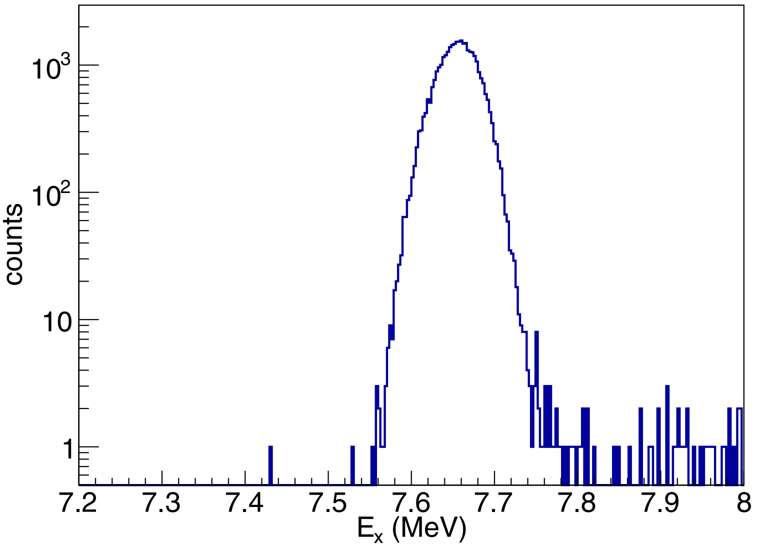

Figure 3. Invariant mass ^{12}C spectrum (E_x) obtained using fully reconstructed events, as shown in the Figure 2, and by selecting the Hoyle peak. A cut on the peak observed in the Q-value spectrum has been also done close to the Q_{gggg}.

3. Preliminary analysis

As a preliminary analysis, we will comment here on the possibility of correctly reconstruct the decay in 3α with our apparatus. After selecting the fully reconstructed events from the anti-

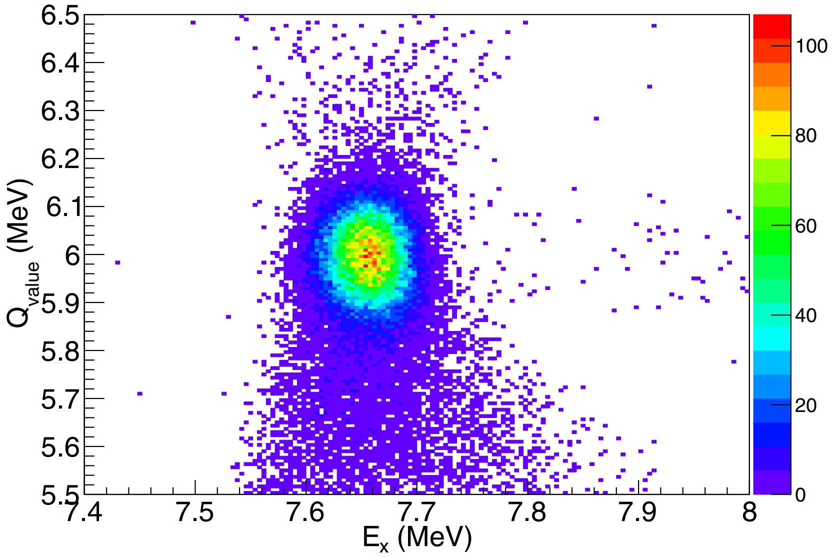

Figure 4. Bi-dimensional plot Q-value vs E_x. A peak is well visible indicating events in which both Q-value and invariant mass are well reconstructed.

coincidence telescope, we can proceed with the analysis of the 4 particles detected. A further improvement to the spectrum of Figure 2, and to the analysis itself, can be indeed obtained by analysing the detected particles in terms of Q-value and *invariant mass*. An inspection on the Q-value is the first step of the analysis, since it can be reconstructed without assumptions on the flight directions of the particles, using only kinetic energies. As expected, we find a prominent peak corresponding to the Q_{gggg} value, indicating the events correctly reconstructed. A simple selection on the Q-value spectrum allows to obtain, using the invariant mass technique on the 3α detected at forward angles, the excitation energy spectrum of the emitting ^{12}C, shown in Figure 3. The result is extremely satisfactory, the good energy resolution and angular segmentation of the superOSCAR device allow to reconstruct a narrow excitation energy peak ($FWHM \approx 50$keV) centered at 7.654MeV with a precision of 1keV. Furthermore, a very low background level is present under the peak, as testified by the right and left tails of the peak.

An improvement of the *fully reconstructed* class of events is finally possible by simultaneously selecting on Q-value and *invariant mass*. This is possible by using the bi-dimensional plot of Figure 4, where the reconstructed Q-value is plotted versus the excitation energy (Figure 3). The presence of a peak, with a low background level (see the color scale) allows to improve the selection by using circular cuts.

4. Conclusions and Perspectives

In conclusion, strong efforts were devoted to a precise measurement of the direct decay branching ratio of the Hoyle state in ^{12}C. We developed a new experiment at INFN-LNS by using the ^{14}N(d,α)^{12}C at 10.5MeV. A backward angle telescope detector was used to provide identification of the (d,α_2) contribution, strongly suppressing the background due to contaminant reactions by means of the anti-coincidence technique. We have shown that the corresponding decays in 3α of the Hoyle state can be precisely, and with a negligible background, reconstructed with the superOSCAR device. With the high resolution and unambiguous track identification of this device, we expect to give very soon further results in the resolution of such a complicated problem.

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