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The γ decay of the Hoyle and higher excitation energy states of ^{12}C

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Abstract. The 0_2^+ Hoyle state and few other excited levels of ^{12}C are fundamental for the production of carbon in the universe. In particular, the γ decay branching ratio is of utmost importance, being the only way to produce a carbon at the ground state. For the purpose to precisely investigate the decay mechanism of such states we conducted an experiment, at Laboratori Nazionali del Sud-Istituto Nazionale di Fisica Nucleare (INFN-LNS), using the reaction α + ^{12}C at 64 MeV. We used the 4π CHIMERA detector to detect both α and γ ^{12}C decay channels. Details of the experiment and preliminary results are discussed in the paper.

1. Introduction

The synthesis of ^{12}C is a key in the origins of organic life. The carbon synthesis occurs in the He-burning phase through the well-known triple α-process. Such a process proceeds via the initial fusion of two α particles to form ^{8}Be, the second step is the fusion with a third α particle to form ^{12}C*. However, ^{8}Be has a very short lifetime against α decay, implying that it would almost always break up rather than become the seed for carbon. Fred Hoyle suggested the presence of an excited state at an energy close to the α+^{8}Be emission threshold, in order to account for the absolute abundance of ^{12}C [1–3]. Several measurements confirmed the presence of such a resonant state, providing a value for the energy state of 7.653 $\pm$ 0.008 MeV, and indicating the most probable spin and parity to be $J_\pi = 0^+$ [4, 5].

The energy and width of the Hoyle state are among the key parameters needed for a precise determination of the reaction rate of the astrophysical 3α-reaction, the small radiative width can be indeed considered as the main responsible of ^{12}C production in stars. Moreover, the Hoyle state potentially has a cluster structure, which links to the nature of strong interaction [1,6,7]. In such a context the investigation of the Hoyle state becomes a touchstone for nuclear astrophysics, nuclear structure, and nuclear forces.

The open decay channels of the Hoyle state are the 3α-decay and the electromagnetic decay. The latter occurs through the 4.44 MeV level, with emission of two cascade γ-rays of 3.21 MeV and 4.44 MeV, together with π decay via the emission of a pair e^+e^- [8]. The most commonly adopted strategy is to explore how the Hoyle state decays via 3α emission [1, 6]. However, the total radiative width is fundamental in astrophysics, which width is determined via measurements of the total radiative branching ratio (Γ_{rad}/Γ), and the pair-decay branching ratio (Γ_π/Γ). The Γ_π has been recently investigated in ref. [8], with a re-analysis of previous inelastic electron scattering data, and a low-energy measurement performed at S-DALINAC, providing a value of 62.3 $\pm$ 2.0 μeV. The total radiative width of such level was instead studied in a series of works, following the one of ref. [9], establishing the technique of measuring recoiling carbon in kinematic coincidence with scattered projectile. A recommended value for Γ_{rad}/Γ of 4.12 $\pm$ 0.11 10^{-4} was suggested in ref. [10] based on an average of previous investigations [9, 11, 12], also including direct measurements of the coincidence of two γ-decay as in ref. [13].

In more explosive environments, like in supernova, when the temperature is in the range of 10^9 K, also higher excited levels can be involved in the production of ^{12}C, e.g., the 3^- at 9.64 MeV. Chamberlin et al. [14] attempted to measure the total radiative width of this level providing an upper limit of 14 meV for Γ_{rad} and $\Gamma_{rad}/\Gamma < 4.1 \times 10^{-7}$.

This kind of measurements is rather complex. For instance, in the case of direct measurements of γ-decay one must take into account also the angular correlation effects to correctly evaluate the efficiency, because of the multi-polarity decay.

2. Experiment

In this framework the basic goal of our experiment was to detect α particles, recoiling ^{12}C and γ-rays in order to estimate in an accurate way the width of the Hoyle and 9.64 MeV level, also aiming to advance the understanding of the elements production in the universe.

A 64 MeV α beam was provided by the Superconducting Cyclotron (SC) of the INFN-LNS (Catania). We used the 4π CHIMERA multidetector [15] to detect scattered α particles, the ^{12}C recoils and also the emitted γ-rays.

A multicoincidence technique analysis has been developed in order to obtain a very high rejection of the background, necessary to measure the rare γ-decays of these states [16, 17]. The CHIMERA multidetector (Fig. 1) includes 1192 telescopes, each of them consisting of a silicon detector followed by a CsI(Tl). CHIMERA is divided into two main parts: the forward part, made of 688 telescopes, and covering the θ angles from 1° to 30°, and the backward part, with 504 telescopes covering the angles from 30° to 176°. The backward part telescopes form a sphere around the target, with a radius of 40 cm. In order to detect the γ-rays, we used the CsI(Tl) stage of the CHIMERA multidetector sphere, employing the pulse shape discrimination method for the γ-rays identification. The complete angular coverage also allows for a large efficiency in the detection of kinematic coincidences, with automatic corrections for possible beam misalignments [18, 19]. The measurement was the first one in which we used the digital GET electronics for all detectors in the sphere [20]. However, due to the γ-resolution of the CHIMERA scintillators at low energy, the discrimination of the full energy peak against the first and second escape peaks was not achieved. As an example, the 4.44 MeV energy is peaked at around 4 MeV (energy of the first escape peak).

We employed the kinematic coincidences, with the goal to see the loci of excited levels, counting

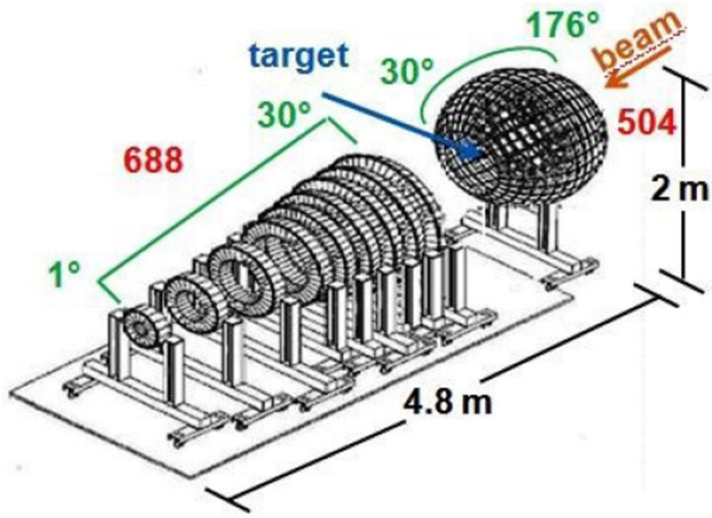

Figure 1. Scheme of the CHIMERA multidetector .

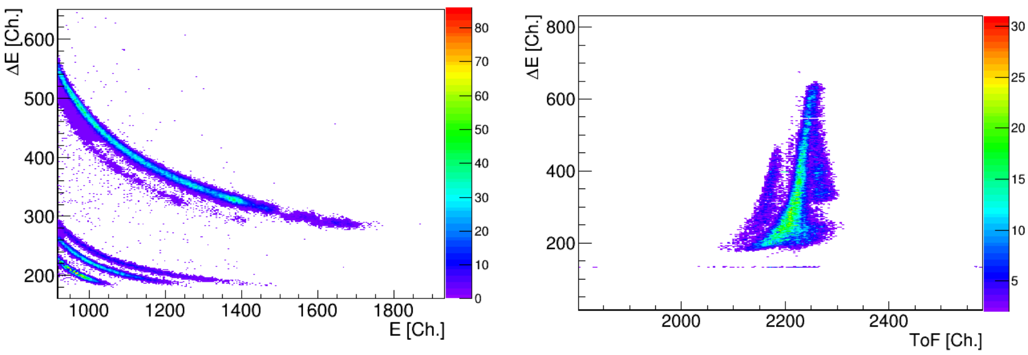

Figure 2. ΔE-E plot for a telescope of CHIMERA multidetector. α and ^{3}He particles are seen at the top while the three regions at the bottom correspond to protons, deuterons and tritons particles (left). ΔE-ToF plot for a telescope of the CHIMERA multidetector, the line corresponding to ^{12}C is clearly visible (right).

the events in which γ-rays are emitted, and to clean the scatter plot from spurious coincidences. Such kinematic coincidences allow to decrease the background contribution. We included in the event selection the identification of α-^{12}C particles coincidences, by ΔE-E and Time of Flight (ToF) methods, corresponding to well defined kinematic constraints. Fig. 2 (left) shows a ΔE-E plot for $\theta \approx 23°$, in this figure the lines of α, ^{3}He, protons, deuterons, tritons particles are clearly visible. We also identified carbon using the ToF method, assuming as a reference time the radio-frequency of the superconducting cyclotron. An example of ΔE-ToF for $\theta \approx 58°$ identification plot is given in Fig. 2 (right).

Having the calibration and identification of all detectors, we considered the kinematic coincidence (Fig. 3 (left)) of couples of calibrated detectors. In Fig. 3 (left) we show a kinematic plot in which the ground state and the first excited 4.44 MeV level are evident. However, to

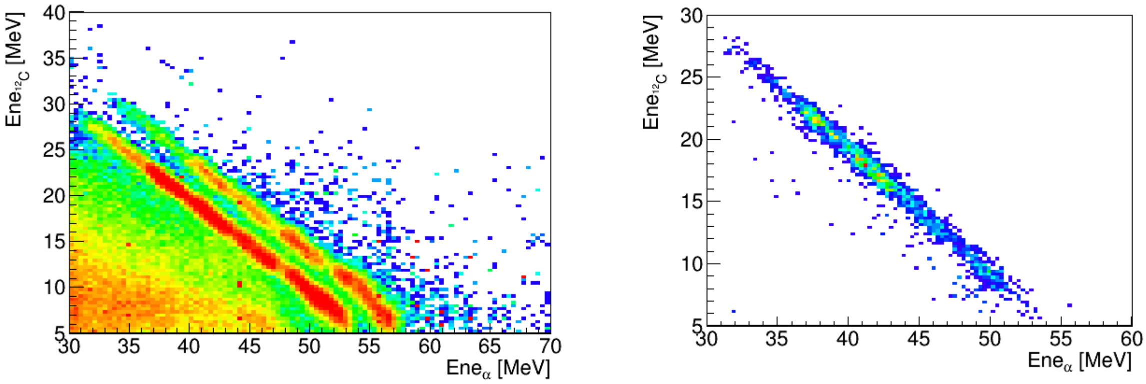

Figure 3. Example of kinematic coincidences of α particles and ^{12}C recoils. The ground state and the 4.44 MeV level can be seen (left). Kinematic plot of α particles and ^{12}C in coincidence with two γ-rays, some spurious coincidences of the 4.44 level are still present (right).

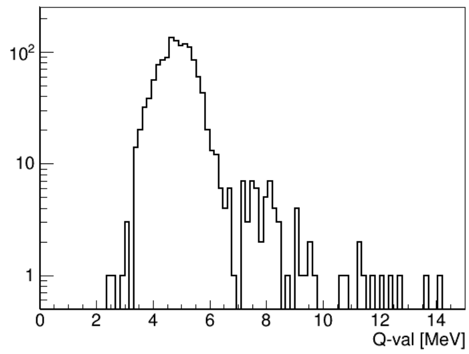

Figure 4. Q-value for the reaction α + ^{12}C, in the figure we see the Q-value for the 4.44 MeV level and the corresponding region for the Hoyle state.

underline the presence of the Hoyle state we have to consider the coincidence with γ-rays detected using the CHIMERA sphere as shown in Fig. 3 (right).
We reconstructed also the Q-value for such events, shown in Fig. 4. In this figure we can observe the region of the Hoyle state, and also spurious coincidences of the 4.44 level are still present. While, we do not have a large statistics in the region of the 9.64 MeV.

3. Conclusion

We have studied the Hoyle state decay in ^{12}C simultaneously detecting the α particles, ^{12}C recoils and γ-rays. The preliminary results give us the confidence on the possibility to produce useful results. However, the data analysis is still in progress. In particular, we are performing simulations to precisely estimate the efficiency. Moreover, we will also be able to detect and to identify the 3α decay of the excited levels, measuring at the same time both decay channels, and thus providing a more reliable information on the branching ratio.

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