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Abstract

The γ-decays of ^{12}C excited levels (the Hoyle state 0^+ at 7.65 MeV and the 9.64 MeV 3^-) are essential for its production in the universe. We present here a new attempt to precisely measure such γ-decay probabilities. The measurement was performed at INFN-LNS in Catania using the 4π CHIMERA multidetector. In order to measure these low probability decay-channels we performed 4-fold coincidence measurements. The ^{12}C target nuclei were excited by using a beam of 64 MeV α-particles produced by the Superconducting Cyclotron (CS) of INFN-LNS. The scattered α-particles and the ^{12}C recoils were detected and identified by ΔE-E and ToF methods using CHIMERA telescopes. The two emitted γ-rays in the decay chain were detected and identified by using the second stage of the telescopes, CsI(Tl) scintillators, by means of fast-slow and rise time techniques. Kinematics and energy-momentum conservation laws were used to constrain the data analysis. Also the 3-α decay channel probability was measured. Such a simultaneous measurement of all known decay channels was useful to reduce the systematic errors. Preliminary results of the data analysis are reported.

Keywords: Hoyle state, gamma decay, redundant kinematics

1. Introduction

The well-studied 3-α process is the main source of ^{12}C production in the universe [1,2]. The presence of the Hoyle level at 7.65 MeV excitation energy [3], very close to the threshold for 3-α decay of ^{12}C, enhances the reaction cross section between ^{8}Be and α-particles for instance in the alpha core of Red Giant stars [1] or in the alpha shell of AGB stars [2] and in various others some time explosives scenarios. In such environments two α-particles can have enough energy to interact generating a ^{8}Be. Due to the density of α-particles there is the possibility that, before its decay, ^{8}Be further reacts with a third α-particle generating the excited ^{12}C*. The most probable event, after the generation of this excited Carbon, is its decay through the emission of a new α-particle and a ^{8}Be. This game can continue for a long time; in fact, only in approximately one event over 2500 [4,5] the Hoyle state decays by emitting a first γ-ray to the 4.44 MeV 2^+ ^{12}C excited level, and a second one to the ground state 0^+. It is only after this γ-cascade that a stable carbon nucleus is formed so that we have the seed for the synthesis of heavier elements. If the α-particle energy is higher, other ^{12}C excited levels can come into play, as taken into account in some rate evaluations of the previous century [6,7]. In particular, the 9.64 MeV (3^-) could be excited or the 2^+ level recently observed around 10.3 MeV, that is assumed to be the second level of the rotational band based on the Hoyle state [5,8]. Again, to generate a stable carbon the excited level must decay by emitting γ-rays. However, up to now the γ-ray decay probabilities of such high excitation levels are not well known. Due to ^{13}C background only an upper limit $\Gamma_\gamma/\Gamma \leq 4.1 \times 10^{-7}$ is being available for the 9.64 MeV level [9]. The method used to extract the Γ_γ/Γ value in ref. [9] consisted in measuring, in coincidence with scattered beam particles, the ^{12}C produced in the reaction, following the idea that γ-decay produces a stable carbon. In this work we present some preliminary results obtained with a method which we call Complete Redundant Measurement (CRM) described in some details in the following sections. Other measurements with the use of magnetic spectrometers and pure ice hydrogen target are on-going in Japan [10].

2. Preliminary experimental results

The experiment was performed at INFN LNS using an α-particle beam of 64 MeV produced by the Superconducting Cyclotron of the Laboratory. A natural carbon target was used for the test in order to verify the validity of the CRM method to extract information about the γ-decay of the Hoyle state and nearest ^{12}C levels. The method consists in the complete detection of all particles and γ-rays. The multiple coincidence automatically suppresses the background. This suppression is enhanced by including constraints from kinematics and energy-momentum conservation rules. The method was described in previous conferences [11,12], here we show the results of the first test experiment.

The method is ideal for the use with CHIMERA detector at LNS [13]. CHIMERA is in fact a 4π detector in which kinematical coincidences have naturally an efficiency close to 100% for charged particles thanks to its full angular coverage. Moreover, it was recently shown its ability to detect and identify γ-rays [14] especially useful in rare decay modes [15]. Part of the cleaning effect of the kinematical coincidence between two particles (in this case the scattered α-particle and the recoiling ^{12}C) is given by requiring the detection of two particles in coincidence from the two opposite sides of the reaction planes at Δϕ=180°. Obviously, also the identification of the two particles is very important. For most of carbon ions, detected in the spherical part

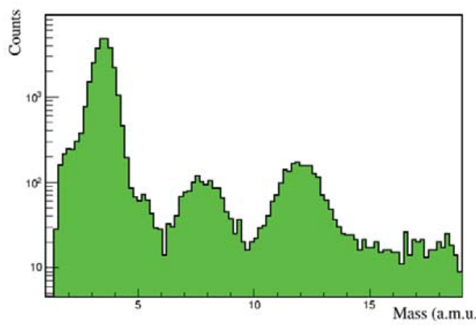

Fig. 1 Mass spectrum evaluated for the particles stopped in the silicon stage of a CHIMERA detector of the sphere.

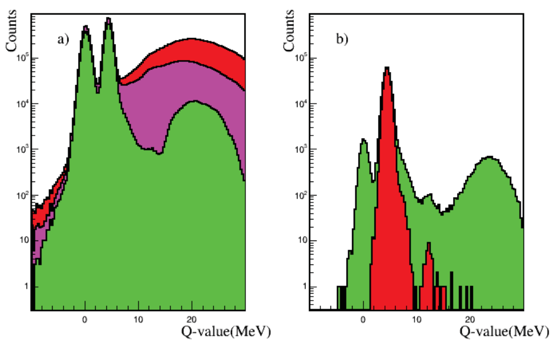

Fig. 2 Q-value spectra obtained in the data analysis inserting different conditions (see text).

of CHIMERA with a distance target-detector of only 40 cm, we do not have mass-by-mass identification. However, the mass

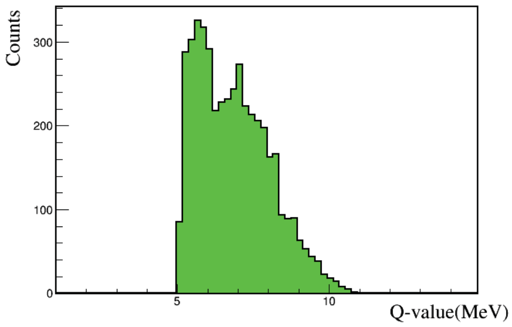

Fig. 3 Q-value spectrum obtained selecting the difference between the measured Q-value and the total detected γ-ray energy measured equal to the missing γ-ray in one gamma coincidence events

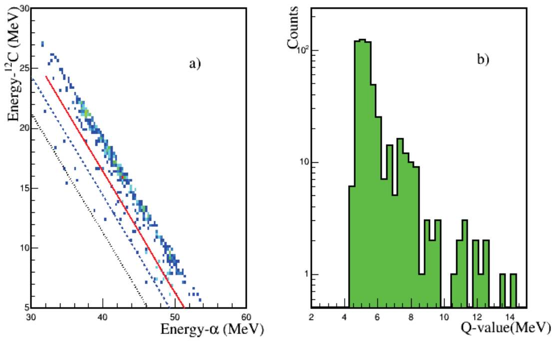

Fig. 4 a) Lines show kinematic loci expected for some levels of ^{12}C. Data show the energy of the two detected particles (^{12}C and α) in two γ-ray coincidence events; b) Q-value plot obtained for the same events

spectrum reported in fig.1 shows a resolution sufficient to have a clean separation of α-particles from carbon and ^{8}Be events (two α-particles detected in the same detector). In order to show the effect of the various cuts that can be applied to clean data from background, in the two panels of fig.2 we show the Q-value spectra measured assuming different conditions. The Q-value is obtained subtracting the total energy measured for the two detected particles from the available beam energy. In detail, in panel a) we show the Q-value spectrum obtained requiring a simple coincidence between an α-particle from the beam, identified in charge and mass using ΔE-E method, and another particle (red spectrum). The two prominent peaks relative to the ground state and 4.44 MeV level population can be observed but at higher energy this simple coincidence is not able to clean the background and no peaks can be easily observed. The magenta spectrum is obtained by adding the request of $\Delta\phi$=180° thus reducing by a factor 2 the background around 10 MeV. The spectrum in green is obtained by adding two further conditions. First, we require a mass ~12 (with the resolution observed in fig.1) for the coincident particle. Moreover, the momentum conservation is also imposed asking that the total momentum measured in the x and y axis is equal to zero and the one along the beam axis, assumed as z axis, is the one of the beam. These further requests reduce the spurious coincidences by more than one order of magnitude. However, this is still not sufficient to observe high energy γ-ray decay. Only after switching on the detection in coincidence with at least one γ-ray, we strongly suppress the elastic peak, fig.2b green. Finally, to complete the cleaning of the data, we impose a requirement on the energy of the γ-ray detected in coincidence, that must be correlated with Q-value measurement (fig.2b red). The reduction of the coincidences with ground state events accounts for more than 5 order of magnitude. In this figure one can see quite well also the 12.7 MeV 1^{+} level (around 30 events) that was covered by the background in the other selections.

Comparing these results with previous measurements [4 and references therein] one clearly observes that in our case the simple particle coincidence method is apparently less effective, because we are unable, only with the kinematics coincidence, to observe the population of the Hoyle state. This is mainly due to the kinematical broadening due to the large size of our detectors and their consequently limited angular resolution (±4° at angles larger than 30°). An effect partially compensated by the larger efficiency of our device that allows to gain more sensitivity with lower beam intensity.

The Hoyle state presence can noted in the red spectrum of fig.2b as a bump on the side of the 4.44 Gaussian distribution. A fit could be attempted to extract information on its population subtracting the residual contribution from the 4.44 MeV level. However, the coincidence with one γ-ray is even more powerful than what shown in fig.2b. Actually, if one knows that there are levels that decay emitting two γ-rays in cascade, one can search for such levels playing with the equivalence between Q-value and γ-energy. In fig.3 it is shown the cleaning effect obtained by assuming undetected the 4.44 MeV level from the decay of the Hoyle state and so requiring a shift between the Q-value measured and the γ-ray energy detected. Even if the energy resolution of our scintillators is of the order of 1 MeV (also due to the escape peaks) the effect of such a selection is rather impressive. The resulting suppression of the 4.44 MeV contribution is quite important and the spectrum from the decay of the Hoyle state become much clear. Regarding the 9.63 MeV level there it is difficult to observe something from both fig.2b and 3. However, due to the 3^{-} spin of the level, the probability to emit a γ-ray to the ground state is much smaller than the one to

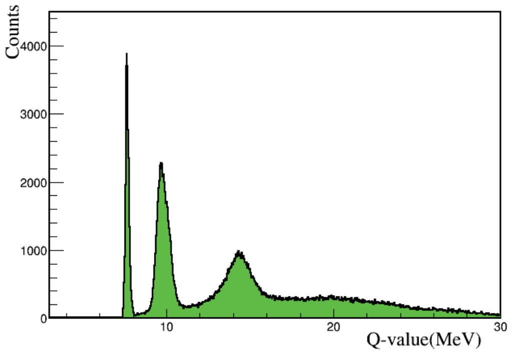

Fig. 5 Q-value plot for 3 α-particle decay events obtained summing the energy of the 3 α-particles in the CM to the decay channel Q-value.

emit a first E1 transition to the 4.44 level and the subsequent E2 γ-ray to the ground state. Therefore, for both levels we have to look to two γ–ray coincidence channel.

In fig. 4a it is shown the kinematic graph obtained plotting on the x axis the energy of the detected α-particle and on the y axis the energy of the ^{12}C, in events with two γ-rays in coincidence (the equivalence between Q-value and total energy of detected γ-rays is also requested). The lines show the expected loci for some excited levels (red continuous line for the Hoyle state, blue dashed line for the 9.64 MeV and black dot line for the 12.7 MeV level). This last level has also a decay branch with emission of two γ-rays through the 4.44 MeV level 15% respect to Γ_0 decay [16]. In fig. 4b we show the corresponding Q-value plot. With the request of two coincidence γ-rays the 4.44 MeV level is suppressed by a factor around 700 (compared with the spectrum of fig. 2b). The population of the Hoyle state is clearly seen. About 70 events lie in the correct Q-value window. Few events (from 5 to 8) are also observed in the Q-value window of the 9.64 MeV level. Some events (3-5) are also seen belonging to the 12.7 MeV level (see kinematic lines fig.4.a). These events are consistent, inside error bars, with the yield of 12.7 MeV level observed in fig2b. In fact, taking into account the above reported decay probability Γ_1/Γ_0, we expect to see around 5 events. They should be reduced to about 3 events taking into account that the efficiency to detect the two γ-rays is of the order of 75% than the efficiency to detect the single γ-ray of 12.7 MeV.

In order to extract the γ-decay widths, we must also measure the most important decay channel to be sure to have the correct number of populated levels. This is a rather simple task by exploiting the full angular coverage of CHIMERA. It is enough to search for particles stopped in silicon detectors (the 3 α-particles share the relatively low energy of the ^{12}C so they will be stopped in the 300 μm of our silicon detectors), and then impose the constraint on the masses of the 3 detected particles. The excitation energy of ^{12}C can be very simply and precisely obtained looking to the CM (center of mass) reference system of the 3 α-particles and summing their CM energies. To obtain the ^{12}C excitation energy we summed the decay-channel Q-value to α-particle CM energies and the result is shown in fig.5. The energy resolution that can be obtained in this way is much better than the one computed with the method of the total energy measurement. In fact, in this case there is no CsI(Tl) contribution, moreover the subtraction of the CM motion strongly reduces the effect of calibration uncertainties. As a result, the energy resolution observed in fig.5 is quite good. A sigma value of about 90 keV is found for the 7.65 MeV Hoyle state. Other levels are also observed the 9.63 and the 14.1 MeV. It is difficult to understand if in the region of the 9.63 level is embedded also a contribution due to the 10.3 MeV levels observed in [8]. An accurate analysis of the alpha angular distribution is necessary and it is out of the scope of this contribution.

In order to extract reliable Γ-decay widths we are performing accurate simulations necessary to evaluate the total efficiency of the apparatus taking into account not working detectors and γ-ray's angular distributions. This work is still on-going. However, because of the detection efficiency for particles and γ-rays from the Hoyle state and the 9.64 MeV level is similar, we can extract some preliminary conclusions. In fact, assuming for the γ-decay width of the Hoyle state the value available from literature [4], we can compare the population and decay probability of 7.65 and 9.64 MeV levels. In this way we can extract an approximate value for the decay width of 9.64 MeV level. In the spectrum of Fig.5 we detected about 35000 events belonging to the Hoyle state (with practically no background) and around 63000 events (background subtracted) belonging to 9.64 MeV level. Regarding the γ-decay we measure about 70 γ-ray's couples from the Hoyle state and not more than 5 decays near the 9.64 MeV. From the ratio, we can deduce that the 9.64 MeV level has more than two orders of magnitude less probability to decay to the ^{12}C ground state with respect to the Hoyle state. So a decay probability of about $1.5x10^{-5}$ seems observed. This is somewhat surprising. The error bar of this preliminary rough evaluation is surely very large due to the small number of counts and to the crude approximations performed. Such ratio explain also why we do not observe in fig.5 evidence of the 12.7 MeV level. This level has $3 \cdot 10^{-3}$ probability to decay by two γ-ray's emission. Observing no more than 4 events for this level and about 70 for the Hoyle one in fig.4, and comparing the yields and decay probabilities, one should see about 300 events in the region of this peak in fig.5. This is just a small fluctuation on the side of the two most prominent levels, explaining the missing peak. Due to the strong event selection performed the contribution of ^{13}C contamination of the target to the background is negligible. This was verified irradiating an enriched ^{13}C target. It was further confirmed, with larger statistics, by measuring, in the events in which an ^{3}He was detected, the decay of ^{13}C levels excited via one neutron transfer reactions. Comparing with the result of ref. [9], The reason for the much better background suppression probably lies in the request of two γ-rays in coincidence. This strongly suppress the ^{13}C contribution. This is due to the relatively small neutron decay Q-value of ^{13}C that increases the neutron decay width suppressing, for many channels, the Γ-decay width.

More accurate decay probability evaluations will be soon available also due to the analysis of a new run performed in July 2019 in order to increase the statistics.

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