Measurement of the γ-decay branching ratio of the Hoyle state and first excited 3$^-$ level of ^{12}C

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ABSTRACT

A new method for the measurement of the γ-decay branching ratio is used to improve the knowledge of this value for the Hoyle state and first 3$^-$ level in ^{12}C. The method require to measure in coincidence inelastically scattered beam particle, the recoil ^{12}C nucleus, and decay γ–rays. The quadruple coincidence and kinematics rules allow to strongly decrease background for the precise measurement of these quantities, very important for the production yield of ^{12}C in stellar and supernova explosive environments. The CHIMERA detector is used for such a measurement.

PHYSICS CASE

The Hoyle state of the ^{12}C nucleus, at 7.65 MeV excitation energy, is very important for the element nucleosynthesis in stellar environments in the phase of helium burning. It is in fact involved in the ^{12}C production through the 3-α reaction [1]. The small radiative width of this level can be considered as the main responsible of ^{12}C production in stars. Various experiments have been done to measure this width. The Hoyle state is a 0$^+$ level and it cannot directly decay to the G.S. through the emission of a single γ-ray. Only the two step decay, trough 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 couple e^+e^- decay are allowed. The most recent work to determine the Γ_π width was reported in ref [2] with a reanalysis of previous electron inelastic scattering data and a low energy measurement performed at S-DALINAC, leading to the result Γ_π=62.3±2.0 μeV. The total radiative width of such level was instead studied in a series of works during the 70th, following the one of Chamberlain [3] establishing the technique of measuring recoiling carbon in kinematical coincidence with scattered projectile. The summary of this work was done in [4] were a measurement of ^{12}C recoil is reported, in the α+^{12}C reaction at 40 MeV, and a recommended value for Γ_{rad}/Γ of 4.12±0.11 10^{-4}, was suggested based on an average of all previous investigations [3,5,6], also including direct measurement of the coincidence two γ-decay as [7].

In more explosive environments, like in supernova explosions, when the temperature is in the range of 10^9 k, also higher excited levels can be involved, as the 3$^-$ at 9.64 MeV one and others less pronounced levels recently evidenced in this energy range [8]. For the 9.64 level the direct γ-decay to the G.S. is possible with E3 transition and was evaluated through electron scattering measurement to have a width $\Gamma_{\gamma 0}$= 0.31(4) meV. Chamberlain [9] attempted to measure the total radiative width of this level but the result was only an upper limit of 14 mV for Γ_γ and $\Gamma_\gamma/\Gamma<4.1\mathrm{x}10^{-7}$. Recently some test experiments to precisely measure such value were presented [10,11] to conferences. Again the kinematical coincidence method was used but inverse kinematic was chosen for the reaction. The Grand Raiden spectrometer at the Osaka University was used to identify the recoiling carbon nuclei; a test with solid proton target was also performed [11] to improve signal to noise level. Another attempt for a direct measurement of the two γ-decay from the Hoyle state was also recently presented to a conference, aiming to improve of a factor of two the measurement of the Γ_γ / Γ [12] branching ratio.

As one can infer by the above short summary, this kind of measurements are rather complex. For instance, in the case of direct measurement of γ-decay one must take into account also the angular correlation effects to correctly evaluate the efficiency due to the multi-polarity of the decay [13]. Moreover, due to the small decay branch, large efficiency detection arrays, possibly 4π, are needed. In the indirect method spurious coincidences, also from target contaminants, pile-up and other reaction mechanisms produce a background limiting the possibility of the method.

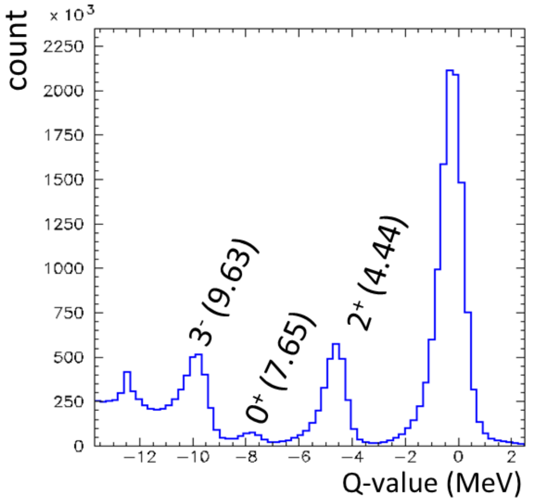

Fig. 1 Q-value spectrum of the p+^{12}C reaction at 24 MeV

A possible way to improve the sensibility of the measurement would be to use both methods together. For such a measurement an apparatus able to detect with large solid angle, coincidence γ-rays, ^{12}C recoils and in-elastically scattered projectile particles, would be of utmost utility. Angular correlations measurements are also needed to precisely evaluate the branching ratio. Recently we have shown the ability of the CHIMERA detector to detect and identify γ-rays using the CsI(Tl) stage of its telescopes. Moreover, precise measurements of γ-ray angular correlations [13] are simply obtained also thanks to the granularity and the 4π configuration. The complete angular coverage allows also a large efficiency in the detection of kinematical coincidences, with automatic corrections for possible beam misalignments, as we recently demonstrated in reactions induced by radioactive fragmentation beams [14]. Therefore, the CHIMERA detector could be used for such a complete measurement. Having this in mind we performed a dedicated analysis of the data we collected with 24 MeV proton tandem beam on ^{12}C target, during the calibration and background measurement of the PYGMY experiment. In fig. 1 we show a Q-value spectrum obtained in this experiment measuring proton inelastic scattering. The 9.64 MeV level was populated with good intensity and also the Hoyle state could be clearly seen. In one day of beam time with the relatively small proton beam intensity of .1 pnA (also due to the thick target used 75μm) we were able to collect about 3.5x10^5 events with population of the Hoyle state and about 2.7x10^6 with the population of the 9.64 MeV level. This large number of events should have allowed us to see coincidence events at least in the case of the Hoyle state, however this was not the case because without the RF timing our fast slow discrimination is rather poor and no γ-identification was possible, therefore the true coincidence data are covered by the large background. This analysis was however useful to better understand how to design a new experiment.

THE PROPOSED EXPERIMENT

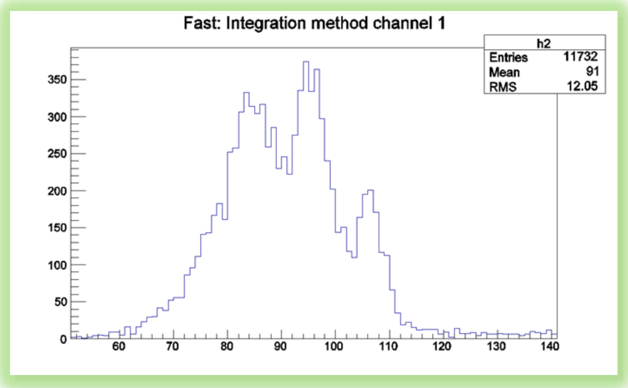

Fig.2 The 4.44 MeV γ-ray emitted by Am-Be source detected in a CsI(Tl) of the FARCOS array as seen with GET electronics. Similar quality is expected for CHIMERA CsI(Tl) using dual gain modules.

We propose to excite high energy levels of ^{12}C, in particular the Hoyle state at 7.65 MeV and the 9.64 MeV level, by inelastic scattering using a 60 MeV α-particle beam delivered by the Superconducting Cyclotron. The experiment will be performed using the 4π CHIMERA detector. We will detect events with at least two particles firing the first stage silicon detectors of the CHIMERA telescopes. We are in fact interested to events in which both the scattered α-particle and the recoiling ^{12}C are detected. We will exclude from the trigger the most forward rings in order to decrease the events due to the 3-alpha break-up of the target (at large angles the expected energy of such α-particles is low enough to be lower than the thresholds). Time of flight will be used to discriminate ^{12}C from other particles emitted with various reaction mechanisms. The new GET electronics is now available for the CsI(Tl) detectors of CHIMERA. The GET electronics can be triggered both by internal multiplicity or by some external trigger. In this experiment we will use the external silicon multiplicity trigger. We have equipped the CsI(Tl) chain with a dual gain module. Each signal produced by CsI(Tl) detectors will pass through this module able to split in two the signal and to give a different gain to the two lines. In this way we can improve the signal to noise ratio, as the relatively small signals left by γ-rays can be amplified up to a factor 16 and well discriminated by the background. With this method we can improve the signal to noise ratio. In fig. 2 we show an example of detection of the 4.44 MeV γ-ray emitted by an Am-Be source using GET electronics. A CsI(Tl) of the FARCOS array was used, slightly worse quality is expected using a CsI(Tl) of the CHIMERA detector due to the larger size. Moreover in the analysis we can implement the concept of detector cluster, signals detected in neighboring detectors can be summed, so increasing the full energy peak probability. The purpose of CsI(Tl) detectors is to detect and identify the γ-ray cascade relative to the decay of both the Hoyle state and the 9.64 MeV. As above reported nothing is known about the γ-decay of this level through for instance the 4.44 MeV. The direct decay of this level to G.S. has very small probability, of the order of 10^{-8} [10], therefore it will be probably impossible to see this direct decay even with the relatively large efficiency for the detection of 9 MeV γ-rays (>20%) of our detection system. The detection of the 4.44 MeV γ-decay from the first 2^+ excited level, with 100% branching ratio and of the other known γ-decays from levels (like the 12.7 MeV and at higher energy 15.1 MeV) will be used to accurately verify and calibrate detection efficiency. The never fulfilled search of γ-decay of the 9.64 MeV level will be a very important test of the limits of validity of the presently available evaluation of its radiative decay. Our experiment should also further improve the precision in the measurement for the Hoyle state radiative branch.

BEAM TIME REQUEST

As above reported we have already performed an experiment to populate the Hoyle state and the 9.64 MeV levels. From this attempt we know that the cross section for the population of the 7.65 MeV Hoyle state via inelastic scattering is much smaller than the one of the 9.64 MeV level. We expect the excitation cross section for α-particles at 15 MeV/A to be very similar to that obtained for the proton beam at 24 MeV/A. The following calculations are done assuming a cross section of about 1 mb/sr for the Hoyle state population in the region between 20°-60°. Our detection system has a fully solid angle coverage in this region of about 3 sr therefore, with a beam intensity of the order of 2 pnA and a relatively thin target of 50 $\mu g/cm^2$, allowing for recoil detection, we will have:

$1.2x10^{10}x1x10^{-27}x3x2.5x10^{18}$ = 90 event/sec

Due to the 4π coverage we should have at least 90% efficiency for the detection of the recoiling carbon. If the γ-decay probability of the Hoyle state is of the order of $4x10^{-4}$, as reported in literature, this means that we should have 2 γ cascade/min. the total γ-ray efficiency of our detection system for γ-rays around 4 MeV is of the order of 30%, therefore the detection efficiency for the two coincidence γ-rays in the cascade is around 10%. With this efficiency we expect about 10 γ–γ coincidence per hour. In order to be able to perform precise angular correlation measurement with good statistical error, taking into account also background subtraction, we need to measure for at least 5 days. Another day is needed to perform measurements with a ^{13}C target with the purpose of measuring the detection efficiency for γ-ray energy around 3 MeV and at the same time to measure the possible background due to a residual ^{13}C in the ^{12}C isotopically enriched target (this was the main contribution to the background affecting the results in ref [9]). A day for setting up the electronics is also required for a total beam time request of 7 days or 21 BTU. The smaller decay probability by the emission of two cascade γ-rays of the 9.64 MeV level is partially compensated by its rather large population cross section (one order of magnitude larger than the other) that can be inferred by inspection of fig.1. We therefore expect a yield of the order of 2 events per day assuming $\Gamma_\gamma/\Gamma=4x10^{-7}$. We underline that the request of 4-fold coincidence (scattered alpha, recoiling carbon, two γ-rays) with suitable alpha identification, carbon mass identification (via TOF measurements thank to RF timing of the CS), kinematical correlation of the two particles, with correct Q-value and energy identification of the cascade γ-rays, will strongly decrease the background. Only CHIMERA is at present able to perform such a complete measurement in the world.

Runs with multiplicity 1 trigger will be also performed in order to verify the total efficiency, a percentage of events at multiplicity 1 and pulser with well-defined rate will be also acquired to allow the precise evaluation of the radiative width of the measured levels.

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