Potential experimental evidence of an Efimov state in ^{12}C and its influence on astrophysical carbon creation

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Abstract. We describe the search of the Efimov state in ^{12}C performed by analysing a large set of 3-α particles coincidence data measured at the LNS laboratories with the CHIMERA detector. The data are compatible with the presence of an Efimov state at the excitation energy of 7.485 MeV, with an excitation probability smaller than 0.3% of the population probability of the Hoyle state. The Efimov state gamma decay probability should be around 30%, much larger than the one of the Hoyle state. The population of this level is compatible with the Suda limit for the 3-α reaction rate in stars because its population should be possible only through direct 3-α reaction. More investigations improving the detector angular resolution are needed to confirm these preliminary observations.

1 Introduction

In the 70th of last century Efimov [1], following an idea of Thomas [2], demonstrated that if there is a two body system experiencing a resonance, it will generate a bound level in the 3 body system and, in principle, infinite excited levels over it. Efimov aimed at the demonstration that the Hoyle state [3] belongs to this class of levels but it was unable to reach its objective. However, later on, the presence of Thomas-Efimov (TE) levels was demonstrated in atomic physics experiments [4]. The search of this effect in nuclear physics was also very active [5–7] but up to now no convincing evidences were found both for Carbon and lighter systems. An attempt to describe the decay characteristics of such a state in ^{12}C was performed by Zheng and collaborators [8]. More recently a paper presenting some evidences against the existence of this level in ^{12}C was published by Bishop et al [9]. In particular, Bishop et al presented an astrophysical objection based on the so called Suda limit for the 3-α reaction rate in

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stars [10]. In practice the presence of the TE level would enhance the production yield of ^{12}C in stars at much lower temperatures than what was expected up to now. The TE state could be in fact a very efficient way to build carbon with respect to the Hoyle state having a gamma decay probability nearly 100% [9], while in the case of the Hoyle state this probability is only around 1 over 2500 [11]. In this short report, we present some evidences observed in a recent experiment performed with the CHIMERA detector [12] at the INFN - Laboratori Nazionali del Sud (LNS) in Catania (Italy). In the α+^{12}C reaction at 64 MeV, we have detected a possible signature of the direct decay of the TE state in 3 α particles [13, 14]. This observation combined with an extra-yield of the gamma decay in the region of the Hoyle state [15, 16], could be explained by the population and decay of the TE state. However, we do not find any evidence of a sequential decay of such level in the α+^{8}Be channel. This means that in stars the TE state - if it exists - cannot be populated through this channel, but only by direct 3-α reactions. This fact decreases of many order of magnitude its population probability in stars, overcoming the problem underlined by Bishop et al of the Suda limit. Also the gamma decay probability seems smaller than that deduced by Bishop et al. We underline that these results are based only on accurate simulations of the experimental findings, therefore a more precise measurement will be performed soon to definitely prove or exclude the existence of this level. In the next section we shortly present the experimental results and data analysis, while in the last section we show possible improvements coming with a new experimental setup.

2 Experimental results and simulations

The experiment was performed at INFN-LNS, by using an α beam of 64 MeV delivered by the Cyclotron accelerator of the Laboratories. The beam impinged on a carbon target placed in the target holder of the CHIMERA detector. CHIMERA is a 4π detector for charged particles, mainly devoted to isospin studies (see for instance [17–20]), that in the last years was used also as a nearly 4π gamma ray detector. This was possible thanks to the sensitivity to gamma rays of the second stage (CsI(Tl) scintillators with photodiode readout) of the telescopes of the spherical part of CHIMERA covering the angles from 30° to 176° [21–23]. The high efficiency of the detector allowed the collection of a large number of coincidences between 3-α particles from the decay of the Hoyle state (about 85000 events with an average detection efficiency of the order of 50%), and also a reasonable statistics (30% error bar) in the coincidence measurement of the scattered beam, the recoiling ^{12}C, and the two decay gamma rays from the Hoyle state. The measured relative gamma decay width of the Hoyle state was of the order of $1.8 \cdot 10^{-3}$ [15]. This number is more than 3 times larger than the most recent measurement on this level [16], that is already 50% larger than the accepted value of this decay probability [11]. Due to the low energy resolution of the measurement, the possibility of some contamination by other levels was investigated also by looking at the 3-α decay channel. We emphasize that the scattered beam can be discriminate by the α particles emitted from carbon decay because of the higher energy. A detailed simulation of the detected events was performed obtaining a rather accurate modelling of the detected excitation energy spectrum in the region of the Hoyle state [13]. The ratio between the simulated and the experimental spectra shows only small differences at high excitation energy, due to random coincidences not included in the simulations. Some discrepancy is present also in the low excitation energy region. This could be a signature of the presence of the TE state. The same simulation tool was used to understand the expected behaviour of decay events from the TE state both for sequential α+^{8}Be and for direct 3-α decays. Guided by the results of the simulations we could search for such events in our data. More in detail we analyse the center of mass (CM) energy of the 3 couples of α particles obtained combining the 3 detected α particles selecting only the events in which one of these energies is equal to 92

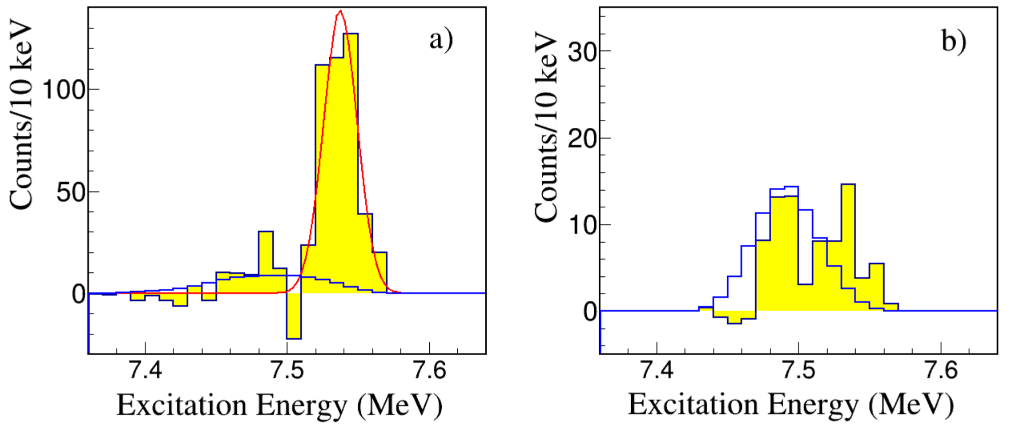

Figure 1. The filled yellow spectra are the experimental events compatible with the decay of the TE state; a) assuming sequential α+^{8}Be decay; b) assuming direct 3-α decay. The blue histograms are simulated TE decay spectra in the two decay modes. The red Gaussian line is a fit of the extra-peak observed in the sequential decay mode.

keV as the average of the other two. More than 4500 events were observed compatible with the sequential TE decay while only about 400 were found for the direct decay. However, as shown by simulations, most of the events are genuine Hoyle level decays badly measured because of the uncertainty in the detection angle of the α particles. Fig. 1a and fig. 1b show, as filled yellow histograms (adapted from ref. [14]), the spectra obtained from the experimental data subtracted of the aforementioned badly assigned events. They are compared to the blue spectra that are simulated decays of the TE state arbitrarily normalized. We note that the sequential decay spectrum of fig.1a is dominated by a peak (fitted in the figure with a red Gaussian) that it is not comparable to the decay of a TE state. This peak shows that our simulation is somewhat incomplete. Apart this peak, we note that the lower energy tail of the spectrum presents a small contribution, similar to the behaviour expected for a sequential TE decay. However this tail is much smaller than the error bar of the background evaluation of badly reconstructed events (approximately 40 events with an error bar of ±90). We conclude that our data are fully compatible with zero contribution from the sequential TE decay within error bars. The plot of fig.1b is obtained assuming the direct decay. This decay mode requires that the 3 α particles are emitted with similar energy - 60 keV in their CM - and with a relative angle around 120°. These conditions are very difficult to be fulfilled by events coming from the decay of the Hoyle state. Only few events are observed compatible with this behaviour in our data set (around 400). The background subtracted spectrum looks quite similar to the expected one from a TE state direct decay (blue histogram). A residual contribution at the high energy side could be due to simulation incompleteness, but statistics is low. The integral of the events compatible with the TE sequential decay is around 47±27 events. The statistical error comes from the subtraction of the simulated events. The enhancement of the gamma decay given by the presence of the TE state was evaluated in ref. [14] to be of the order of 270 events each 200000 Hoyle state population events. Therefore about 1 event every 1000 Hoyle events could be due to a TE level decaying by gamma emission. Taking into account selection efficiencies our data are compatible with the population and 3-α decay of 1 TE state each approximately 400 Hoyle events. Therefore summing both gamma and α decays it is deduced that the probability of the TE state population is of the order of 3 events each 1000 Hoyle state population events. Moreover we can also say that the gamma decay probability of this state is at least two times smaller than the 3-α decay probability. The large error bars and the strong dependence of these results from the details of the simulations do not allow a more precise and final answer on the existence of this level.

3 Conclusions and outlook

In this paper we present the results of the analysis carried out on a large data set of 3-α particles coincidence data measured at the INFN-LNS laboratories with the CHIMERA detector and related simulations, showing the possible evidence of the direct 3-α decay of the TE state. No evidence was observed for its sequential decay, inside our large error bars. The presence of some Gaussian prominent peak on the difference between simulated and analysed events tells us that there are still some experimental details not well included in our simulation method. This fact and the incoherent results that we obtain with other analysis methods reported in ref. [13], prevent us to extract a firm conclusion. However we underline that if the sequential α+^{8}Be channel is suppressed and only the direct 3-α decays is possible there are consequences in the 3-α process in stars. This could be the solution to the problem of Suda limit [10] reported by Bishop's work [9]. The direct 3-α reaction needs in fact a rather large density of α particles not available in stars.

Since from our data the α decay channel is not negligible with respect to the gamma decay one, a more precise experiment looking at the 3-α decay channel, could better highlight the presence of the TE state. An attempt was already performed by Bishop et al in their work with an active target [9], however the level of badly reconstructed events was too large to clearly observe the TE region in its spectrum notwithstanding the 55 keV energy resolution obtained and the detection of about 23000 Hoyle decays.

Recently we have coupled to the CHIMERA detector an array of high energy resolution telescopes named FARCOS, (see one of the adopted configuration in fig. 2-right) each one made of two double sided silicon strip detectors (DSSSD) followed by a final CsI(Tl) stage [24, 25]. With FARCOS we can determine the detection angle of an α particle with a precision of about 0.3°. In a preliminary test experiment we have already detected 3-α events in the FARCOS telescopes with an energy resolution of the order of 28 keV. With this energy resolution the contribution of the tail of the Hoyle spectrum to the TE region is reduced by more than 6 orders of magnitude. Fig. 2-left shows the obtained CM energy spectrum (filled yellow) compared to the previous one measured with CHIMERA (filled green). This enhanced resolution should be enough to discriminate the few expected events of the TE decay from the ones of the dominant Hoyle decay channel (we need to detect 100000 Hoyle events in order to observe at least 100 TE events). An experiment is planned in the next future hoping to definitively determine the existence of the TE state in Carbon.

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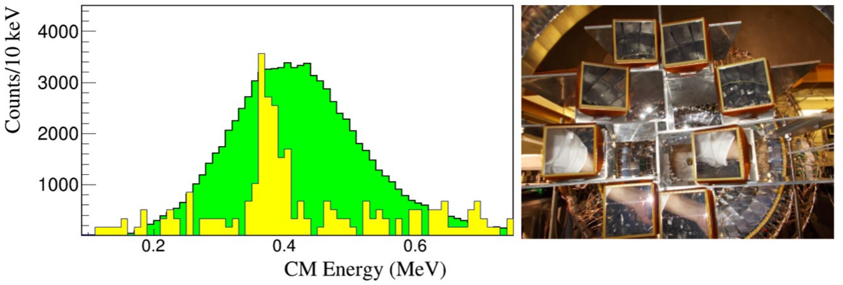

Figure 2. Left - The green spectrum is the Hoyle CM energy spectrum reconstructed with CHIMERA data, the yellow spectrum is the one reconstructed by using FARCOS telescopes in a preliminary test experiment, (random coincidences are not subtracted). Right - photo of one of the adopted configuration for the FARCOS array inside CHIMERA.

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