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Population and decay of ^{12}C states

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Summary. — By using the CHIMERA detector, we have measured the γ-ray and α decay width of excited ^{12}C states important for the carbon production in astrophysical environments. For the first time, we directly observed the γ-ray decay of the 9.64 MeV level. A γ-ray decay width larger than previous observations was observed for the Hoyle state. In order to explain this enhanced yield we investigated on the recently proposed population of an Efimov state at 7.458 MeV. The decay characteristics of such level are inferred.

1. – Introduction

The Hoyle state of the ^{12}C nucleus, at 7.65 MeV excitation energy, and higher excitation energy levels as the 9.64 MeV play a crucial role in the nucleosynthesis processes in stellar environments. More in detail, the Hoyle level is involved in the ^{12}C production in the helium burning phase through the 3-α reaction [1-3]. Fundamental for this process is the partial width, for γ-ray decay. Until 2020, the accepted value for such decay width for the Hoyle state was based on the work of Markham *et al.* [4], with its recommended weighted value for the Γ_{rad}/Γ of $4.12 \pm 0.11 \times 10^{-4}$. This average was extracted by looking at experiments mostly performed with the Chamberlin method [5] (measuring in coincidence scattered beam and recoiling target). Since that work, only small corrections have been suggested, see for instance [6]. In 2020, an unexpected result was published by Kibedi *et al.* [7]. This group performed the reaction p + ^{12}C, measuring a triple γ-γ-p coincidence. They reported a 50% larger γ-ray decay width of about 6.2×10^{-4}. In 2021, also the γ-ray decay width of the 9.64 MeV level was revised by the group of Tsumura *et al.* [8] reporting a yield $\Gamma_{rad}/\Gamma_{tot} = 1.3(+1.2-1.1) \times 10^{-6}$, one order of magnitude larger than previously accepted upper limit given by Chamberlin *et al.* $\Gamma_{rad}/\Gamma < 4.1 \times 10^{-7}$ [9]. As emphasized in the same work, this new value has consequences in explosive stellar environment with an interacting α particles plasma temperature of 10^9 K. It is interesting to note that the work of Tsumura *et al.* was also performed with the Chamberlin method, but pushing at maximum the level of the present technology, using a solid hydrogen target, and a spectrometer for ^{12}C detector. Notwithstanding this, a huge background was observed resulting in a large error bar. We must note that in Tsumura experiment also the Hoyle decay width was measured, reporting a quite standard value for the γ-ray decay width $\approx 4.3 \times 10^{-4}$, so leaving without confirmation the surprising result of Kibedi measurement.

A further complication to this scenario was produced by some recent papers suggesting the presence of an Efimov state (ES) [10-14] at excitation energy of 7.458 MeV, very near to the Hoyle state. This state is characterized by the fact that each couple of α particles is in the level of the ^{8}Be resonance energy (around 92 keV), so the total CM energy of the three α particles is 192 keV. The presence of such state could strongly influence the reaction rate in stars as it was shown by Bishop *et al.* [15] that used also this reason to exclude its existence. The presence of this state was not investigated in both Kibedi and Tsumura works.

Recently, we published the result of a new measurement [16] based on a 4 fold coincidence technique, called Complete Redundant Measurement (CRM) [17], in which, for the first time, we were able to directly measure few events of the γ-ray decay cascade from the 9.64 MeV level, and again the γ-decay of the Hoyle state. While the obtained γ-ray decay width for the 9.64 MeV level is in reasonable agreement with the Tsumura *et al.* result, we obtain for the Hoyle decay width a 3 times larger value with respect to the already anomalous Kibedi result.

In this work we show that this enhanced decay probability can be explained by the excitation of an ES. Its population cross section should be 0.3% with respect to the one of the Hoyle state. This state should mainly decay through γ-ray emission (around 30% probability), the remaining decay width should be in the 3-α direct decay channel, with emission of 3 equal energy α particles. By analysing the present data, the sequential decay through a ^{8}Be formation seems excluded. This implies this state can be populated in stars only by contemporary 3-α interaction. This reaction needs a very large α density in the stellar plasma cancelling part of the objections of Bishop *et al.*'s work.

In the next section, we will recall few experimental details. In the third section , simulations more extensively presented in ref. [18] are described. The discussion about the characteristics of the ES is reported in the last section.

2. – Experimental method and results

In fig. 1 (adapted from [16]) an example of the cleaning effect obtained is reported. In the two axis we plot the energies of the scattered α particle and of the recoiling ^{12}C measured in coincidence. The kinematic lines expected for the ground state, 4.44, 7.65, 9.64 and 12.7 MeV levels are also drawn. Experimental data, represented by the filled

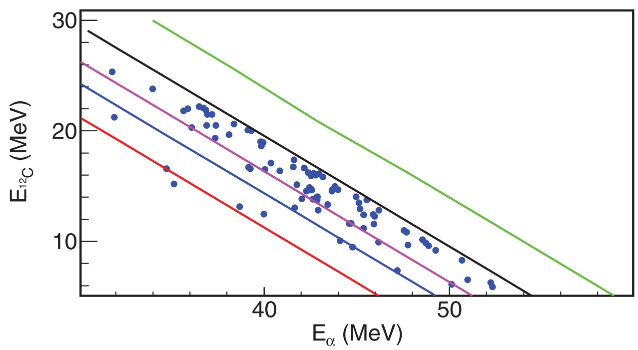

Fig. 1. – Kinematic plot obtained with the energy of recoiling carbon plotted against the energy of scattered α particles. The green, black, purple, blue, and red lines correspond to the ground, 4.44, 7.65, 9.64, and 12.7 MeV states respectively.

dots, are clearly grouped along the kinematic lines. It is impressive to note the cleaning effect of the CRM method. Only few counts of spurious background are present near the 4.44 MeV level for which nearly 2.5 million of events were detected in simple coincidence. The background near the 9.64 MeV level is practically absent as compared to the very large background (8 times the good events) observed by Tsumura. The experiment was performed at Laboratori Nazionali del Sud INFN by using an α beam of 64 MeV delivered by the superconducting cyclotron. We used the CHIMERA array to detect and to identify α beam scattered by the thin ^{12}C target by the ΔE-E method. The recoiling target in coincidence was also measured. The ^{12}C recoil was identified in mass by time of flight (TOF) measurement as shown in [17]. In addition to the basic detection of the scattered beam and recoiling target, suggested by the Chamberlin method, with CHIMERA we are also able to measure the γ-rays eventually emitted in the decay stage of the levels. We can also measure the particles emitted in the decay of excited levels with very large detection efficiency. This allows us to extend and improve the Chamberlin method using the CRM method, suppressing the background of the measurement that can be very large in case of small γ-ray decay probability, as seen by Chamberlin and Tsumura experiments. In fact, apart from the obvious reduction of spurious coincidences due to the request of 4 fold coincidence (scattered beam, recoiling target and two γ-rays), we can also use kinematics and conservation rules to further reduce background. Moreover, the direct comparison of γ-rays and particle decay width allows reducing also systematic errors.

3. – Simulations

In order to extract the decay yield it is mandatory to fully understand the detection efficiency of the system, so we developed complete simulations for both γ-ray and particle detection efficiency. Moreover, detection efficiencies were tested experimentally by using the known decay width of γ-ray decaying levels as the 4.44 and 12.7 MeV levels and the distribution of detected α particle multiplicity. We can therefore exclude that the anomalous level of γ-ray decay width for the Hoyle state is due to badly evaluated efficiency. The error due to the efficiency evaluation cannot be larger than 10% due to systematic errors. Also, angular correlation effects due to the full coverage of the solid angle guaranteed by the detector are quite small. In fact, angular correlations produce a concentration of particles or γ-rays in different angular regions. This can strongly deteriorate the detection efficiency of small detection arrays, while it has much less effects in 4π detectors. We have experimentally evaluated angular correlation effects by analyzing the detection efficiency of the 4.44 MeV γ-rays as a function of the detection angle of the recoiling target. Variations of the efficiency smaller than 0.2% on an average efficiency of the order of 18% were observed and this is the maximum error evaluated for the γ-ray efficiency.

Being excluded the error on efficiency as a source of the anomalous γ-ray decay width measured for the Hoyle state, we attempted a different solution for this puzzle. The energy resolution of the γ-ray CsI(Tl) detectors (photodiode readout) is of the order of 10% at low energy and also the scattered α particles are measured with a resolution of the order of 1 MeV. Therefore, we can compare the total energy conservation with an error of the order of ± 1 MeV. This does not allow us to exclude the presence of other levels under the level analysed that could interfere with the extraction of the decay width.

A different analysis method, which allows obtaining a lower experimental energy uncertainty, can be attained in the study of the α decay of the Hoyle state. This is due to various reasons, the first one is that the α particles have low energy and are detected in the silicon detectors with a resolution better than 100 keV. The second one is that we can extract by kinematics the center of mass (CM) energy of the 3-α particles and this is quite small, of the order of 400 keV for the Hoyle state, so even a large relative error of 25% produces a reasonable absolute error of the order of 100 keV in the excitation energy measurement. Therefore, by analysing the 3-α channel decay of the Hoyle state , we can have the possibility to evidence the contribution of another level near to it, as the ES.

We searched for signals of the presence of this level by analysing a set of about 85000 3-α events collected in the reaction following indications obtained by precise simulations of the decay of both the Hoyle and ES.

The simulations performed include the angular and energy resolution of the silicon detectors. Energy thresholds and not working detectors are also taken into account; the reproduction of the angular distribution of the events detected is fundamental for the study. Also the energy loss in the target and in the dead region of the detectors plays a not negligible role in the simulation of such low energy alpha particles (α particles with energy of few MeV are also involved). The largest contribution to the energy resolution is however given by the large angular range covered by detectors. All events were in fact detected in the spherical region of the CHIMERA detector from 30° up to around 80° (the limiting angle of recoiling ^{12}C is 66°). In this region detectors cover an angular range of 8° in the polar angle θ and 11.5° in the azimuthal angle ϕ. For each α particle detected, we must assign the correct detection angle. The smallest error is performed by choosing the center of the detector (CA central angle). Different choices are also possible as the random angle (RA) inside the detector range. This last choice ensures a smoother distribution of the relative energy but at the cost of a worse energy resolution. In fig. 2 we show the plot in log scale of the excitation energy distribution in the region of the Hoyle state obtained with CA choice (filled green spectrum) adapted from [18]. In the same plot, the simulations obtained assuming 2 and 5% energy resolution are plotted. The ratio of the simulated (2%) and experimental plot is also plotted to evidence the generally good reproduction of the experimental result obtained (ratio around 1), apart from the high energy side where some background is present, not added to simulations, and at low energy where, in effect, we should observe some contribution of the ES, if present. This small deviation at low energy is not enough to evidence the presence of such state; and thus we must study the decay of ES and search more detailed evidences.

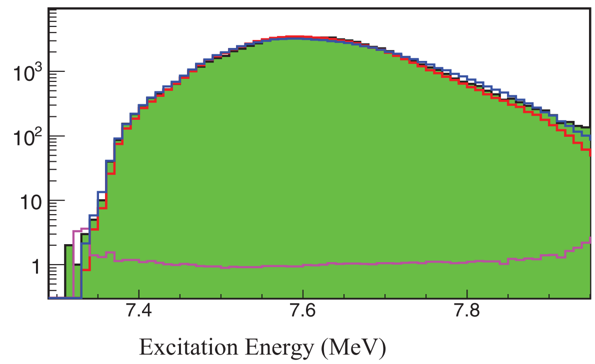

Fig. 2. – Hoyle energy spectrum (filled green spectrum) compared with two simulations with 2% resolution (red histogram) and 5% (blue histogram). The violet spectrum is the ratio between data and simulation with 2% energy resolution.

From [12] we know that the ES can decay by direct 3-α decay or by sequential emission of an α particle and a ^{8}Be. This last decay mode should be more important due to a smaller effect of the decay barrier. Simulations show that in the sequential decay the symmetry of the relative energy of the 3 couples of α particles is broken. This is because the relative angle of the first emitted α particle and of the other two is no more fixed but it is randomized by the sequential decay. Therefore, to search the ES decay in experimental data, we must look for an α couple with CM energy of 92 keV and for the average energy of the two other couples, again of 92 keV. The decay of the Hoyle state is quite different, in fact the average energy of the other two couples is larger than 250 keV. Analysing the experimental data (inside reasonable error bars) we find about 4500 events with such characteristics. They are plotted as a filled green histogram adapted from [18] in fig. 3(a). However, most of them are pure Hoyle decays that behave like an ES decay due to the error in the angle measurement. This can be demonstrated by analysing simulation data from pure Hoyle decay (blue empty histogram). Subtracting such data (normalized as in fig. 2) to the experimental selected data we obtained the filled yellow histogram that is not in agreement with the expected simulated spectrum of the ES sequential decay (violet histogram arbitrarily normalized). Our data therefore exclude the sequential decay of the ES in agreement with findings of Bishop work [15]. We note that the findings of ref. [13] in which three α couples with relative energy of 92 keV are observed and attributed to ES decay cannot be attributed to sequential decay mode. As already observed, simulations show that this symmetry is broken by the sequential decay.

Another possible decay mode is the direct decay by emission of 3 equal energy α particles. Also this decay mode can be simulated and the search of these events has quite trivial conditions, the α particles must have approximately the same energy (around 61 keV). Moreover, the three couples will have around 92 keV CM energy, and the relative emission angle of the 3 α will be around 120° in their CM. Such events are plotted as a filled green histogram in fig. 3(b), adapted from ref. [18]. They are much less than the event observed for the sequential decay, around 400 events. Again, most of them are pure Hoyle decays with badly measured angle. Simulations help to quantify such events and are plotted also as a blue empty spectrum. This time the yellow filled spectrum, obtained subtracting simulations from experimental data, reasonably follows simulations of the pure ES decay (violet histogram). The integral of such spectrum is 47 events.

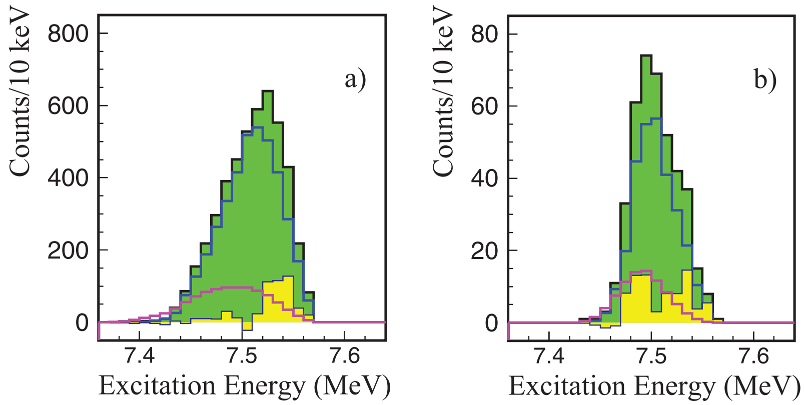

Fig. 3. – Excitation energy spectra extracted searching (a) the sequential and (b) the direct decay of the ES. The filled green spectrum represents the selected experimental data, the blue histogram Hoyle state represents simulated badly measured data, the yellow filled spectrum represents data subtracted by Hoyle events and random coincidences. The violet histogram represents the simulated ES decay.

Such number must be corrected by selection efficiency. We must take into account how many pure ES decay events survive to the relatively narrow cuts adopted to exclude Hoyle decays. This is of the order of 24%. So the data with CA choice are compatible with the presence of around 195 ES events, this is around 0.2% of the whole Hoyle state population.

4. – Discussion and future perspectives

The findings of CA choice are not fully confirmed by different data analysis techniques as the RA choice attributing to each α particle a random angle inside the detector. Also in this case the sequential decay of the ES is excluded by the selected data, but for the direct decay we find more events, namely 108 events, with a smaller selection efficiency of the used cuts (only 8%). Therefore, in this case there should be more than 1300 events due to the decay of the ES. The incoherence of the two data analysis methods does not allow us to extract a definitive conclusion. We can only say that the present data are compatible with the direct decay of an ES with yield between the observations produced by the two analysis methods. Being conservative we can assume the number of events observed with CA method. We can compare these observations to the findings of γ-ray decay of the Hoyle state [16]. From such set of data we evaluated that approximately 200000 Hoyle events were excited. The detection efficiency of two γ-rays was around 3.3%. If we assume that all the enhancement of the decay of γ-rays is due to ES γ-ray decay, about 9 events of the 12 detected in ref. [16] were due to ES decay. Correcting this for the efficiency we should have around 270 events from the γ-ray decay of the ES. From the findings of direct 3α decay, we can evaluate at the same time around 450 ES decay by this other mode. The sum of both decay modes (720 events) corresponds to around 0.35% population of the ES respect to the Hoyle state. From such numbers one can also evaluate that the γ-ray decay yield of the ES seems around 40% of the total yield.

The results here presented are not enough to fully evidence the presence of an ES population. The incoherence between the various analysis methods does not allow us to claim this observation. Also the ratio of α and γ-ray decay probability strongly depends on this evaluation. New more precise experimental investigations are needed. We will use the new FARCOS array coupled to CHIMERA detector to produce better resolved Q-value spectra in order to separate the eventual ES decay contribution.

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REFERENCES

[1] Bedding T. R. *et al.*, *Nature*, **471** (2011) 608.
[2] Herwig F., Austin S. M. and Lattanzio J. C., *Phys. Rev. C*, **73** (2006) 025802.
[3] Hoyle F., *Astrophys. J. Suppl. Ser.*, **1** (1954) 121.
[4] Markham R. G., Austin S. M. and Shahabuddin M. A. M., *Nucl. Phys. A*, **270** (1976) 489.
[5] Chamberlin D., Bodansky D., Jacobs W. W. and Oberg D. L., *Phys. Rev. C*, **9** (1974) 69.
[6] Angulo C. *et al.*, *Nucl. Phys. A*, **656** (1999) 3.
[7] Kibédi T. *et al.*, *Phys. Rev. Lett.*, **125** (2020) 182701.
[8] Tsumura M. *et al.*, *Phys. Lett. B*, **817** (2021) 136283.
[9] Chamberlin D., Bodansky D., Jacobs W. W. and Oberg D. L., *Phys. Rev. C*, **10** (1974) 909.
[10] Efimov V., *Phys. Lett. B*, **33** (1970) 563.
[11] Naidon P. and Endo S., *Rep. Prog. Phys.*, **80** (2017) 056001.
[12] Zheng H. *et al.*, *Phys. Lett. B*, **779** (2018) 460.
[13] Zhang S. *et al.*, *Phys. Rev. C*, **99** (2019) 044605.
[14] Zheng H. and Bonasera A., *J. Phys. Commun.*, **4** (2020) 085011.
[15] Bishop J. *et al.*, *Phys. Rev. C*, **103** (2021) L051303.
[16] Cardella G. *et al.*, *Phys. Rev. C*, **104** (2021) 064315.
[17] Cardella G. *et al.*, *J. Phys.: Conf. Ser.*, **1668** (2020) 012004.
[18] Cardella G. *et al.*, *Nucl. Phys. A*, **1020** (2022) 122395.