INVESTIGATION OF THE γ-RAY PROPERTIES OF THE 2^+ STATES IN ^{14}C*

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The properties of the 2^+_1 and 2^+_2 excited states in ^{14}C were studied in an experiment conducted at the Argonne National Laboratory. A ^{9}Be(^{6}Li,$p\gamma$) fusion–evaporation reaction and the GRETINA–ORRUBA setup were employed to populate states of ^{14}C and detect γ-particle coincidence events. The precise determination of the 2^+_1 level energy, complemented by the estimation of the γ-ray branch of the 2^+_2 near-threshold state, will serve as a benchmark to test the Shell Model Embedded in the Continuum calculations.

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1. Introduction

The excitation energy spectra of atomic nuclei are characterized by the appearance of bound discrete states, below particle-separation energies, and unbound resonances in the continuum. In light nuclei ($A < 20$), particular near-threshold states may appear. Such resonances, located in the proximity of particle/cluster-emission threshold, are typically few-keV wide and their properties are influenced by the coupling of discrete bound states with particle-decay channels. Based on recent results of the Shell Model Embedded in the Continuum (SMEC) [1], which describes nuclei as open quantum systems, the existence of near-threshold states in light systems is expected to be a universal phenomenon. The structure of these near-threshold states, described as a core coupled to the corresponding decay channel, can provide relevant information on the onset of collectivization and clusterization phenomena in molecular-like nuclei, such as C, O, and Ne. In this paper, we focused on the ^{14}C case, which presents a 2_2^+ near-threshold state at 8318 keV, just 142 keV above the neutron separation energy [2]. This state is predicated by the SMEC to gain collectivity when the coupling with bound states is considered, in contrast with the standard Shell-Model calculations. This coupling is expected to affect the transition probabilities from the 2_1^+, 2_2^+, and 2_3^+ states, due to the configuration mixing of this 2^+ triplet [3].

This paper is focused on the measurement of the energy of the 2_1^+ state, currently known with large uncertainty, and of its γ-ray decay towards the ground state. By combining such results with data from the AGATA–VAMOS experiment of Refs. [4–6], it should be possible to obtain a new estimate for the lifetime of the 2_1^+ state using the DSAM method described in Ref. [7]. Such a result would contribute towards achieving a comprehensive description of the fragmented 2^+ strength in ^{14}C, in comparison with theory predictions.

2. Experimental details

The experiment was performed at the Argonne National Laboratory, during the 2021 GODDESS (GRETINA ORRUBA: Dual Detectors for Experimental Structure Studies) campaign. A 7 MeV ^{6}Li beam, provided by the ATLAS accelerator, impinged on a ^{9}Be target (200 and 400 μg/cm^2 thick), inducing a fusion–evaporation reaction. After the evaporation of a proton from the ^{15}N compound nucleus, ground and excited states of ^{14}C were populated with a total cross section of 95 mb, estimated with the PACE code [8]. The identification of the reaction channel was achieved by the detection of protons in the ORRUBA charged particle detector [9]. At the time of this experiment, the barrel array comprised 1 mg/cm^2 thick SX3 and QQQ5 detectors, with a 65 μg/cm^2 ΔE layer on the forward ring, covering an angular range between $\sim 50^\circ$ and $\sim 165^\circ$ with respect to the beam axis. On the other hand, γ rays emitted in coincidence with protons were detected by the GRETINA spectrometer [10], consisting of 48 HPGe segmented detectors. Given the expected high-rate condition, a particle-γ trigger, and a particle-only trigger were set, with the latter downscaled by a factor of ≈ 100.

3. Analysis

With the purpose of constraining the $B(\mathrm{E2}; 2_1^+ \rightarrow 0_1^+)$ value by measuring the $2_1^+ \rightarrow 0_1^+$ γ-ray energy, particular attention was devoted to the preliminary analysis of the data from GRETINA HPGe detectors. At first, a calibration with a first-order polynomial was applied in the 0–3 MeV range, using ^{56}Co, ^{60}Co, and ^{152}Eu sources. The range was then extended up to 6 MeV by including lines of ^{16}O, obtained by using an α source.

Although the gain alignment improved with respect to raw data, energy residues, computed from the literature values, showed staggering for different energy regions, leading to discrepancies up to 6 keV. This issue was related to the signal processing in the digitizers due to baseline oscillations, resulting in the pattern shown in Fig. 1. It is important to note that these oscillations were different for each detector and were worsened by the high counting rate.

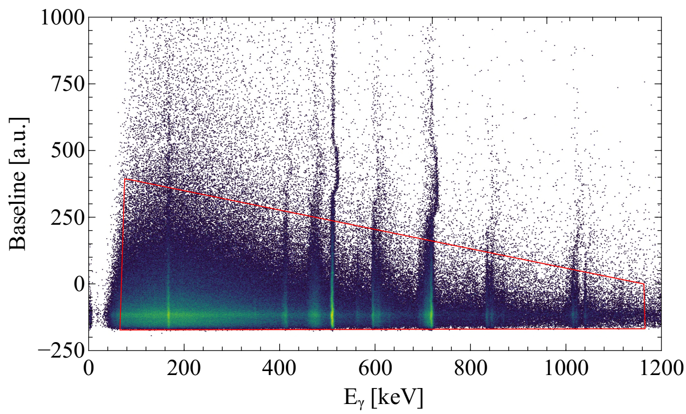

Fig. 1. (Colour on-line) Matrix correlating the γ-ray energy and the baseline of the signal of crystal 25. The 2-dimensional gate applied to the data is indicated by the red/grey contour.

To overcome this calibration issue, we explored the possibility of an indirect measurement of the 2_1^+ state energy, focusing our analysis on the low-energy part of the γ-ray spectrum (up to 1 MeV). In particular, the 2_1^+ energy can be calculated as

$$E_x\left(2_1^+\right) = E_\gamma\left(2_1^+ \rightarrow 1_1^-\right) + E_\gamma\left(1_1^- \rightarrow 0_1^+\right) + T_\mathrm{r}\,, \tag{1}$$

where $E_\gamma(2_1^+ \rightarrow 1_1^-)$ is the transition energy to be measured (918(4) keV from Ref. [11] and 920 keV from Ref. [12]), $E_\gamma(1_1^- \rightarrow 0_1^+)$ is known with a small uncertainty (6092.4(2) keV from Ref. [13]), and T_{r} indicates the recoil energy correction.

In the low-energy region of the γ-ray spectrum, it is possible to reduce the impact of the baseline fluctuation by applying 2-dimensional gates on the "γ-ray energy *versus* baseline" matrix for each crystal. This is shown in Fig. 1, where events affected by the baseline offset are rejected and excluded from the analysis. Such gates were applied before performing the first calibration with ^{152}Eu source, but also in the recalibration procedure, where the 511, 844, and 1014 keV Al peaks were used to correct the energy calibration on a run-by-run basis. Moreover, since we aimed at obtaining an accurate measurement and the statistics was still significant, only the most stable 31 out of 48 detectors were considered.

The effectiveness of this procedure was tested by comparing γ-ray energies obtained in this experiment with the ones measured with small uncertainty via (n,γ) in Ref. [13]. Discrepancies of 0.15 and 0.2 keV were observed for the 495.35(10) and 808.8(3) keV peaks.

The last steps of this analysis focused on the reconstruction of the reaction kinematics, the event-by-event Doppler correction, and the correlation of γ-particle events, exploiting the granularity of the ORRUBA detector. The result is depicted in Fig. 2, where a Doppler-corrected γ-ray spectrum (red/grey line) is compared with a non-Doppler-corrected one, gated on the reconstructed excitation energy E_x between 6500 and 7500 keV. In the latter, we have considered relative angles $\theta_{\gamma,\mathrm{recoil}}$ around 90°, to avoid uncertainties related to the Doppler-correction procedure.

The distribution of counts in the two spectra is very similar, leading to a centroid of 924.3(10) keV, where the variance is calculated as the quadratic sum of the fit uncertainty and the systematic error of the calibration procedure, assumed to be $\sigma_{\mathrm{s}} = \pm 1$ keV. Using Eq. (1), the corresponding excitation energy of the 2_1^+ state becomes 7018.1(10) keV.

Previously, only one direct measurement of the $2_1^+ \rightarrow 1_1^-$ γ-ray was performed: the evaluated energy of Ref. [11] is deduced from the level excitation energy corrected for the nucleus recoil induced by the γ-ray emission, while the direct observation of Ref. [12] was obtained with a NaI detector and error bars were not provided. Furthermore, the $2_1^+ \rightarrow 0_1^+$ transition has only been directly observed in an experiment using a Ge(Li) detector [14] that resulted in its energy of 7011.7(52) keV, affected by an even greater uncertainty. On the other hand, indirect measurements of Refs. [11, 15] point to a value closer to 7012 keV, with an uncertainty of 4 keV. However, these discrepancies call for additional investigations, and a direct measurement of the $2_1^+ \rightarrow 0_1^+$ γ-ray and its $B(\mathrm{E2})$ transition probability is necessary.

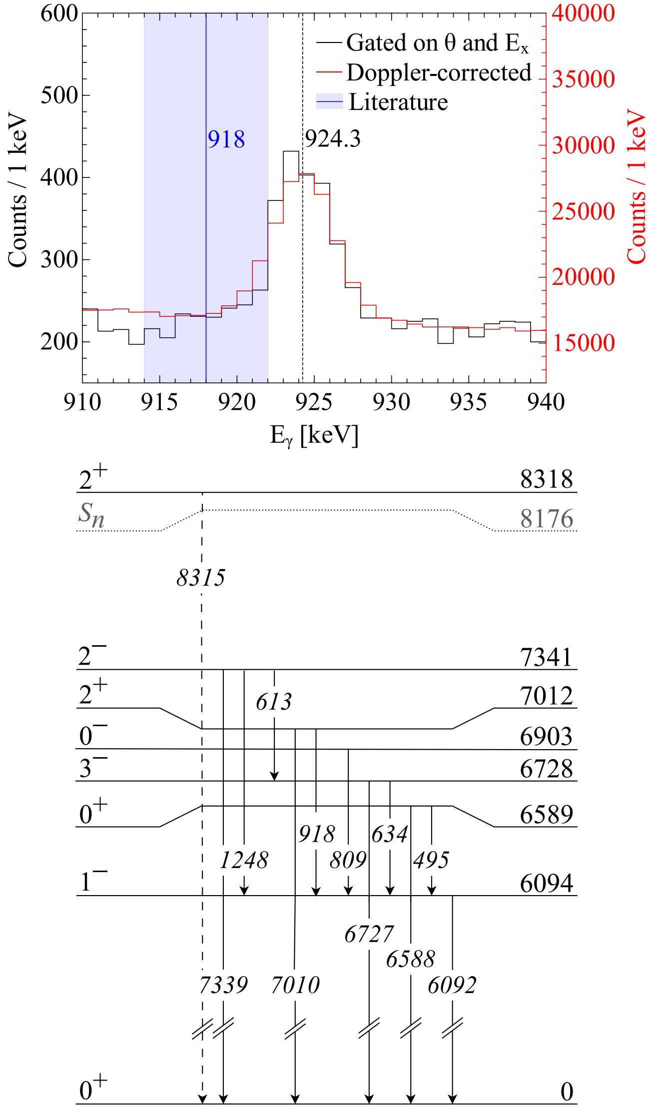

Fig. 2. (Colour on-line) Top: γ-ray spectra measured in coincidence with protons, zoomed on the $2^+_1 \rightarrow 1^-_1$ transition. The black line shows the spectrum gated on $88.2° < \theta_{\gamma,\mathrm{recoil}} < 90.2°$ and on $6500 < E_x$ [keV] < 7500, while the Doppler-corrected spectrum is shown with the red/grey line (see the text for details). The $2^+_1 \rightarrow 1^-_1$ transition energy measured in Ref. [11], along with its error bars, is indicated by the blue vertical line, blue shaded area, and the label. Bottom: Partial level scheme of ^{14}C. Energies of levels and transitions are reported from Ref. [2] and expressed in keV.

The results here presented will be compared with the (E_γ, τ) χ^2 surface obtained from the DSAM measurement of Ref. [6] in order to determine a new value for the lifetime of the state.

4. Conclusion

The 2_1^+ state in ^{14}C has been studied in an experiment performed at the Argonne National Laboratory, in order to determine the B(E2) transition probability of the direct decay towards the ground state. The analysis procedure allowed us to indirectly measure the energy of the 2_1^+ excited state, which will be combined with previous DSAM measurements to extract the lifetime of the state. Complementary results on the B(E2) of the γ-ray from the 2_2^+ near-threshold state, partially discussed in Ref. [16], will be published soon and will give additional information on the decay properties of the 2_2^+ near-threshold state in ^{14}C, to be compared with the predictions of the SMEC calculations.

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