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γ DECAY FROM THE NEAR-NEUTRON-THRESHOLD 2^+ STATE IN ^{14}C: A PROBE OF COLLECTIVIZATION PHENOMENA IN LIGHT NUCLEI*

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A search for the γ decay of the 2_2^+ near-threshold resonance in ^{14}C, located 142 keV above the neutron separation energy, was performed at the Argonne National Laboratory with the GRETINA γ-ray spectrometer coupled to the ORRUBA Si detectors. The sensitivity of the experiment was of the order of 2.6×10^{-5}. This is comparable to the gamma branch calculated by the Shell Model Embedded in the Continuum, which predicts a significant enhancement of the $2_2^+ \to 0$ transition probability, as a consequence of the collectivization of the near-threshold state.

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1. Introduction

Light nuclei, with mass of $A < 20$, are among the best probes for modern nuclear structure theory (see, *e.g.*, Refs. [1–3]). Of particular interest are near-threshold states, *i.e.*, narrow resonances lying in the proximity of particle-emission thresholds, which play a crucial role in nuclear astrophysics. The most famous example is the so-called Hoyle state in ^{12}C [4]. According to advanced theory approaches, such as the Shell Model Embedded in the Continuum (SMEC) [5], which describes the nucleus as an open many-body quantum system, the existence of near-threshold states is a universal phenomenon. The structure of these states is expected to provide relevant information on the microscopic mechanism leading to the onset of collectivization in light nuclei, such as C, O, Ne isotopes. The aim of the present experiment was to study the case of ^{14}C, in particular the γ decay of its 2^+_2 state — located 142 keV above the neutron-decay threshold (at 8318 keV). This state is predicated by the SMEC model to gain collectivity when the coupling with the continuum is considered, in contrast with the standard Shell Model calculations. According to the SMEC model [6], the γ-decay branch from the 2^+_2 near-threshold state in ^{14}C is expected to be of the order of 5×10^{-5}. Therefore, state-of-the-art arrays with improved sensitivity based on segmented HPGe crystals, such as GRETINA [7], are needed to possibly detect its 8315-keV γ ray or to provide the best possible upper limit.

2. Experimental technique

The experiment was performed at the ATLAS facility of the Argonne National Laboratory (ANL) in 2021, within the GODDESS (GRETINA ORRUBA: Dual Detectors for Experimental Structure Studies) experimental campaign. The ^{14}C nucleus was populated in the fusion–evaporation reaction induced by a ^{6}Li beam at 7 MeV on different ^{9}Be targets, 200 and 400 μg/cm^2 thick, after the evaporation of a single proton from the ^{15}N compound nucleus. The γ decay and the evaporated protons were measured with the GODDESS setup, consisting of the GRETINA γ-ray spectrometer [7], comprising 48 HPGe segmented detectors, coupled to the ORRUBA charged particle silicon strip detectors arranged in a barrel configuration [8]. Total detection efficiency of $\sim$10%, at 1.3 MeV, and 55% are estimated for GRETINA and ORRUBA, respectively [9]. Data were acquired with two different triggers, a particle–γ coincidence and a particle-only condition, downscaled by a factor of ≈ 100.

3. Data analysis

In order to reconstruct the reaction kinematics, perform an event-by-event Doppler correction, and build γ-particle coincidences, an accurate pre-analysis of the data was needed. Regarding the GRETINA detectors, a preliminary linear calibration in the 0–6 MeV range was performed. Furthermore, an in-beam recalibration was applied to each run of the experiment, to account for gain drifts over time. A ^{228}Th α source was employed to calibrate all the ORRUBA silicon strip detectors in the 5–9 MeV region. A position calibration of the SX3 barrel detectors was also performed to determine the interaction position of the evaporated protons along a single resistive strip, resulting in a resolution of $\Delta\theta \sim 1^\circ$. By measuring the energy and direction of the evaporated protons, it was possible to reconstruct the kinematics of the reaction, hence the excitation energy spectrum of the ^{14}C nucleus.

Finally, the GRETINA and ORRUBA data were merged, and γ–particle coincident spectra were built, after the reconstruction of γ events with the add-back procedure and the application of an event-by-event Doppler correction. Prompt γ rays were identified within a 200 ns coincidence window between GRETINA and ORRUBA. The energy and direction of incident γ rays were obtained with the add-back technique, by summing up energy core signals within a spherical volume ($r = 80$ mm) centered around the most energetic interaction, which was assumed as a first hit. An event-by-event Doppler correction was then applied to the reconstructed γ-ray energy, using the relative angle $\theta_{\gamma,\mathrm{rec}}$ between the recoiling ^{14}C nucleus and the direction of the γ ray. The former was obtained from the energy and direction of

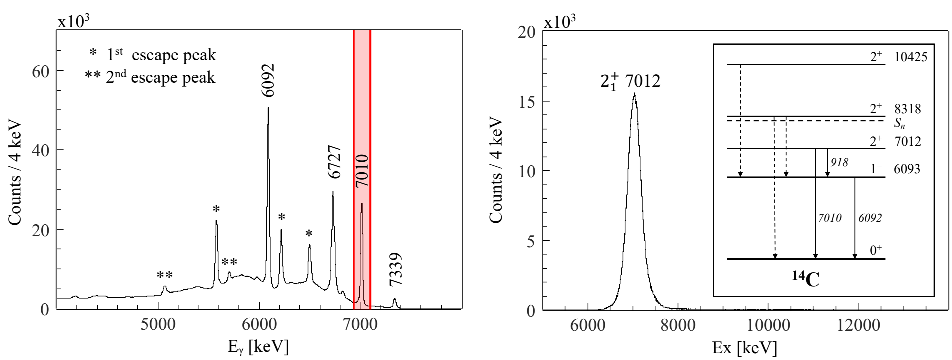

Fig. 1. (Color online) Left: Doppler corrected γ-ray spectrum of ^{14}C in coincidence with protons detected by ORRUBA. The gate on the 7010-keV transition is highlighted in red/gray. Right: Projection of the background-subtracted excitation energy spectrum in coincidence with the 7010-keV γ ray. Inset: Partial level scheme of ^{14}C showing known (solid lines) and expected (dotted lines) γ decays.

the detected protons. Particle–γ coincidence spectra were initially analyzed in the energy region of discrete states of ^{14}C, as shown in the left panel of Fig. 1. The projection on the excitation energy axis, gated on the 7010-keV γ ray depopulating the 2^+_1 state, is presented in the right panel of Fig. 1, demonstrating the effectiveness of the experimental technique. By assuming a similar cross section for the population of the 2^+_1 and 2^+_2 states, as observed in [11] and in our work, a detection limit of 2.6×10^{-5} is obtained for the γ-decay branch from the 2^+_2 state. A detailed analysis of the 8-MeV region of the gamma spectrum, using different background subtraction techniques, is ongoing and final results will be reported in a future publication.

4. Conclusions and perspectives

A search for the γ decay from the 2^+_2 near-neutron-threshold state in ^{14}C was performed at the Argonne National Laboratory to investigate the impact of the continuum on the electromagnetic decay properties of this resonance. A detailed pre-analysis was performed to calibrate the GRETINA and ORRUBA arrays in order to reconstruct the reaction kinematics and build γ-particle events. In the future, an estimate for the 8315-keV γ decay from the 2^+_2 state will be given and the results will be compared with the SMEC model predictions.

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