IL NUOVO CIMENTO **46 C** (2023) 90
DOI 10.1393/ncc/i2023-23090-1

COMMUNICATIONS: SIF Congress 2022

Searching for the γ decay from the near-neutron threshold 2^+ state in ^{14}C: A probe of collectivization phenomena in light nuclei

G. CORBARI(1)(2), S. BOTTONI(1)(2), M. CIEMAŁA(3), F. C. L. CRESPI(1)(2), S. LEONI(1)(2), B. FORNAL(3), R. V. F. JANSSENS(4)(9), S. D. PAIN(5), M. SICILIANO(6), E. ALBANESE(1)(2), A. D. AYANGEAKAA(4)(9), G. BENZONI(2), S. CARMICHAEL(7), M. CARPENTER(6), K. CHIPPS(5), N. CIEPLICKA(3), P. COPP(6), J. FORSON(8), E. GAMBA(1)(2), Ł.W. ISKRA(3), H. JAYATISSA(6), F. KONDEV(6), T. LAURITSEN(6), B. MILLION(2), C. MÜLLER-GATERMANN(6), A. PALMISANO(8), M. POLETTINI(1)(2), C. PORZIO(1)(2), W. REVIOL(6), N. SENSHARMA(4)(9), D. SEWERYNIAK(6), C. UMMEL(10), O. WIELAND(2), G. WILSON(6)(11), S. ZHU(12) and S. ZILIANI(1)(2)

(1) *Dipartimento di Fisica, Università di Milano - Milano, Italy*
(2) *INFN, Sezione di Milano - Milano, Italy*
(3) *Institute of Nuclear Physics, IFJ-PAN - Krakow, Poland*
(4) *University of North Carolina at Chapel Hill - Chapel Hill, NC, USA*
(5) *Oak Ridge National Laboratory - Oak Ridge, TN, USA*
(6) *Argonne National Laboratory - Lemont, IL, USA*
(7) *Notre Dame University - Notre Dame, IN, USA*
(8) *University of Tennessee-Knoxville - Knoxville, TN, USA*
(9) *Triangle Universities Nuclear Laboratory, Duke University - Durham, NC, USA*
(10) *Rutgers University - Piscataway, NJ, USA*
(11) *Louisiana State University - Baton Rouge, LA, USA*
(12) *Brookhaven National Laboratory - Upton, NY, USA*

received 20 February 2023

Summary. — The γ decay from the 2_2^+ near-threshold resonance in ^{14}C, located 142 keV above the neutron emission threshold, was searched for in a fusion-evaporation experiment at Argonne National Laboratory with the GODDESS setup, comprising the GRETINA γ-ray spectrometer coupled to the ORRUBA charged particle detector. The Shell Model Embedded in the Continuum predicts a significant enhancement of the $2_2^+ \rightarrow 0$ transition probability, owing to a collectivization of the near-threshold state. The corresponding γ branch is expected to be of the order of 5×10^{-5}, which is comparable with the sensitivity of this experiment.

1. – Introduction

Light nuclei, with mass $A < 20$, have proven to be optimal test benches for modern nuclear structure models (see, *e.g.*, refs. [1-3]). Of particular interest are near-threshold states, *i.e.*, narrow resonances lying in the proximity of particle-emission threshold, induced by the coupling of discrete bound states with particle-decay channels. Within the Shell Model Embedded in the Continuum (SMEC) framework [4], which describes nuclei as open quantum systems, the existence of near-threshold states emerges as 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, including clustering phenomena.

In the present work, we studied the case of ^{14}C, which presents a 2^+_2 near-threshold state at 8318 keV–142 keV above the neutron separation energy. This state is predicated by the SMEC model to gain collectivity when the coupling with the continuum is considered, in contrast with standard Shell-Model calculations, resulting in enhanced electromagnetic transition probabilities. According to the SMEC model [5], 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 [6], are needed to possibly detect the 8315-keV γ-ray from the 2^+_2 narrow resonance, or to provide the best possible upper limit.

2. – Experimental details

In this experiment, the ^{14}C nucleus was populated using the ^{6}Li + ^{9}Be fusion-evaporation reaction, after the evaporation of a single proton from the ^{15}N compound nucleus. The ^{6}Li beam was provided by the ATLAS facility of Argonne National Laboratory (ANL), at an energy of 7 MeV, impinging on a ^{9}Be target with a thickness of 200 or 400 μg/cm^2. The GODDESS setup (GRETINA ORRUBA: Dual Detectors for Experimental Structure Studies) was employed: evaporated protons were detected by the ORRUBA charged particle silicon strip detectors, arranged in a barrel configuration [7], while γ-rays were detected by the GRETINA γ-ray spectrometer [6], comprising 48 HPGe segmented detectors. A total detection efficiency of $\sim$10%, at 1.3 MeV, and 55% are estimated for GRETINA and ORRUBA, respectively [8]. 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

The initial stages of the data analysis were focused on the reconstruction of the reaction kinematics, which was a necessary step to obtain i) the excitation energy spectrum of the ^{14}C nucleus, ii) perform an event-by-event Doppler correction and iii) build γ-particle coincidences.

By exploiting the highly segmented QQQ5 endcap detectors and the resistive strips of the SX3 barrel detectors, it was possible to determine the interaction position of the evaporated protons in ORRUBA, with a resolution of $\Delta\theta \sim 1^\circ$. Furthermore, to prevent α particle (and other evaporation channels) from reaching the ORRUBA detectors, Al absorbers of about 200, 250 and 500 μm were mounted. As shown in fig. 1, this allowed obtaining a rather clean kinematic line matrix, at the cost of worsening the energy resolution due to the straggling of protons in the absorbers. The reconstructed excitation

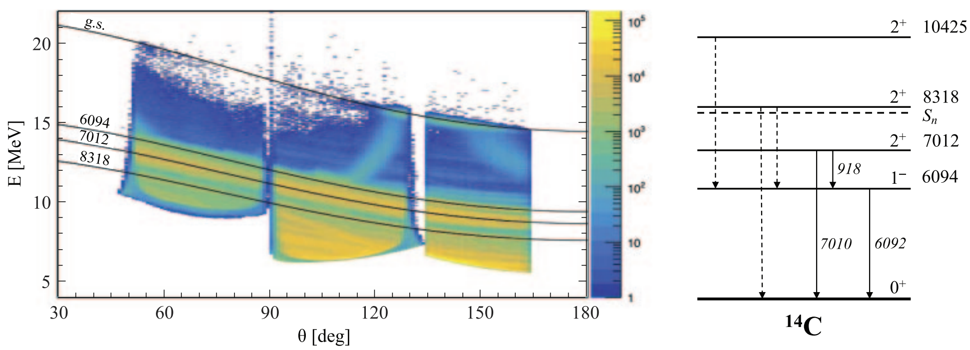

Fig. 1. – Left: proton energy E versus laboratory angle θ matrix. Superimposed black lines correspond to expected kinematic lines for protons feeding both ground and excited states of ^{14}C. Experimental data correspond to runs with the $400\,\mu$g/cm^2 target. Calculations performed with the nptool software [9]. Right: partial level scheme of ^{14}C showing known (solid lines) and expected γ decays (dashed lines) from the 2^+_1, 2^+_2 and 2^+_3 states. Energies in keV from ref. [10].

energy spectrum of ^{14}C is presented on the left panel of fig. 2: the first excited 1^- state and the near-threshold 2^+_2 state of interest are well separated, while peaks in the 7 MeV region are not completely resolved due to the high density of states and the limited energy resolution, the latter being $\sim$400 and $\sim$500 keV for the 200 and $400\,\mu$g/cm^2 targets, respectively.

Finally, 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 determined with the add-back technique, by sum-

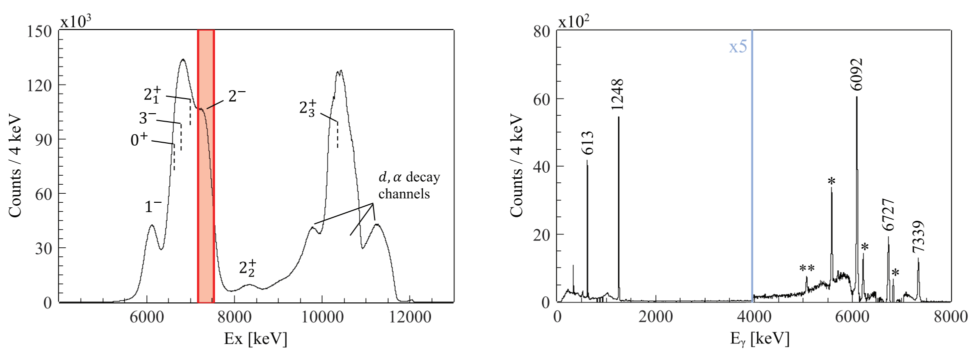

Fig. 2. – Left: reconstructed excitation energy spectrum of ^{14}C, in coincidence with γ-rays. The red region corresponds to the gate interval on the 7341-keV state of the excitation energy spectrum of ^{14}C in coincidence with γ-rays. Right: projection of the background-subtracted γ-ray spectrum in coincidence with the 2^- state. Transitions of 613, 1248, 6092, 6727 and 7339 keV are observed, corresponding to the γ-decay towards the 3^- and 1^- excited states, as well as the ground state. Single and double star symbols indicate 1st and 2nd escape peaks, respectively.

ming 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 $\theta_{\gamma,rec}$ between the recoiling ^{14}C nucleus and the direction of the γ-ray. The former was obtained from the energy and direction of 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. 2. The projection on the γ-ray energy axis, gated on the 7341-keV 2^- excited state, is presented in the right panel of fig. 2. All of the γ transitions depopulating the 2^- state were clearly identified, 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 on the 2_2^+ γ-decay branch will be reported in a future publication.

4. – Conclusions and perspectives

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

* * *

The authors acknowledge GRETINA and ORRUBA Collaborations and the staff of the Argonne National Laboratory for providing the beam and for the help given during the experiment.

REFERENCES

[1] Ciemała M. *et al.*, *Phys. Rev. C*, **101** (2020) 021303.
[2] Cieplicka-Oryńczak N. *et al.*, *Phys. Lett. B*, **834** (2022) 137398.
[3] Ziliani S. *et al.*, *Phys. Rev. C*, **104** (2021) L041301.
[4] Okołowicz J., Nazarewicz W. and Płoszajczak M., *Fortschr. Phys.*, **61** (2012) 66.
[5] Płoszajczak M. and Okołowicz J., *J. Phys.: Conf. Ser.*, **1643** (2020) 012156.
[6] Paschalis S. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **709** (2013) 44.
[7] Pain S. D. *et al.*, *Phys. Procedia*, **90** (2017) 455.
[8] Lauritsen T. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **836** (2016) 46.
[9] Matta A. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **43** (2016) 045113.
[10] Ajzenberg-Selove F., *Nucl. Phys. A*, **523** (1991) 1.
[11] Ajzenberg-Selove F., Bingham H. and Garrett J., *Nucl. Phys. A*, **202** (1973) 152.