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DECAY OF THE “STRETCHED” M4 RESONANCE
IN $^{13}\text{C}^*$

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“Stretched” states are examples of the simplest nuclear excitations in the continuum, thus offering an excellent testing ground for various theoretical approaches. The decay of the stretched single-particle state in ^{13}C , located at 21.47 MeV, was investigated in an experiment performed recently at the Cyclotron Centre Bronowice (CCB) at IFJ PAN in Kraków. First experimental information on the proton and neutron decay channels of this resonance was obtained by employing coincidence measurement of protons inelastically scattered on the ^{13}C target and γ rays from daughter nuclei. The new experimental findings will be used for testing predictions obtained by the Gamow Shell Model calculations.

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1. Introduction

The “stretched” excitations in nuclei are dominated by a single-particle–hole component for which the excited particle and the residual hole couple to the maximal possible spin value (J_{max}) [1]. It happens when both the particle and the hole occupy the highest angular-momentum orbitals j_p and j_h in their respective shells and couple to $J_{\text{max}} = j_p + j_h$. The configurational purity of such states is assured by the fact that other one-particle–one-hole configurations having the same angular momentum and parity quantum numbers lie at least $2\hbar\omega$ higher in excitation energy. This feature makes stretched states ones of the simplest nuclear excitations. Direct measurement of their properties, such as, for example, decay patterns, should provide data, which may be used as a very demanding test of state-of-the-art theory approaches, from Shell Model Embedded in the Continuum to *ab initio*-type calculations.

In p -shell nuclei, the stretched states can be excited via magnetic ($p_{3/2} \rightarrow d_{5/2}$) M4 transitions [4, 5]. In fact, by using inelastic scattering at large momentum transfer, a few M4 stretched configurations have been identified in p -shell nuclei (such as C, N, O). In turn, the decay of these M4 resonances in light systems is expected to be dominated by the direct decay of proton and neutron over the statistical (compound nucleus) decay, however, experimental information on this decay is largely missing now.

The goal of the present experiment was to investigate, in particular, the structure of the ^{13}C nucleus, which is one of the very few odd- A nuclei for which compelling evidence for magnetic transitions to stretched states was gathered. Here, stretched M4 transitions at 9.50, 16.08 and 21.47 MeV, corresponding to the ($p_{3/2} \rightarrow d_{5/2}$) M4 configuration, have been identified in inelastic pion [6] and proton scattering [7], as well as in inelastic electron scattering [8]. By means of a combined analysis of these (e, e'), (π, π'), and (p, p') data, isoscalar and isovector transition amplitudes for M4 excitations were determined.

The state of interest, a 21.47-MeV resonance, was already populated in the (p, p') reaction. In the spectrum of inelastically-scattered protons, measured at approx. 30° , it appears as a strong and isolated peak with a width of 270 keV, when using a proton beam with energy of 135 MeV, as reported in [7]. The angular distribution of the inelastically scattered protons exciting the 21.47-MeV resonance has a maximum around $\Theta_{\text{CM}} = 30^\circ$ and decreases sharply when going to smaller angles [7].

In this paper, we present preliminary results from the $^{13}\text{C}(p, p')$ experiment, performed at the Cyclotron Centre Bronowice at IFJ PAN (Kraków, Poland), in which the ^{13}C nucleus was studied by using the proton–gamma coincidence technique with the multidetector KRATTA [2]–PARIS [3]–LaBr₃ setup. The collected data allowed to obtain, for the first time, information on the decay of the 21.47-MeV M4 resonance in ^{13}C .

2. Experimental setup

In order to populate the 21.47-MeV stretched M4 excitation in ^{13}C , proton inelastic scattering (p, p') was used. A 135-MeV proton beam from the cyclotron Proteus C-235 at CCB was focused on a thick, 197-mg/cm², pure ^{13}C target which was placed in the centre of a big vacuum chamber. The detection setup consisted of: (i) the KRATTA telescope array for scattered protons measurement, (ii) four LaBr₃ detectors and two clusters of the PARIS scintillator array for γ -ray detection, and (iii) a thick position-sensitive Si detector for the measurement of light charged particles produced in the reaction. Six modules of the KRATTA telescope array were placed at $\sim 36^\circ$ with respect to the beam axis, where the angular distribution of the scattered protons associated with the production of the 21.47-MeV resonance in ^{13}C should reach its maximum. A single KRATTA detector consists of three identical, 500- μm thick, large area photodiodes, and of two CsI crystals, allowing for identification of protons and measurement of their energy and emission angle. Additionally, each KRATTA module was equipped with 4 plastic scintillators placed in front, to improve angular and timing resolution.

In the following, results of the preliminary analysis of the events comprising coincidences between protons and γ rays measured with the 4 LaBr₃ detectors are presented.

3. Data analysis and results

From the measured energy of the scattered protons, the excitation energy spectrum, shown in Fig. 1 (a), was constructed, confirming the production of the 21.47-MeV M4 resonance in ^{13}C . The data were also sorted into the

proton–gamma coincidence matrix presented in Fig. 2, which was instrumental in associating the excitations in ^{13}C with the corresponding γ decay (in ^{13}C or daughter nuclei). The projection of this matrix on the excitation energy axis is presented in Fig. 1 (b).

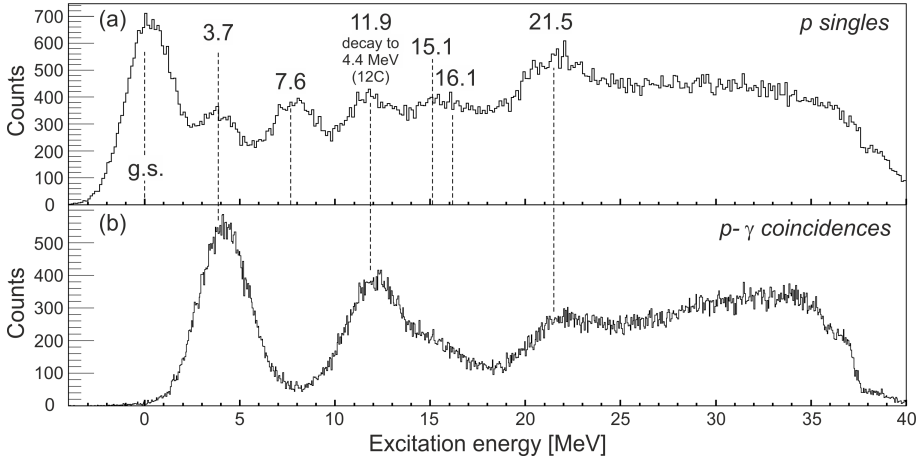


Fig. 1. Excitation energy spectra measured at $\sim 36^\circ$ corresponding to the excitations in the ^{13}C target nucleus measured as singles (a) and in coincidences with γ rays (b).

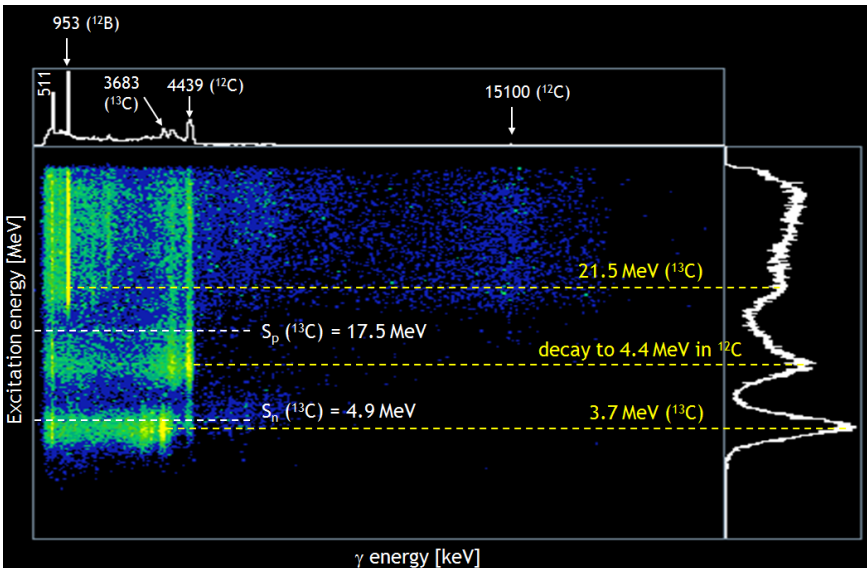


Fig. 2. Two-dimensional matrix from the present experiment, showing the energy of the γ rays detected in the LaBr_3 scintillators *versus* the excitation energy extracted from the energy of scattered protons measured in KRATTA.

The decay scheme of the 21.47-MeV resonant state in ^{13}C resulting from the present analysis is shown in Fig. 3. The two main channels, associated with proton or neutron emission, were expected to be observed in the decay of this state in proton–gamma coincidences. Due to the high proton sep-

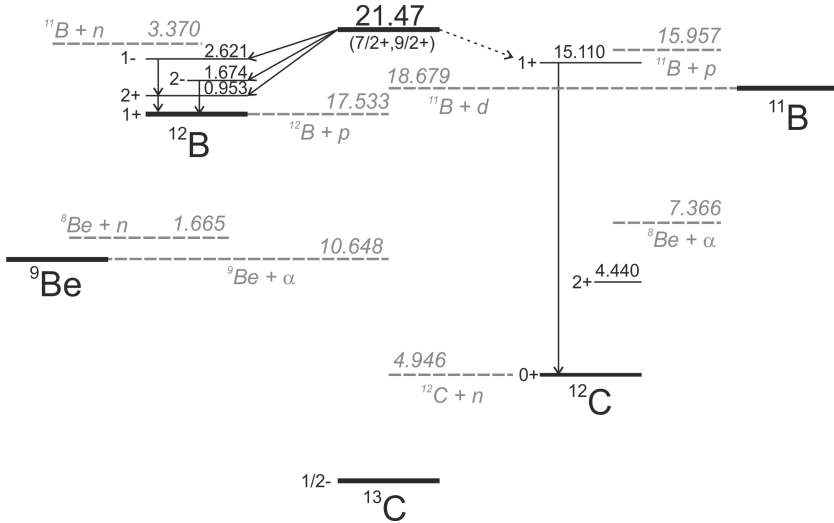


Fig. 3. The decay scheme of the 21.47-MeV M_4 resonant excitation in ^{13}C from the present analysis.

aration energy in ^{13}C ($S_p = 17.533$ MeV), one may expect the population of only low-lying bound states in ^{12}B in the proton decay channel, namely the 953-, 1674-, 2621-, and 2723-keV excitations having spin-parity values of 2^+ , 2^- , 1^- and 0^+ , respectively. The decay of these low-lying states in ^{12}B should involve primarily the 953-, 1668-, 1674-, and 2723-keV γ rays. Out of these transitions, the 953-keV γ ray from the first-excited state in ^{12}B is observed as a strong peak in coincidence with the 21.47-MeV excitation in ^{13}C (Fig. 4). Furthermore, the 1668-keV and 1674-keV transitions could not be separated due to the energy resolution of the LaBr_3 detectors of approximately 40 keV. Therefore, we could not firmly state whether the peak labeled with these energies is due to decay of either the 2.621-MeV state or the 1.674-MeV or both. The most of the intensity of the proton decay, 89(4)%, is associated with the population of the 0.953-MeV state in ^{12}B , while the remaining 11(4)% is distributed between the 2.621- or 1.674-MeV states.

For the neutron decay channel leading to ^{12}C , one may expect to observe branches feeding the states 2^+ at 4.439 MeV and 1^+ at 15.110 MeV, which decay to the ground state via the 4439- and 15100-keV γ rays, respectively. Out of these two transitions, only a trace of the 15100-keV γ ray was observed

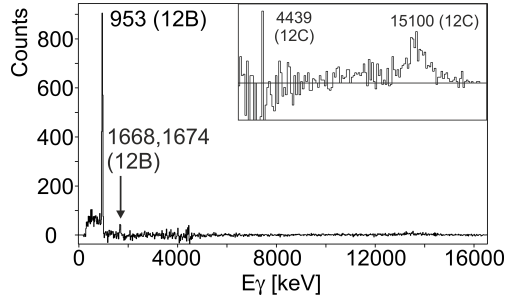


Fig. 4. Gamma-ray coincidence spectrum gated on the 21.47-MeV resonance in ^{13}C .

in coincidence with protons populating the 21.47-MeV resonance (see inset of Fig. 4). Due to a small number of counts in the 15100-keV line and large uncertainty resulting from the background subtraction, a precise value of the intensity feeding the 15.1-MeV state may not be given at this stage of analysis.

We note that all other neutron branches populate states in ^{12}C which decay primarily by protons and alpha particles leading to ^{11}B and ^8Be final nuclei. Both channels are practically not associated with γ -rays emission: in the first case, due to limitation in the available energy, in the second one, due to the unbound nature of the ^8Be final system. Similarly, for the alpha channel, no bound state may be produced in the ^9Be daughter nucleus. Emission of the deuteron from the 21.47-MeV resonance in ^{13}C may lead to the first-excited state in ^{11}B decaying via the 2124-keV γ ray, but such a transition was not observed in the spectrum.

4. Summary

The decay of the 21.47-MeV stretched state in ^{13}C was studied with a (p, p') reaction employing the proton–gamma coincidence technique. For the first time, γ rays following nucleon emission from the resonance provided information on the feeding of specific states in daughter nuclei. The decay branchings leading to states in ^{12}B (proton decay channel) were defined: the most of the intensity, 89(4)%, feeds the 0.953-MeV state, while the remaining 11(4)% is distributed between the 2.621- or 1.674-MeV excitations. The neutron decay channel, involving neutron emission to the 15.110-MeV level in ^{12}C , was observed as well.

As the structure of unbound states such as the M4 resonance at 21.47 MeV in ^{13}C differs from that of bound states located at low excitation energy, a comprehensive understanding of such a system requires an open quantum system description. The model providing a natural framework for such a description is the Gamow Shell Model (GSM) [9, 10], which is capable of

describing both correlations and continuum effects on an equal footing. The decay of the M_4 resonance in ^{13}C , which has been studied in the presented work, provides an excellent testing ground for the GSM approach. In particular, the results here obtained will be useful to probe and constrain the spin–orbit and tensor components of the GSM interaction.

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