M4 RESONANCES IN LIGHT NUCLEI STUDIED AT CCB*

N. Cieplicka-Oryńczak, B. Fornal, M. Ciemała, M. Kmiecik, A. Maj
J. Łukasik, P. Pawłowski, B. Sowicki, B. Wasilewska, M. Ziębliński
P. Bednarczyk, I. Ciepał, K. Dhanmeher, J. Grębosz, Ł.W. Iskra
M. Krzysiek, M. Matejska-Minda, K. Mazurek, W. Parol, B. Włoch

Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

S. Leoni, S. Ziliani, S. Bottoni, A. Bracco, F. Camera
F.C.L. Crespi, E. Gamba

Università degli Studi di Milano and INFN Sezione di Milano, Italy

C. Boiano, S. Brambilla, B. Million

INFN Sezione di Milano, Milano, Italy

Y. Jaganathen

National Centre for Nuclear Research, Warsaw, Poland

M. Płoszajczak

Grand Accélérateur National d'Ions Lourds, CEA/DSM-CNRS/IN2P3, Caen, France

I. Burducea, C. Clisu, N. Florea, D.A. Iancu, N. Marginean
R. Marginean, L. Stan

"Horia Hulubei" National Institute for Physics and Nuclear Engineering
Bucharest-Măgurele, Romania

M.N. Harakeh

Nuclear Energy Group, ESRIG, University of Groningen, Groningen, The Netherlands

P. Kulessa

Institut für Kernphysik, Jülich, Germany

I. Matea

Université Paris-Saclay, CNRS/IN2P3, Orsay, France

M. Sferrazza

Université Libre de Bruxelles, Brussels, Belgium

Received 16 January 2023, accepted 18 January 2023,
published online 22 March 2023

Corrected March 25, 2025
according to Erratum ibid. **18**, 2-E1 (2025)

* Presented at the Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 28 August–4 September, 2022.

M4 resonances in light nuclei result from the $p_{3/2} \to d_{5/2}$ stretched excitations. Their configurations should be relatively simple, which makes them good benchmarks for the theoretical calculations taking into account the role of continuum couplings. The first experimental studies aiming at tracing the decay of the M4 stretched resonance in ^{13}C, located at 21.47 MeV, were undertaken at the Cyclotron Centre Bronowice at the Institute of Nuclear Physics Polish Academy of Sciences in Kraków, Poland (IFJ PAN). They provided information on the proton and neutron decay channels of this resonance to ^{12}B and ^{12}C daughter nuclei, respectively. These experimental results were then compared with the theoretical calculations based on the Gamow Shell Model approach, in terms of energy, width, and in particular, the decay pattern. Furthermore, the studies of the next cases, namely, ^{14}N and ^{16}O, where several M4 resonances appear at around 20 MeV, have been recently performed at CCB. The new experimental findings will serve as a testing ground for future calculations describing the heavier nuclei in this important region of the nuclear chart.

DOI:10.5506/APhysPolBSupp.16.4-A4

1. Introduction

In light nuclei, the theoretical description of low-lying bound states can be provided by state-of-the-art *ab initio* as well as large-scale shell-model calculations [1–9]. In turn, a comprehensive understanding of the higher-lying structures in light species, which could also shed more light on stellar nucleosynthesis processes, requires the inclusion of bound, unbound states, and reaction observables. In this paper, we concentrate on M4 resonances, which in light nuclei appear as high-lying excitations resulting from the proton or neutron $p_{3/2} \to d_{5/2}$ transitions [10]. Their wave functions are dominated by a one-particle–one-hole component for which the excited particle and the residual hole occupy the highest angular-momentum orbitals in their respective shells. Moreover, the particle and the hole couple to the maximal spin value. For this reason, the M4 resonances are called 'stretched' excitations. Due to the expected low density of other single particle–hole configurations of high angular momenta in the energy region where the stretched states appear, the configurations of these stretched states should be relatively simple. This feature makes them attractive as their theoretical analysis could provide clean information about the role of continuum couplings in their structure. For example, an adequate tool for the theoretical description of the stretched states is the Gamow Shell Model (GSM), providing a rigorous treatment of bound and unbound nuclear excitations and a fully consistent calculation of the resonance energy and width and their mutual relation (see Refs. [5, 11] and references cited therein). Therefore, the information on M4 resonances decays, which are currently very limited, should provide data which can be used as a very demanding test of this approach.

It has been proved that the stretched M4 excitations in p-shell nuclei (such as C, N, O) may be populated via inelastic scattering of protons, electrons or pions at large momentum transfer [10]. In turn, the decay of these M4 resonances is expected to proceed mostly by the direct decay of a proton or a neutron. However, it is only now that the experimental techniques provide the access to the information on such decay due to development of coincidence measurement methods. The goal of the experiments presented here was to investigate the decay of the stretched states in ^{13}C, ^{14}N, and ^{16}O nuclei using the proton inelastic scattering reaction as a method of population. The information about the stretched excitations in these nuclei known prior to present studies is summarized in Table 1.

Table 1. Summary of known M4 stretched resonances in ^{13}C, ^{14}N, and ^{16}O nuclei. The corresponding excitation energy in MeV and spin-parity values are reported in the two last columns. The information on the reaction mechanism, with which they were investigated prior to the present studies, is given in the second column, where symbols e, π, p refer to the inelastic scattering of electrons, pions, and protons, respectively.

Nucleus	Mechanism	Energy [MeV]	J^π
^{13}C	e, π, p	9.5	$9/2^+$
		16.08	$(7/2^+)$
		21.47	$(7/2^+, 9/2^+)$
^{14}N	e, π	15.1	$(3^-, 4^-)$
		16.9	(5^-)
		18.5	3^-
		20.1	$(3^-, 4^-)$
^{16}O	e, π, p	17.79	4^-
		18.98	4^-
		19.80	4^-

In this paper, we present the results from the ^{13}C(p,p') experiment, as well as the preliminary results from the ^{14}N(p,p') and ^{16}O(p,p') measurements performed at the Cyclotron Centre Bronowice at IFJ PAN, Kraków. We note, that it was the first time when the stretched states in the ^{14}N isotope were populated in proton inelastic scattering. The nuclei of interest were studied by using the proton–gamma coincidence technique with the multidetector KRATTA [12]–PARIS [13]–$LaBr_3$ setup. The collected data allowed to extract the branching ratios for the 21.47-MeV M4 resonance decay in ^{13}C. Moreover, the first, qualitative information on the decay of the stretched excitation at 16.9 MeV in ^{14}N was obtained. Additionally, it was proved that the decay of the close-lying 17.79-, 18.98-, and 19.80-MeV resonances in ^{16}O may be studied with the present setup at CCB.

2. Experimental setup and technique

The experiments took place at the CCB facility of the IFJ PAN in Kraków. The stretched states of interest were populated in inelastic proton scattering induced by the 135-MeV proton beam from the Proteus C-235 cyclotron focused on the target position. The following targets, produced at the IFIN-HH in Bucharest-Măgurele (Romania), were used:

(a) pure ^{13}C thick target (197 mg/cm^2),

(b) pure ^{13}C thin target (1 mg/cm^2) — in order to detect light-charged particles from the resonance decay using a 1.5-mm thick position-sensitive double-sided silicon strip detector (DSSSD),

(c) lithium amide (Li^{14}NH$_2$) thick target (160 mg/cm^2) — chosen as the H and Li components do not pollute the measurement. However, during the analysis, large oxygen contamination was observed, caused most probably by the high hygroscopicity of the compound, which absorbed humidity from the air.

To study the decay of the stretched states in ^{13}C, ^{14}N, and ^{16}O, a proton–gamma and proton–particle coincidence technique was used. Protons and γ rays were detected in a multidetector setup composed of:

(a) Kraków Triple Telescope Array (KRATTA) [12] for scattered protons measurement, placed forward with respect to the beam axis: 6 modules at $\sim 36^\circ$ in the ^{13}C thick-target experiment, and 30 modules covering the 30°–42° range in Θ in the ^{13}C thin-target and ^{14}N/^{16}O experiments. Additionally, four plastic detectors were placed in front of each KRATTA module, to improve timing and position information,

(b) two 9-fold clusters of the Photon Array for studies with Radioactive Ion and Stable beams (PARIS) [13] for γ-ray detection. One cluster was composed of the CeBr$_3$–NaI(Tl) phoswich detectors, while the other had LaBr$_3$(Ce)–NaI(Tl) crystals,

(c) four large-volume (3.5” × 8.0”) LaBr$_3$ crystals for γ-ray detection,

(d) thick, 1.5-mm Double-Sided Silicon Strip Detector (DSSSD) for light-charged particles measurement, situated backwards at 138°. The detector consisted of 16 vertical and 16 horizontal strips allowing also for position determination.

The KRATTA modules and the DSSD were placed inside the large, 1.5-m diameter vacuum chamber (as illustrated schematically in Fig. 1). PARIS and the $LaBr_3$ scintillators were inserted in specifically designed niches in the vacuum chamber walls and lid, respectively, that allowed the detectors to be put close to the target without being placed in vacuum.

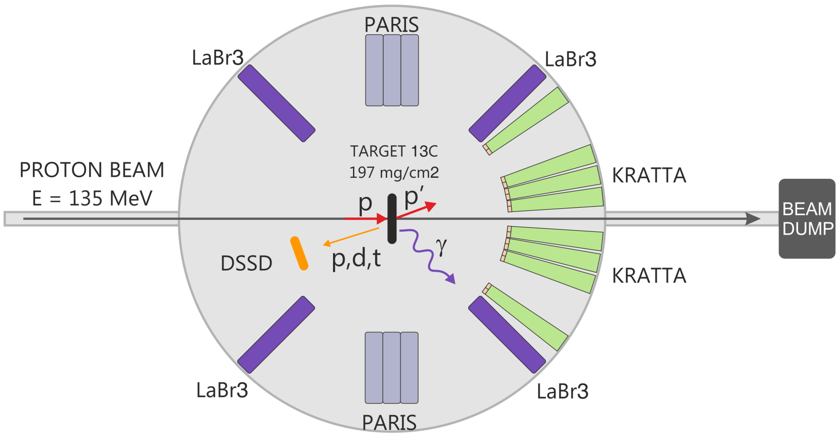

Fig. 1. Experimental setup at CCB: the KRATTA array, with plastic scintillators in front, together with the two PARIS clusters, four $LaBr_3$ detectors, and the DSSSD are shown. The setup is sketched as projected on a horizontal plane passing through the target. The $LaBr_3$ scintillators do not lie in this plane, they are placed above the target in dedicated top-lid niches, forming an angle of 45° with respect to an axis orthogonal to the plane.

From the measured energy of the scattered protons, the excitation energy spectra of the target nuclei were reconstructed. Moreover, the time coincidences between scattered protons, γ rays, and light-charged particles from the resonances decay were also registered.

3. Studied cases of M4 stretched resonances decays

3.1. Stretched state at 21.47 MeV in ^{13}C

A pilot experiment aiming at studying the decay of an M4 stretched resonance located at 21.47 MeV in ^{13}C, populated in a (p, p') reaction was performed at CCB in 2019 [14, 15]. ^{13}C was chosen as an object of investigation because three well-separated excitations resulting from stretched configurations, at 9.50, 16.08, and 21.47 MeV, had been already identified in this nucleus in the past, in inelastic scattering of electrons [16], pions [17], and protons [18]. In particular, the 21.47-MeV state was observed as an intense, well-isolated peak having the width of 270 keV [19].

From the proton–gamma coincidence studies at CCB, a clear identification of the γ rays from excited states in daughter nuclei, in coincidence with the population of the 21.47-MeV resonance, was obtained for the first time [15]. In particular, proton- and neutron-decay channels from this stretched state were observed. The strongest branch of the proton-decay channel (69(6)%) leads to the 2^+, 953-MeV first-excited state in ^{12}B, while a less intense one (7(2)%) to the 2.621- and/or 1.674-MeV states in ^{12}B. In the neutron-decay channel, a branch feeding the 15.11-MeV state in ^{12}C (24(5)%) was measured, while no sign of a population of the 4.44-MeV state in ^{12}C, was observed. Moreover, the analysis of the second part of the experiment, performed at CCB in 2020 with the thin ^{13}C target and employing proton–particle coincidences, made possible estimation of the decay branch leading to the ground state of ^{12}B ($< 23\%$) [15], which cannot be observed in proton–gamma measurement. The decay scheme of the 21.47-MeV stretched resonance in ^{13}C obtained from the present studies is reported in Fig. 2.

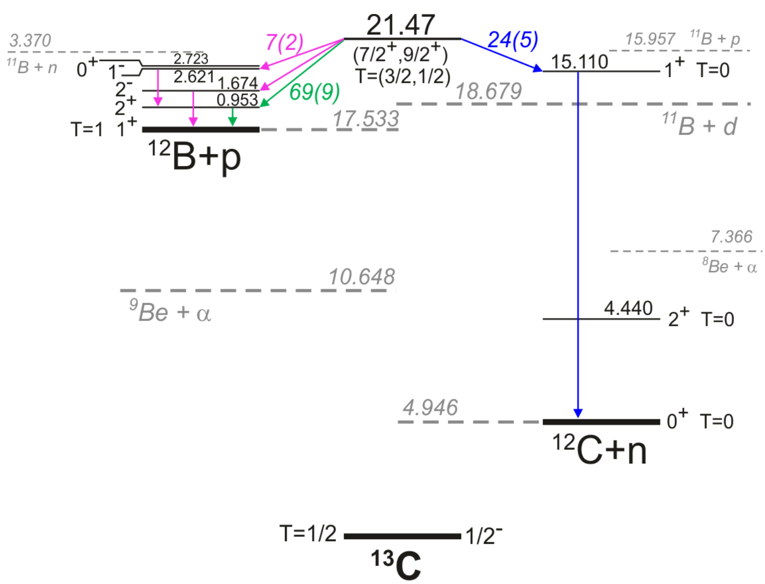

Fig. 2. Decay scheme of the 21.47-MeV stretched resonance in ^{13}C established in the present studies.

These experimental results served as a testing field for a recently-developed version of the GSM, which was used to interpret the properties (spin/parity, isospin, and wave function composition) of the 21.47-MeV stretched resonance in ^{13}C. The calculations were performed with a model space specifically adapted to describe the state of interest (as described in [15]), which in the literature is reported to be either $7/2^+$ or $9/2^+$. The calculations predicted the 20.9-MeV resonance arising from the stretched $p_{3/2} \rightarrow d_{5/2}$ excitation and having spin-parity $J^{\pi} = 7/2^{+}$ and isospin $T = 3/2$ which is in concordance with the experimental results.

3.2. Stretched states at 16.9 and 20.1 MeV in ^{14}N

M4 resonances in ^{14}N were previously observed at 15.0, 16.9, 18.5, and 20.1 MeV in the scattering of electrons [20] and pions of both charges [21]. No investigation has been performed, thus far, using inelastic proton scattering, although high-energy protons are known to excite this type of stretched configurations [22]. In particular, the strongest M4 transitions were observed to the 16.9-MeV and 20.1-MeV resonances, tentatively assigned as 5^{-} [20] and 3^{-} [21], respectively.

The goal of the experiment performed at CCB in 2019/2020 was to study the decay of these two resonances in ^{14}N, which are the most intense and rather well isolated from all other lower-lying excitations. The $Li^{14}NH_2$ lithium amide target was used, because no γ rays from ^{7}Li decay products, namely ^{4}He, ^{6}He, and ^{6}Li, were expected, as these products have no bound states. Only ^{7}Li itself has one bound state at 477.6 keV, which emits a γ ray of the same energy. However, during the analysis, we discovered a large oxygen contamination: the ^{14}N content of the target was roughly 15 times lower than the oxygen one. In consequence, it was very difficult to identify γ rays following the decay of the stretched states in ^{14}N as they were dominated by the radiation from the oxygen-decay products.

For the proton-decay channel of ^{14}N, one expects to observe the branches feeding the 3089-, 3685-, and 3854-keV states in ^{13}C, which decay to the ground state via emission of the 3853-, 3684-, 3089-, and 169-keV γ rays. In addition, the d- and α-decay branches are also expected, followed by the $2^{+} \rightarrow$ g.s., 4.439-MeV transition in ^{12}C and the 414-, 718-, 1022-, and 2868-keV main γ rays from the excited states in ^{10}B, respectively. All other decay channels, including the neutron-emission channel, will, practically, not be associated with γ-ray emission, either due to the limitation in the available energy, or due to the unbound nature of the final excitations.

The collected data were sorted into an excitation-energy *versus* γ-energy coincidence matrix. Due to strong oxygen contamination, no reliable background subtracted gates could be set on the excitation energy, while projecting on the γ-ray energy axis. *Vice versa*, gates on the γ-ray transitions, projected on the excitation energy axis, could be more reliable. Yet, the treatment of the background appeared to be rather complex, due to the presence of a high number of transitions and escape peaks that overlapped. Consequently, we decided to use an alternative analysis approach, namely, a scanning of the area of the γ-ray peaks corresponding to the decay of the M4 resonances of interest as a function of the excitation energy. The 600-keV-wide gates were set on the excitation-energy spectrum without any background subtraction and then projected on the γ-ray energy axis. For each projection, the area of the peaks of interest was measured, fitting the peak with a Gaussian function and a linear background.

Only two γ transitions have been identified with sufficient statistics to be associated with ^{14}N α decay: 414 and 718 keV, deexciting the 1_2^+ third- and the 1_1^+ first-excited states in ^{10}B, respectively. The area scanning of these two peaks shows an excess of counts around the region at 17 MeV, which could be assigned to the 16.9-MeV M4 resonance. However, the very limited statistics prevented from obtaining quantitative results. Regarding the α-decay channel towards ^{10}B, no 2868-keV γ ray deexciting the 2_1^+ 3587-keV state was observed, while the $0_1^+ \to 1_1^+$ 1022-keV transition remained uncertain, since it would appear as unresolved from the 1015-keV ^{27}Al transition, coming from spurious beam interactions with surrounding materials. Finally, two other, less intense γ-ray transitions (1435 keV and 2154 keV) depopulating the 1_2^+ in ^{10}B were not observed either.

Regarding the other possible decay channels, the corresponding γ rays were not observed or remain uncertain due to the ^{16}O contamination. For example, no information on the deuteron-emission decay towards the 4440-keV state in ^{12}C could be extracted due to the fact that oxygen itself strongly decays to this state in carbon. As concerns the proton emission towards ^{13}C, no hint of the 3089-keV γ ray, deexciting the $1/2_1^+$ state, has been observed in an energy region rather clean from other transitions. On the other hand, hints for the presence of the 3684-keV γ ray depopulating the $3/2_1^-$ state in ^{13}C were seen, but very limited statistics prevented a reliable identification of this transition — even the area scanning procedure could not be applied. The $5/2_1^+ \to$ g.s. γ-ray transition of 3854-keV energy would instead lie too close to the ^{12}C 4439-keV first-escape peak and would be too low in statistics to be observed.

The qualitative decay scheme for the ^{14}N 16.9-MeV resonance, which can be deduced from the present analysis, is summarized in Fig. 3. No information could be obtained regarding the decay of the 20.1-MeV state.

3.3. Stretched states at 17.79, 18.98, and 19.80 MeV in ^{16}O

In the ^{16}O nucleus, three M4 resonances have been reported in literature at the energies of 17.79, 18.98, and 19.80 MeV. They were populated in electron [23], pion [24], and proton [25] inelastic-scattering reactions and identified as 4^- excitations. This triplet of stretched states around 18 MeV is located in an energy window of just 2 MeV. The energy resolution of the KRATTA telescopes (2–3 MeV), used to reconstruct the excitation energy,

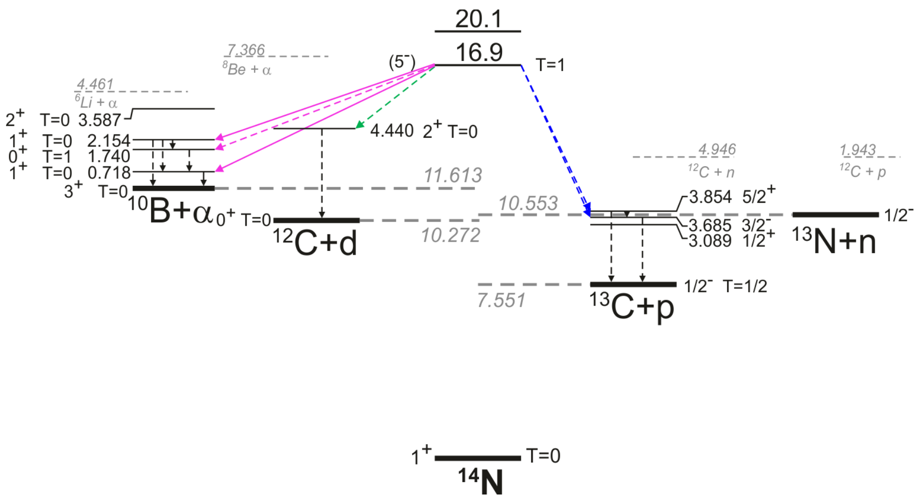

Fig. 3. Decay scheme of the 16.9-MeV stretched resonance in ^{14}N deduced from the present studies. Dashed arrows mean the decay channels that are uncertain due to limited statistics or the presence of contaminations.

was not sufficient to discriminate between the three resonances. They appear as unresolved also in proton–gamma coincidence data and this makes a standard analysis impossible. Therefore, for the investigation of M4 states decay in the ^{16}O nucleus, the technique described for the ^{14}N case has been applied. We note that the data for ^{16}O were obtained with the same target as for ^{14}N.

All the three states can decay through α emission to the first-excited 2^+ state in ^{12}C at 4439 keV. For the proton-decay channel, branches to the excited states at 5270, 5300, 6324, and 7155 keV in ^{15}N are expected. On the contrary, a neutron decay, possible only to the ground state of ^{15}O, is not detectable with the present setup. Finally, no deuteron decay channel to ^{14}N is expected, since the deuteron-emission threshold is located at 20.74 MeV.

^{16}O is a rather exceptional case, as it is one of the very few systems for which the decay of the M4 resonances has been investigated in the past. Branching ratios for proton decays and alpha-particle decays of hole states in ^{16}O have been determined in the experiment by Breuer *et al.* [26], where ^{17}O$(d,t)^{16}$O and ^{17}O$(^3$He, $\alpha)^{16}$O reactions were employed. Therefore, the case of ^{16}O is particularly suitable to validate the experimental technique presented here, that exploits proton–gamma coincidence measurements to determine the decay branching ratios of the resonances of interest.

Scanning of the area of the γ-ray peaks associated with the decay of the resonances, namely, the 4439-keV line from ^{12}C and the 5269- and 6332-keV γ rays from ^{15}N, as a function of the ^{16}O excitation energy, has been performed. It was observed that sensitivity to decay channels of the three M4 states can be achieved with this kind of approach. The area of the 5269-keV peak reaches a maximum around the energy of the 18.98-MeV resonance, which can be associated with the decay of this resonance towards the $5/2^+_1$ state in ^{15}N. In turn, in the curve plotted for the 6322-keV peak, a small component deriving from the decay of the 19.80-MeV resonance has been identified, indicating a branch leading to the third excited state in ^{15}N. Furthermore, the area of the 4439-keV γ peak exhibits a broad structure with a maximum around the energy of the 17.79-MeV stretched state and a smaller component around the energy of the 19.80-MeV excitation in ^{16}O. This behaviour can be associated with the decay of these two resonances towards the ^{12}C first excited state. The decay scheme of the three stretched resonances in 16O obtained from the present analysis is shown in Fig. 4.

Further analysis will be carried out in order to extract quantitatively the branching ratios and compare them to the results from Breuer *et al.* [26].

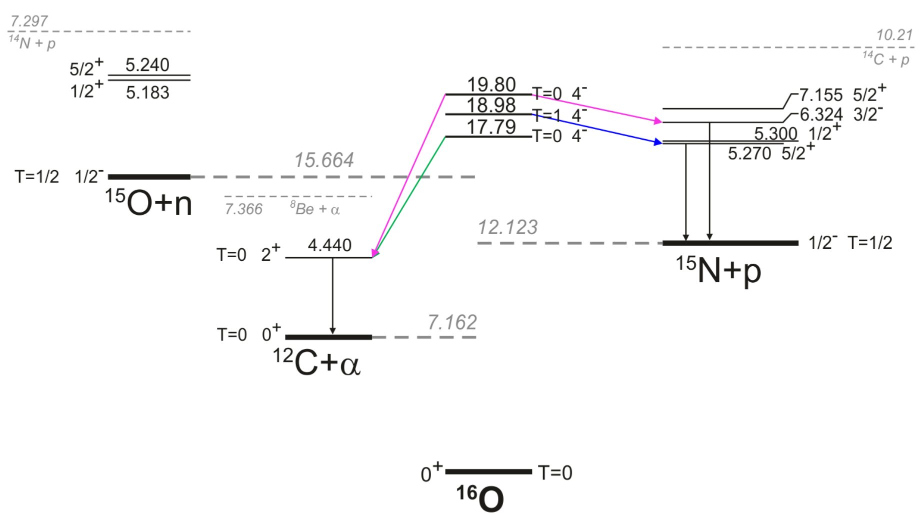

Fig. 4. Decay branches of the stretched resonances at 17.79, 18.98, and 19.80 MeV in ^{16}O deduced from the present studies.

4. Summary

The results of the ^{13}C stretched-state decay experiment at CCB clearly support the power of the experimental setup used, and assess the validity of the proton–gamma coincidence technique that can be directly extended to study other M4 resonances in the nearby nuclei in this mass region. The consecutive experiment, devoted to the studies of the stretched excitations in ^{14}N, which was performed at CCB, suffered from a significant contamination of ^{16}O. Despite the fact that only a qualitative picture could be obtained for the ^{14}N nucleus, there is evidence that the 16.9-MeV M4 resonance is populated in the inelastic proton-scattering reaction and that our detection technique provides sufficient sensitivity to observe its decay. Therefore, the experiment with non-contaminated ^{14}N target is planned in the nearest future. In turn, the analysis of M4 stretched states decay in ^{16}O (^{16}O appeared in the target as a dominating contaminant) showed usefulness of the technique relying on scanning of the gamma-peak area in the excitation energy–gamma energy matrix. It was observed that, with this approach, a reasonable sensitivity in determining the presence of decay channels of the three M4 states in ^{16}O, can be achieved.

From a broader perspective, the studies of the decay of M4 resonances, as the ones presented here, provide excellent testing grounds for the state-of-the-art theoretical models, like the Gamow Shell Model, which aim at a consistent description of the excited states in nuclei, including those lying in the energy continuum.

The project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 654002 (ENSAR2 project). This work was also supported in part by the Italian Istituto Nazionale di Fisica Nucleare, by the National Science Centre, Poland (NCN) under research projects Nos. 2020/39/D/ST2/03443, 2018/31/D/ST2/03009, and 2015/17/B/ST2/01534, and by the COPIN and COPIGAL French–Polish scientific exchange programs. M. Sferrazza is supported by the Fonds de la Recherche Scientifique — FNRS under grants numbers J.0174.22 and 4.45.10.08.

REFERENCES

[1] C. Forssén, R. Roth, P. Navrátil, *J. Phys. G: Nucl. Part. Phys.* **40**, 055105 (2013).

[2] B.R. Barrett, P. Navrátil, J.P. Vary, *Prog. Part. Nucl. Phys.* **69**, 131 (2013).

[3] S. Baroni, P. Navrátil, S. Quaglioni, *Phys. Rev. C* **87**, 034326 (2013).

[4] G. Papadimitriou *et al.*, *Phys. Rev. C* **88**, 044318 (2013).

[5] N. Michel, M. Płoszajczak, «Gamow Shell Model, The Unified Theory of Nuclear Structure and Reactions» Vol. 983, *Springer International Publishing*, Cham 2021.

[6] T. Otsuka *et al.*, *Phys. Rev. Lett.* **105**, 032501 (2010).

[7] C. Yuan *et al.*, *Phys. Rev. C* **85**, 064324 (2012).
[8] M. Ciemała *et al.*, *Phys. Rev. C* **101**, 021303(R) (2020).
[9] S. Ziliani *et al.*, *Phys. Rev. C* **104**, L041301 (2021).
[10] S. Raman, L.W. Fagg, R.S. Hicks, «Giant Magnetic Resonances», in: J. Speth (Ed.) «Electric and Magnetic Giant Resonances in Nuclei», *World Scientific Publishing Company*, 1991.
[11] N. Michel, W Nazarewicz, M. Płoszajczak, T. Vertse, *J. Phys. G: Nucl. Part. Phys.* **36**, 013101 (2009).
[12] J. Łukasik *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **709**, 120 (2013).
[13] A. Maj *et al.*, *Acta Phys. Pol. B* **40**, 565 (2009), and `http://paris.ifj.edu.pl`
[14] N. Cieplicka-Oryńczak *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **13**, 389 (2020).
[15] N. Cieplicka-Oryńczak *et al.*, *Phys. Lett. B* **834**, 137398 (2022).
[16] R.S. Hicks *et al.*, *Phys. Rev. C* **34**, 1161 (1986).
[17] S.J. Seestrom-Morris *et al.*, *Phys. Rev. C* **26**, 594 (1982).
[18] S.F. Collins *et al.*, *Nucl. Phys. A* **481**, 494 (1988).
[19] F. Ajzenberg-Selove, *Nucl. Phys. A* **523**, 1 (1991).
[20] J.C. Bergstrom, R. Neuhausen, G. Lahm, *Phys. Rev. C* **29**, 1168 (1984).
[21] D.F. Geesaman *et al.*, *Phys. Rev. C* **27**, 1134 (1983).
[22] F. Petrovich, W.G. Love, *Nucl. Phys. A* **354**, 499 (1981).
[23] C.E. Hyde-Wright *et al.*, *Phys. Rev. C* **35**, 880 (1987).
[24] D.B. Holtkamp *et al.*, *Phys. Rev. Lett.* **45**, 420 (1980).
[25] R.S. Henderson *et al.*, *Aust. J. Phys.* **32**, 411 (1979).
[26] H. Breuer *et al.*, *Phys. Lett. B* **96**, 35 (1980).