SPECTROSCOPY OF NEUTRON-RICH NITROGEN ISOTOPES WITH AGATA+PARIS+VAMOS*

S. Ziliani[a,b], M. Ciemała[c], F.C.L. Crespi[a,b], S. Leoni[a,b]
B. Fornal[c], A. Maj[c], P. Bednarczyk[c], G. Benzoni[b], A. Bracco[a,b]
C. Boiano[b], S. Bottoni[a,b], S. Brambilla[b], M. Bast[d], M. Beckers[d]
T. Braunroth[d], F. Camera[a,b], N. Cieplicka-Oryńczak[c]
E. Clément[e], S. Coelli[b], O. Dorvaux[f], S. Erturk[g]
G. de France[e], C. Fransen[d], A. Goldkuhle[d], J. Grębosz[c]
M.N. Harakeh[h], Ł.W. Iskra[b,c], B. Jacquot[e], A. Karpov[i]
M. Kicińska-Habior[j], Y. Kim[e], M. Kmiecik[c], A. Lemasson[e]
S.M. Lenzi[k,l], M. Lewitowicz[e], H. Li[e], I. Matea[m], K. Mazurek[c]
C. Michelagnoli[n], M. Matejska-Minda[c,o], B. Million[b]
C. Müller-Gatermann[d], V. Nanal[p], P. Napiorkowski[o]
D.R. Napoli[q], R. Palit[p], M. Rejmund[e], Ch. Schmitt[f]
M. Stanoiu[r], I. Stefan[m], E. Vardaci[s], B. Wasilewska[c]
O. Wieland[b], M. Ziębliński[c], M. Zielińska[t]

AGATA, PARIS, VAMOS collaborations

[a]Dipartimento di Fisica, Università degli Studi di Milano, Italy
[b]INFN Sezione di Milano, Italy
[c]Institute of Nuclear Physics Polish Academy of Science, Kraków, Poland
[d]IKP Cologne, Germany
[e]GANIL, CEA/DRF and CNRS/IN2P3, Caen, France
[f]CNRS/IN2P3, IPHC UMR 7178, Strasbourg, France
[g]Nigde University, Turkey
[h]KVI — Center for Advanced Radiation Technology, Groningen, The Netherlands
[i]FLNR, JINR, Dubna, Russia
[j]Faculty of Physics, University of Warsaw, Poland
[k]INFN Sezione di Padova, Italy
[l]Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Italy
[m]IPN Orsay, France
[n]Institut Laue-Langevin (ILL), Grenoble, France
[o]Heavy Ion Laboratory, University of Warsaw, Poland
[p]Tata Institute of Fundamental Research, Mumbai, India
[q]INFN Laboratori Nazionali di Legnaro, Italy
[r]IFIN-HH, Bucharest, Romania
[s]Università degli Studi di Napoli and INFN Sezione di Napoli, Italy
[t]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

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Excited states of ^{17}N, ^{18}N and ^{19}N were investigated through the measurement of gamma rays, following their population via deep-inelastic reactions induced by an ^{18}O beam (7 MeV/u) on a thick ^{181}Ta target. The experimental setup comprised the AGATA+PARIS detection system, coupled to the VAMOS++ magnetic spectrometer. In the ^{17}N nucleus, the analysis of gamma-ray transitions de-exciting two states around 4–5 MeV clearly pointed to discrepancies with the lifetime values reported in literature. Three new gamma rays were observed in ^{18}N at the energies of 1662.3 (3) keV, 2073.4 (8) keV and 2300.9 (8) keV, and hints for other two new transitions around 1566 keV and 1720 keV were found. In addition, a new transition with energy of 2489.7 (8) keV was observed in ^{19}N.

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1. Introduction

Neutron-rich light nuclei, in the region of the nuclear chart from carbon to fluorine, are an ideal test ground for different nuclear structure models, including shell model, cluster models and *ab initio* approaches. In *ab initio* calculations, the electromagnetic decay (EM) from excited states is found to be strongly sensitive to the details of the nucleon–nucleon interaction, in particular, to the role played by three-body forces. This points to the need of high-precision gamma-ray spectroscopy measurements as a powerful tool to obtain detailed information on the properties of excited nuclear states. Indeed, in this region of mass, many nuclei are not well-known and, in some cases, the only available data come from very old experiments. It is also important to underline that a detailed knowledge of the structure of light nuclei is mandatory for the understanding of astrophysics processes, such as nucleosynthesis.

In the following, we will concentrate on N isotopes. In particular, we will present a preliminary spectroscopic analysis of ^{17}N, ^{18}N and ^{19}N, observed, with rather good statistics, as a by-product of the experiment of Ref. [1], aiming at the lifetime measurement of the 2_2^+ states in ^{16}C and ^{20}O.

2. Experiment and setup

An experiment of thirteen days was performed at the GANIL (Grand Accélérateur National d'Ions Lourds) laboratory in Caen, France, in July 2017, aiming at the population of light neutron-rich C, N and O nuclei via deep-inelastic reactions, induced by an ^{18}O beam at 7.0 MeV/u on a thick ^{181}Ta target (6.7 mg/cm^2).

The experimental setup included the *Advanced Gamma Tracking Array* (AGATA) [2], with 31 HPGe crystals, coupled to the *Photon Array for Studies with Radioactive Ion and Stable Beams* (PARIS) [3], consisting of two complete clusters of nine phoswich scintillators and two large volume

($3.5'' \times 8''$) $LaBr_3$:Ce detectors at 90°. The reaction products were identified in the *VAriable MOde high acceptance Spectrometer* (VAMOS++) [4], placed at 45° with respect to the beam direction and aligned with the centre of AGATA (which covered the angular range between 115° and 175°).

With the above setup, high-precision spectroscopic studies could be perfomed, including lifetime measurements in the range from tens to few hundreds of femtosectonds. In fact, if a gamma ray is emitted while the nucleus is slowing down inside the thick target material, which means that its velocity is larger than the one measured in VAMOS++ outside the target, a Doppler-broadened line shape is observed and the peak appears to be non-Gaussian, with a tail towards lower energies, with respect to the tabulated values. This happens when the state lifetime is of the order of the target crossing time, that in the present case is about 100 fs. If the γ-ray emission direction with respect to the reaction product is known, the Doppler-broadened line shape can be used to determine the lifetime of the state, exploiting a Monte Carlo simulation of the entire process [5]. On the contrary, in the case of transitions from relatively long-lived levels (> 1 ps), the gamma rays are emitted in flight outside the target and narrow peaks are expected, with energies in agreement with the values coming from earlier studies.

3. Spectroscopic analysis

In the reaction process, several nuclei have been populated: in figure 1, a two-dimensional histogram shows the distribution of the reaction products detected in VAMOS++, in coincidence with at least one gamma ray in AGATA. All charge states of the reaction products have been considered to produce the distribution. We will focus here on the cases of the most exotic nitrogen isotopes, *i.e.* ^{17}N, ^{18}N and ^{19}N.

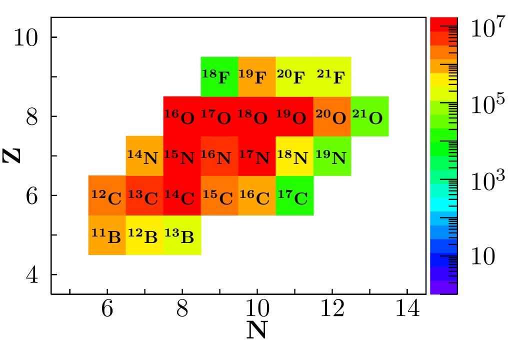

Fig. 1. Measured yields of the isotopes produced in the deep-inelastic reaction ^{18}O (7.0 MeV/u) + ^{181}Ta, with a coincidence required between the ions detected in VAMOS++ and the gamma rays in AGATA. All the charge states of the reaction products were considered to produce the histogram.

3.1. ^{17}N

The decay pattern of ^{17}N is rather well-established, while limited information is available in terms of states lifetimes. ^{17}N has been already investigated in the past, mainly by Rogers *et al.* in 1974 [6], who reported short lifetimes (< 61 fs) for two states above 4 MeV (see Table I). For these states, however, the lineshapes of the depopulating transitions, observed in the present experiment, seem to point towards longer lifetimes, and discrepancies are also observed with the transition energy values quoted by Rogers *et al.*, which seem to be underestimated.

TABLE I

Information about the gamma-ray transitions in ^{17}N de-exciting the two states of interest: the transition energy obtained in this work, the one reported in literature and the energy, spin and parity of the initial and final states. The upper limit for the initial state lifetime from NuDat [7] is also given. State and transition energies are expressed in keV.

E_{i} (level)	J_{i}^{π}	E_{f}	J_{f}^{π}	τ [fs]	$E_{\gamma}^{\mathrm{literature}}$	$E_{\gamma}^{\mathrm{measured}}$
4415(3)	$(3/2,5/2)^-$	1906.8(3)	$5/2^-$	< 61	2508(3)	2510.9(8)
5170(2)	$(9/2^+)$	3128.9(5)	$7/2^-$	< 61	2041(2)	2045.1(3)
5170(2)	$(9/2^+)$	2526.0(5)	$5/2^+$	< 61	2644(2)	2646.9(11)

In figure 2, the Doppler-corrected AGATA energy spectrum of ^{17}N measured in this work, is shown: in black are indicated the most intense known transitions, while in grey/red there are reported the three gamma rays of interest, depopulating the states at 4415 (3) keV and 5170 (2) keV (see Table I for detailed specifics). Regarding the 5170-keV state, we observe ~ 3 keV higher energies of the two depopulating gamma rays with respect to the tabulated values: the 2647-keV transition energy is within the error bar of the older value, while the 2045-keV is not in agreement with the tabulated energy. In addition, no large widths or tails are visible: a non-Gaussian behaviour of the gamma peaks is excluded. This points in the direction of a lifetime longer than few hundreds of femtoseconds, in disagreement with the one in the femtoseconds range quoted in literature.

Regarding the 2510-keV line depopulating the 4415-keV state, the measured energy is in agreement with the value found in literature (although it should be lower for a short-lived state, see Section 2) and the peak appears quite narrow (the same width of the 2526-keV transition de-exciting the 2526-keV state with $\tau = 33\,(3)$ ps [7]). However, the peak is in a region with high background and the statistics is limited. Therefore, it is very likely that no precise information on the lifetime will be extracted. A detailed lifetime analysis of ^{17}N, measured in the present AGATA experiment, is ongoing.

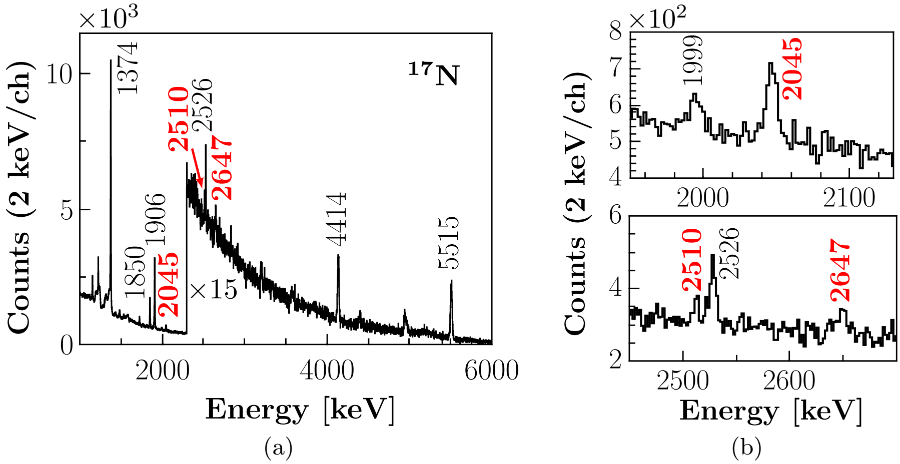

Fig. 2. (Colour on-line) (a) AGATA Doppler-corrected ^{17}N γ-ray energy spectrum and (b) parts of the same spectrum expanded around the transitions of interest (marked in grey/red).

3.2. ^{18}N

Unlike ^{17}N, ^{18}N spectroscopy is not well-established and very limited information is available [7], although this nucleus is of fundamental importance in astrophysics. ^{18}N can be produced in supernovae environments, as its neutron separation energy is larger than 2 MeV (the typical temperature of this environment). Terasawa *et al.* [8] have predicted a new nuclear reaction path in the very light neutron-rich region that can change the final heavy-element abundances by as much as an order of magnitude and ^{18}N is involved in this process through the ^{17}N$(n,\gamma)^{18}$N reaction.

From the theory point of view, ^{18}N is a real challenge. Its level scheme has been calculated using shell model in Refs. [9] and [10], but none of these calculations can reproduce the ordering of the ground state and the first excited state, and the level energies largely deviate from the experimental ones. More recently, advanced *ab initio* calculations of the excitation energy spectrum of ^{18}N have been published in Ref. [11]: in these calculations, the ordering of the ground state and the first excited state is properly reproduced, but the state energies still significantly deviate from the experimental ones, in particular for higher-lying states. Nevertheless, neither the shell model nor the *ab initio* approach provide any information about the level scheme above 2 MeV.

The gamma-ray energy spectrum of ^{18}N, obtained in this work, is shown in figure 3: three new transitions have been observed, with measured energies of 1662.3 (3) keV, 2073.4 (8) keV and 2300.9 (8) keV. Two peaks are also visible around 1566 keV and 1720 keV, but the statistics is too limited

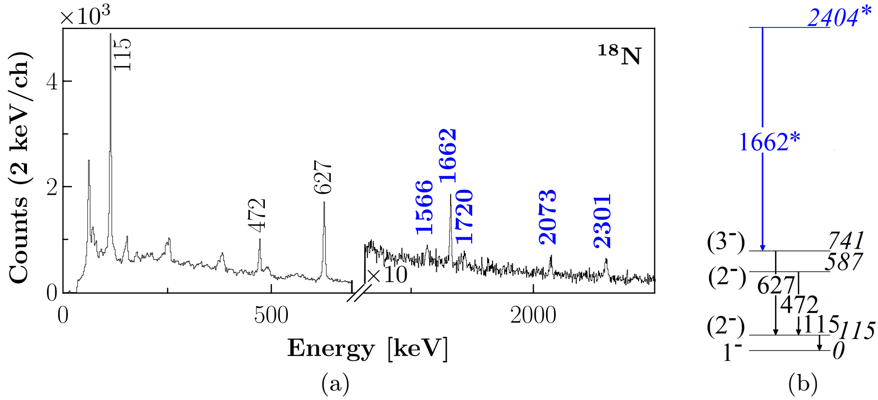

Fig. 3. (Colour on-line) (a) AGATA Doppler-corrected ^{18}N γ-ray energy spectrum and (b) revised level scheme of ^{18}N. The newly observed gamma rays are labelled in thick black/blue (the transitions around 1566 keV and 1720 keV are tentatively assigned to the same nucleus). The energies reported in the new part of the level scheme with the * symbol do not take into account any lifetime effect that can eventually increase the energy of the transition and, therefore, the one of the depopulated state.

to attribute these transitions to ^{18}N with certainty, as they may come from contaminants. No lifetime effects have been considered in the extraction of these energy values. We note that the peak at 1662 keV has a tail and shows an energy shift as a function of the angle between the gamma-ray emission direction and the ion detected in VAMOS++. This indicates that the depopulating state may have a lifetime of the order of hundreds of femtoseconds and the exact energy of the transition could be higher (see previous section). This point is now under investigation.

An effort has been made to place the new transitions in the level scheme, but only the 1662-keV γ ray has been found to be in coincidence with other lines, due to lack of statistics in the coincidence matrix. The 1662-keV line is in coincidence with the 115-keV ($2_1^- \to$ g.s.) and 627-keV ($3_1^- \to 2_1^-$) transitions, and not with the 472-keV ($2_2^- \to 2_1^-$) line. Therefore, it depopulates a new level at 2403.5 (3) keV. The revised level scheme is reported in figure 3 (b). No spin assignments have been investigated so far.

At present, no further comparison with theoretical models is possible, since no predictions are available for excited states above 1.2 MeV. We note that a previous experimental work with charged-particles spectroscopy, by Hoffman *et al.* [12], pointed to the existence of bound states in the region above 1.5–2 MeV, which is consistent with the observation of the 2404-keV state reported here.

3.3. ^{19}N

An extensive study of the ^{19}N nucleus was performed in 2008 by Sohler *et al.* [13], detecting gamma rays with the so-called "Château de Cristal" BaF_2 array, with a 38 keV FWHM at the gamma-ray energy of about 1500 keV after Doppler correction. In our work, thanks to the use of AGATA coupled to VAMOS++, we reached a much better energy resolution (few keV around 1 MeV) and we measured the energy spectrum shown in figure 4.

We observed many known transitions (shown in black in figure 4), but also a new line at the energy of 2489.7 (8) keV. A hint of the presence of this new line is also visible in the PARIS spectrum. We note that the peak visible at 984 keV does not come from ^{19}N, but from its partner, produced in the reaction ^{18}O(^{181}Ta,^{180}W)^{19}N. The peak is a residue of the $2_1^- \rightarrow 2_1^+$ transition at 902.814 (13) keV in ^{180}W [7], which has not been completely smeared out after the Doppler correction. No other contaminants from ^{180}W are visible in the spectrum.

As for ^{18}N, the poor statistics in the γ–γ coincidence matrix does not allow us to place the new transition in the level scheme using coincidence methods. Unlike ^{18}N, ^{19}N is reasonably described by theory, as reported in the work by Sohler *et al.* [13], even if it is not possible on the basis of the model, alone, to place the new 2490-keV gamma ray in the level scheme.

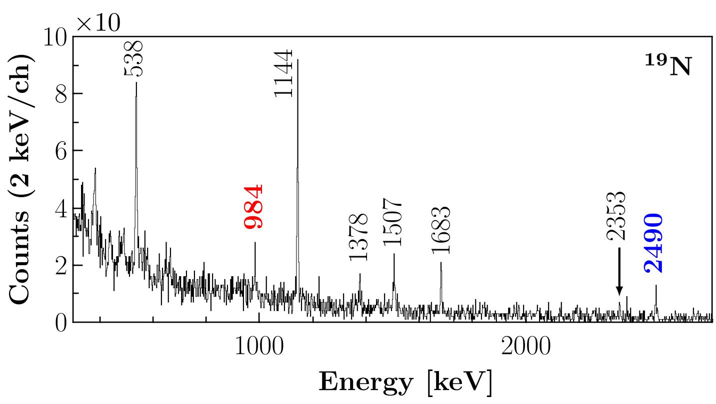

Fig. 4. (Colour on-line) AGATA Doppler-corrected ^{19}N γ-ray energy spectrum. The newly observed gamma ray is labelled in thick black/blue, and labelled in grey/red is the remnant of the ^{180}W transition at 902.814 (13) keV [7], after the Doppler correction.

4. Conclusions

High-precision gamma-ray spectroscopy measurements of ^{17}N, ^{18}N and ^{19}N have been performed with the AGATA+PARIS array, coupled to

VAMOS++. In ^{17}N, the present data point to discrepancies with the old literature values for the lifetimes of two states above 4 MeV, currently being investigated. In ^{18}N and ^{19}N, a total of four new gamma rays were observed, plus two tentative ones associated to ^{18}N. Regarding ^{18}N, one of the new gamma rays has been placed in the level scheme, but a comparison with theory is not possible yet due to the absence of predictions above 2 MeV excitation energy. ^{19}N, on the other hand, is well-described by theory, but calculations alone could not be used to place the new gamma ray in the level scheme. In the future, investigations of the spin assignments will be performed and an effort will be made to obtain more extended level schemes.

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