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Lifetime analysis of short-lived states in ^{17}N

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Summary. — A recent extension of the Doppler-shift attenuation method to measure short lifetimes of states populated in low-energy binary reactions is applied to the case of ^{17}N. The reliability of the technique is confirmed by measuring the lifetime of the 5515 keV $3/2^-$ state, which is depopulated by two different γ rays. The method is used to measure the lifetime of the 5170 keV $(9/2^+)$ state in the same nucleus. Comparisons with large-scale shell-model predictions are given as well.

1. – Introduction

A novel implementation of the Doppler-shift attenuation method (DSAM) has been recently introduced [1, 2], to extend the lifetime measurement technique to nuclear-state lifetimes of the order of tens-to-hundreds femtoseconds by exploiting low-energy heavy-ion binary reactions. Standard γ-ray lineshape analysis [3] cannot be applied in these cases, due to the large energy dissipation, which leads to complex velocity distributions of the reaction products. The new technique solves this issue by reconstructing the velocity distribution after the reaction via an iterative Monte Carlo simulation procedure. Such a technique is expected to become an important tool for studying exotic neutron-rich nuclei, produced with intense radioactive isotope separation on-line (ISOL) beams [4].

In the present paper, we will discuss the application of the method in the context of an experiment realised at the GANIL laboratory, in France, with the AGATA γ-ray tracking array [5,6]. We will examine the lifetime of two excited states in ^{17}N, namely the $(9/2^+)$ and $3/2^-$ states located at 5170 and 5515 keV of excitation energy, respectively [7]. Such measurements will be used to benchmark large-scale shell-model calculations based on the so-called YSOX interactions, developed by the Tokyo group [8].

2. – Experiment and analysis

In the experiment, direct-transfer and deep-inelastic reactions were induced by a beam of ^{18}O at 7.0 MeV/u on a thick ^{181}Ta target (6.64 mg/cm^2) [1]. Neutron-rich isotopes of B, C, N, O and F nuclei were produced, including ^{17}N, discussed here. The experimental setup consisted of the AGATA tracking array [5, 6] (with 31 high-purity germanium detectors) coupled to an early implementation of the PARIS scintillation-based setup [9] and to the heavy-ion recoil spectrometer [10]. The aim of the experiment was the analysis of short lifetimes ($\sim$tens to hundreds fs) of excited states in different nuclei, which were predicted to be sensitive to the details of the nuclear interaction.

For the purpose of the analysis, a novel implementation of the DSAM has been developed. The method is extensively discussed in ref. [2], where it is also tested on a number of known cases in different oxygen isotopes and lifetime ranges. Here, we consider the ^{17}N $3/2^-$ excited state located at 5515(3) keV, which de-excites via the 4141 keV γ ray to the $3/2^-_1$ state and the 5515 keV transition to the ground state, with comparable intensity (see fig. 1). These transitions can be used, independently from each other, to check the reliability of the new technique, by measuring the lifetime of the 5515 keV state, reported to be $\tau < 100$ fs [11]. As shown in fig. 2, we obtained two separate lifetime (τ) *vs.* γ-ray energy (E_γ) χ^2 minimisation surfaces. From these maps, we could extract both the γ-ray energy and an upper limit for the lifetime: $E_\gamma^{(1)} = 4141.0^{+0.7}_{-3.5}$ keV and $\tau^{(1)} < 60$ fs; $E_\gamma^{(2)} = 5515.0^{+1.7}_{-3.5}$ keV and $\tau^{(2)} < 60$ fs. The energies are well in agreement with the literature values, and the lifetimes agree with each other and with the literature, improving the upper limit by 40%, and confirming the reliability of the technique.

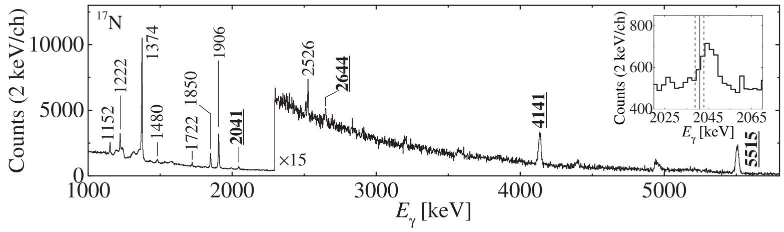

Fig. 1. – AGATA Doppler-corrected ^{17}N γ-ray energy spectrum. The energies of interest for the discussion are indicated in boldface and underlined (literature values [7]). The inset shows a zoom around the 2041 keV line, with the grey vertical line referring to the energy value quoted in the literature, with its uncertainty [7].

In the same ^{17}N nucleus, a detailed investigation of the γ-ray energy spectrum highlighted a discrepancy between the literature energy and the measured one, in the case of the $(9/2^+)_1 \to 7/2^-_1$ and $(9/2^+)_1 \to 5/2^+_1$ transitions, depopulating the 5170 keV state. The literature values are $E_\gamma^{(1)} = 2041(2)$ keV and $E_\gamma^{(2)} = 2644(2)$ keV [7], respectively, while we observed the associated peaks at higher energies, as shown in the inset of fig. 1. The lifetime of the 5170 keV state is quoted to be below 60 fs [11], therefore the discrepancy could be due to an imprecise energy measurement or to a wrong lifetime estimate. In particular, if the lifetime was much longer, the peak should appear at higher energies in our data, since AGATA is placed at backward angles. By applying the new DSAM method, we extracted the lifetime of this state, considering the 2041 keV transition only, which had better statistics. Figure 3(a) shows the corresponding χ^2 map, where the white cross marks the absolute minimum, and the white contour delimits the uncertainty. The comparison between the experimental and simulated data is shown in fig. 3(b). A lifetime $\tau = 35^{+110}_{-30}$ fs for a γ-ray energy of $2045.0^{+1.2}_{-1.7}$ keV was measured, in agreement with the literature value of ref. [11], thus pointing to an imprecise earlier measurement for the γ-ray energy. Therefore, the re-measured energy of the $(9/2^+)_1$ state is $5174.0^{+1.3}_{-1.8}$ keV, while the $(9/2^+)_1 \to 5/2^+_1$ transition energy is $2647.8^{+1.4}_{-1.9}$ keV.

3. – Discussion and conclusions

A new implementation of the DSAM analysis technique to low-energy binary reactions has allowed to determine the lifetime of the $3/2^-$ and $(9/2^+)$ states in ^{17}N at 5515 and 5174 keV, respectively. As a result, we provided a precise energy measurement for the

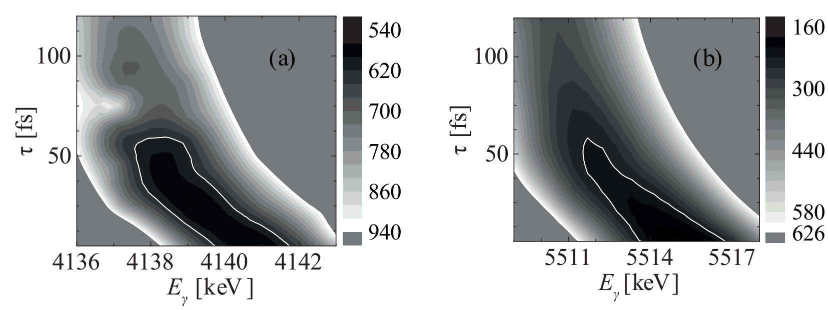

Fig. 2. – Two-dimensional χ^2-minimisation maps obtained after the comparison between measured and simulated data for the $3/2^-_3 \to 3/2^-_1$ and $3/2^-_3 \to$g.s. transitions in ^{17}N, at 4141 keV (a) and 5515 keV (b), respectively. The white contours delimit the uncertainty.

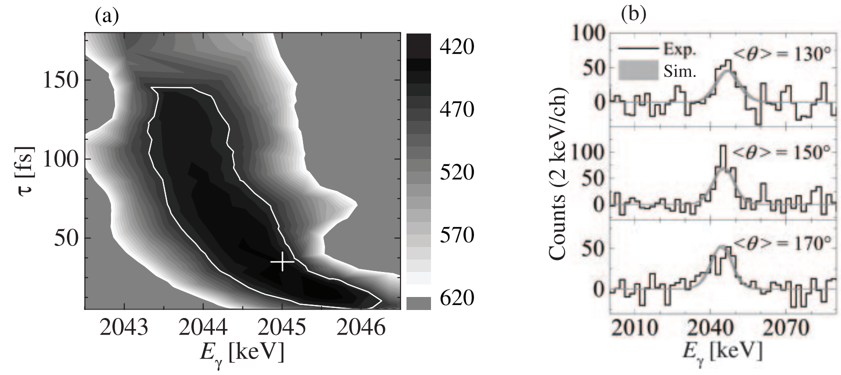

Fig. 3. – Panel (a): same as fig. 2 for the 2041 keV $(9/2^+)_1 \rightarrow 7/2^-_1$ transition. The white cross marks the χ^2 minimum. Panel (b): comparison between the experimental data (black histogram) and the simulated ones within the uncertainty (grey shades) for the 2041 keV transition, for three ranges of angles (θ) between the recoiling ion direction and the emitted γ ray (mean value for each range).

$(9/2^+)$ state, previously reported at lower energy, and an improved upper limit to the lifetime of the $3/2^-_3$ state ($\tau < 60$ fs). This lifetime value is in line with the predictions from large-scale shell-model calculations using the YSOX interaction ($\tau = 0.5$ fs) [8], which locate the state at 7.081 MeV. On the contrary, the lifetime of the $(9/2^+)_1$ state, $\tau = 35^{+110}_{-30}$ fs, is found to be more than an order of magnitude shorter than the predicted value for the corresponding state, which is calculated at much higher energy, ∼7.3 MeV. The difficulty of the shell-model approach in reproducing positive-parity states in N isotopes is well known, and it is related to the calculated size of the $N = 8$ gap. In this context, high-precision γ spectroscopy of light neutron-rich nuclei, such as N isotopes, provides key observables sensitive to the properties of the nuclear interaction, which are essential to improve and benchmark the most advanced theory approaches.

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