SHORT-RANGE LIFETIME MEASUREMENTS FOR DEEP-INELASTIC REACTION PRODUCTS: THE ^{19}O TEST CASE*

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An experiment, aiming at measuring lifetimes of excited states in neu-
tron-rich C and O isotopes, was performed at the GANIL laboratory with
the use of the AGATA segmented HPGe tracking array, coupled to the
PARIS scintillator array and to the VAMOS++ magnetic spectrometer.
The nuclei of interest were populated in transfer and deep-inelastic pro-
cesses induced by an ^{18}O beam at 126 MeV (7.0 MeV/u) on a ^{181}Ta tar-
get. This paper contains a brief description of a novel implementation of
a Monte-Carlo technique, which allowed us to obtain excited states life-
times in the range from tens to hundreds femtoseconds for a reaction with
complex initial velocity distribution, making use of the Doppler-shift at-
tenuation method (DSAM). As a test case, we present here the analysis for
two states in ^{19}O: 2371-keV 9/2$^+$ and 2779-keV 7/2$^+$, for which lifetimes
of $\tau > 400$ fs and $\tau = 140^{+50}_{-40}$ fs were obtained, respectively, in agreement
with literature values. This newly developed approach will be essential for
short lifetimes measurements in neutron-rich systems, exploiting intense
ISOL-type beams, currently under development.

1. Introduction

The experiment was performed in July 2017 at the GANIL laboratory.
The setup included 31 segmented HPGe detectors of the AGATA tracking
array [1, 2], the VAMOS++ spectrometer [3] and the PARIS scintillator-
based calorimeter [4]. The main aim of the measurement was to determine
lifetimes of excited states in neutron-rich C and O isotopes, especially in
^{16}C and ^{20}O produced in low-energy heavy-ion transfer and deep-inelastic
processes. This was motivated by recent advanced *ab initio* calculations,
which predict, for selected electromagnetic transitions, a strong sensitivity
to the details of the nucleon–nucleon interaction, in particular to the three-
body terms of the nuclear force. The lifetime of the second 2$^+$ state in ^{20}O
was measured and compared to the most recent predictions with *ab initio*
methods, while in the case of ^{16}C, an estimate of the lifetime of the state
of interest was extracted [5]. Moreover, new spectroscopic information was
obtained for ^{17,18,19}N isotopes, with preliminary results presented in Ref. [6].
This paper contains a brief description of the results for the ^{19}O nucleus, one
of the test cases which served to validate our lifetime measurement technique.
The proposed method allows access, for the first time, to lifetimes in the
tens-to-hundreds femtoseconds range, for reaction products of deep-inelastic
processes, *i.e.* in cases where the initial velocity distribution is complex and
not well-defined by the reaction kinematics. As discussed in Section 2.2,
a key point of the method is the accurate reconstruction of the complex
initial velocity distribution of the reaction product, which cannot be reliably
modelled, in particular for the population of specific excited states. This

experimental approach will be essential for short lifetimes measurements in exotic regions of the nuclear chart, including r-process nuclei, as soon as intense ISOL-type beams become available.

2. Lifetime determination procedure

2.1. Experimental data

The nuclei of interest were populated in transfer and deep-inelastic processes induced by a ^{18}O beam at 126 MeV (7.0 MeV/u) on a thick ^{181}Ta target, 6.64 mg/cm^2 thick (4 μm), which leads to velocity of projectile-like products of $v \sim 0.1\,c$. The experimental setup contained 31 AGATA crystals placed at backward angles with respect to the entrance of the VAMOS++ spectrometer (from $\sim 120°$ to $\sim 175°$) and an early implementation of the PARIS array placed at $\sim 90°$. VAMOS++ was placed at $45°$ with respect to the beam direction, covering the angular range of $\Theta \pm 6°$.

The calibration, fine tuning and neutron damage corrections for the AGATA detectors were presented in Refs. [7, 8], while the VAMOS++ ion selection and velocity reconstruction was described in Ref. [9].

The selection of the ^{19}O ions at the VAMOS++ focal plane and the reconstruction of theirs velocity allows the event-by-event Doppler correction of γ-ray energies. Figure 1 presents a part of the ^{19}O gated, Doppler corrected AGATA γ-ray spectrum, in which the 2371-keV $9/2^+ \to$ g.s., 2779-keV $7/2^+ \to 5/2^+$ and 2584-keV transition are visible. A partial ^{19}O level scheme, including the γ rays observed in the experiment, based on the NNDC [10] and Ref. [11] information, is presented in Fig. 2. It is worth to note that the 2584-keV γ ray is assigned to decay from a neutron-unbound state [11]. Moreover, in the current data, there is a hint for the decay from the 4990-keV neutron-unbound state by a 4894-keV γ ray, quoted in Ref. [11].
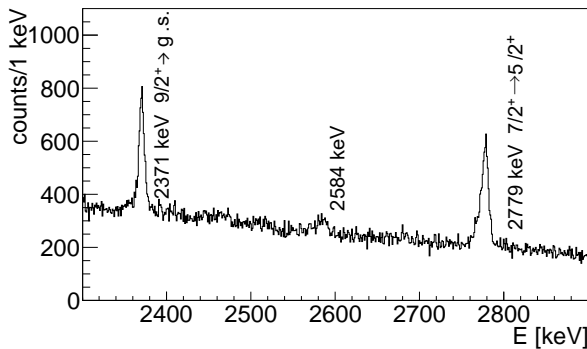

Fig. 1. AGATA Doppler-corrected ^{19}O γ-ray energy spectrum. The 2371-keV $9/2^+ \to$ g.s., 2779-keV $7/2^+ \to 5/2^+$ transitions and the 2584-keV transition feeding the $7/2^+$ state are shown.
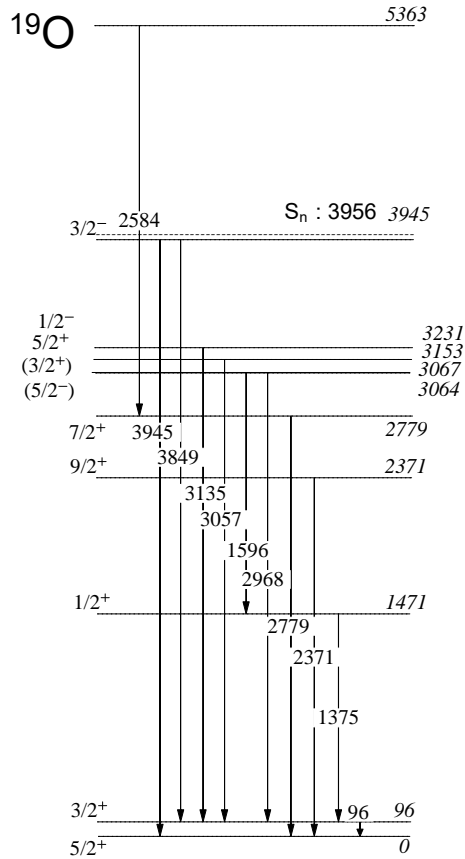
Fig. 2. ^{19}O partial level scheme including the γ rays observed in the present experiment. The placement of the γ rays is based on the data reported in NNDC [10] and Ref. [11].

The evaluated NNDC value for the 2371-keV state lifetime is $\tau > 3.5$ ps [12]. The same Ref. [12] quotes also the 2779-keV state lifetime $\tau = 117 \pm 26$ fs. The lifetime of this state is also provided in Ref. [13], which gives a value of $\tau = 70 \pm 26$ fs. The evaluated NNDC value is the average of these two values: $\tau = 92 \pm 19$ fs.

2.2. Simulations

The nuclear states lifetimes are determined by comparing the measured Doppler-corrected γ-ray energy spectrum line-shapes with simulated ones. As the reaction products velocities were ~ 3 cm/ns, and the target thickness was 6.64 mg/cm^2, we obtain a target-crossing time around few hundreds fs, which constitutes the upper limit of the sensitivity for the technique here employed to extract the lifetimes.

Figure 3 presents an example of simulated γ-ray line-shapes for three different lifetime values: 20 fs, 100 fs and 2 ps. For the lifetime around 100 fs, a tail due to not-properly Doppler-corrected events is appearing, while for $\tau \leq 80$ fs, the presence of a wide shifted peak structure can be observed. In both cases, the effect is dependent on the γ-ray emission angle.
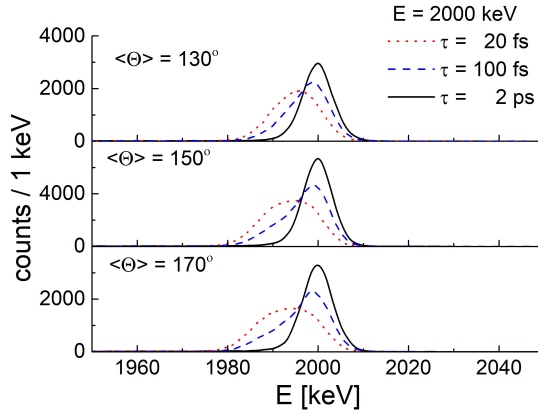

Fig. 3. Results of the realistic simulation of a γ-ray transition with an energy of $E_\gamma = 2000$ keV and three different lifetime values $\tau = 20$ fs, 100 fs, 2000 fs, assuming an emitter ion velocity of 3 cm/ns ($v/c = 0.1$) and the experimental AGATA angular coverage and response.

The simulation process is divided into stages, starting from the generation of the physics event, which is then passed to the AGATA simulation and tracking codes. In the event generator, an input for the AGATA simulation is prepared, taking as parameters the excited-level lifetime and the de-excitation γ-ray energy. The crucial part of this stage is the proper assignment of the ion velocity at the de-excitation point. The reaction mechanism is quite complex: low-energy transfer and deep-inelastic mechanisms compete in the production of the reaction fragments. Therefore, it is not possible to use a standard Doppler-Shift Attenuation Method, and the ion velocity is reconstructed through an iterative process. The initial velocity reconstruction follows the subsequent steps:

1. The ion velocity after the target (v_{out}) is measured in VAMOS++, putting a gate on the γ-ray de-exciting the level of interest. Figure 4 (a) presents the graph of v_{out} *vs.* E_γ for the ^{19}O ions, while Fig. 4 (b) presents two ^{19}O ion velocity distributions corresponding to γ rays de-exciting the 2371-keV and 2779-keV levels of interest for the present test of the method.
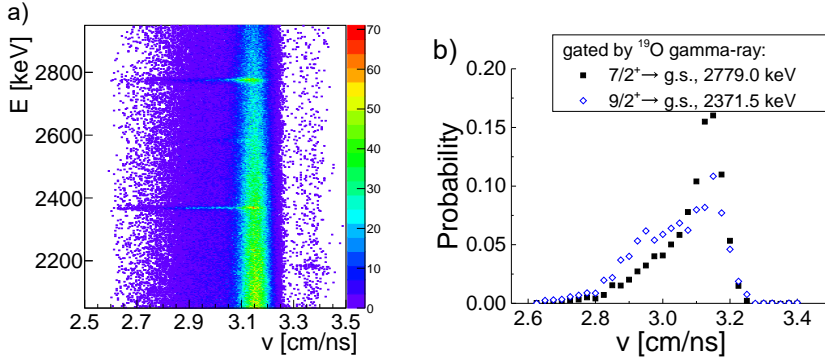
Fig. 4. (a) 2D plot of the AGATA Doppler-corrected γ-ray energy *vs.* ¹⁹O ion velocity measured in VAMOS++. (b) Velocity distributions for ¹⁹O ions corresponding to γ rays de-exciting the 2371-keV and 2779-keV levels.

2. A linear probability for the reaction to take place in the target is considered. After the reaction, the kinetic energy of the fragments is calculated assuming the direct population of the excited level of interest (for example, the state at 2371 keV, shown in Fig. 5). The reaction fragment is then let to cross the remaining thickness of the target (in which it slows down) and the VAMOS++ response is applied (see Fig. 5). Simulated and experimental velocities are normalized to the highest velocity values and the calculated v_{out} is subtracted from the measured one, producing the v_{out} used in the next step.
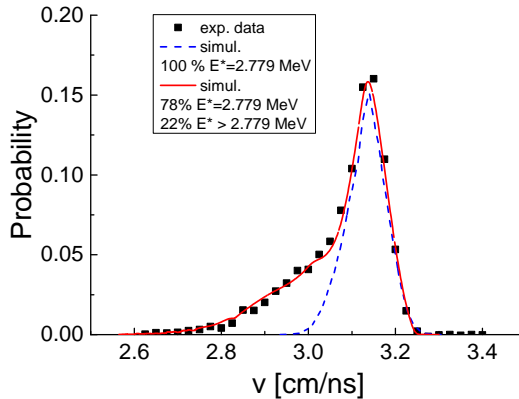

Fig. 5. (Colour on-line) Experimentally measured velocity of ¹⁹O ions, corresponding to γ rays that de-excite the 2779-keV level (black squares), compared to the simulated velocity considering a direct population of the state (dashed blue line) and with additional excitations included (solid red line).

3. Up to now, only direct population of the state of interest has been considered. Then, higher excitations of the projectile-like fragment and the target-like partner are considered with steps of 2 MeV. The process is repeated iteratively until the velocity distribution outside the target is fully described by the simulation.

4. In the Monte-Carlo event generator code, a random choice the of ion excitation energy is made, using weights, which are obtained from step 2 and step 3.

The stopping powers used in the code are those proposed by Ziegler *et al.* [15], which provides very good agreement between measured and calculated maximum v_{out}. The estimated uncertainty of the stopping powers is of the order of $\pm 2\%$, as follows from a number of checks performed considering in-flight decays from long-lived states, directly populated in the reaction process. The ion velocity vector angle in the simulation is taken directly from the measured one as a probability distribution into the Monte-Carlo event generator code. With the procedure described above, good agreement between the simulated and the measured ion velocity after passing through the target is achieved (see Fig. 5).

In the physics event generator, after the reaction takes place in the target, γ rays are emitted at time which is randomly chosen from the probability distribution defined by the input level lifetime value for the level of the interest. The γ-ray Doppler shift is calculated using the ion velocity at the emission point (which for low τ value will be mostly inside the target). The data produced in the event generator are used as input to the AGATA simulation package [14], which has been configured for the 31 AGATA crystals detector geometry. In Fig. 6, a comparison between the experimental and simulated directions covered on the X–Y plane of AGATA is shown. To obtain the agreement, a rotation of the AGATA array by $\phi = -33.9°$ must be applied in the simulation [2].
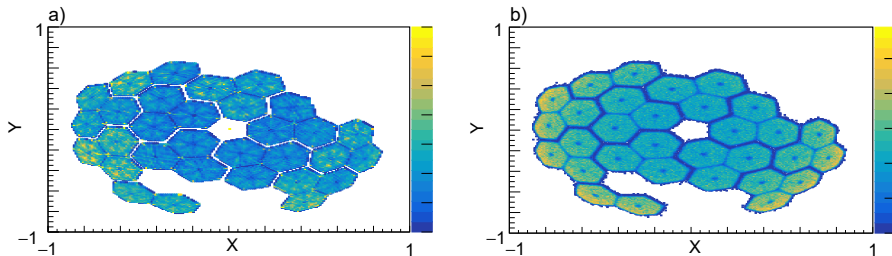

Fig. 6. (a) Experimentally obtained view of the dimensionless X–Y plane directions for the positioning of the AGATA crystals compared to simulated ones (b). Values are calculated as: $X = x_{\text{pos}}/r$, $Y = y_{\text{pos}}/r$, where x_{pos} and y_{pos} are x, y covered by AGATA at distance r.

The AGATA simulated data are then tracked in the same way as the experimental data using the OFT algorithm [16] and Doppler-corrected using the simulated v_{out} vector (*i.e.* the velocity after passing the target). In the simulated data, the experimentally measured energy resolutions for the AGATA crystals are included.

3. Discussion

The simulated γ-ray spectra were compared to the experimentally measured ones for three angular ranges: $120°$–$140°$, $140°$–$160°$ and $160°$–$180°$. The comparison was performed by calculating χ^2 values (Fig. 7 (a), (c)) varying the energy of the transition and the state lifetime, used as parameters in the simulation. The minimum of the χ^2 map obtained for the γ decay of the 2779-keV state in ^{19}O was located at $\tau = 140^{+50}_{-40}$ fs and $E_\gamma = 2779.0^{+1.0}_{-0.8}$ keV. According to Ref. [11], the 2779-keV level can be fed by γ decay of a state at ~ 5360 keV, lying above the neutron-separation energy. In Ref. [11], the energy of the γ-ray transition feeding the 2779-keV state was quoted to be $E_\gamma = 2582(3)$ keV. In the current experiment, a peak at the same energy of
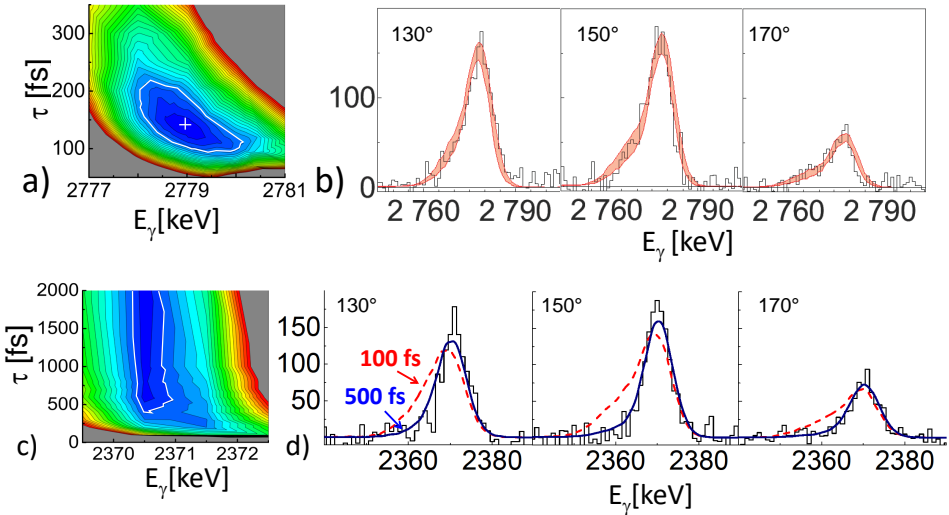

Fig. 7. (Colour on-line) 2D χ^2 minimization map obtained by comparing the experimental γ-ray energy spectra for three angular ranges in the case of the decay from the 2779-keV state (a) and the 2371-keV state (c) in the ^{19}O nucleus. The χ^2 minimum is marked by a white cross (only for the 2779-keV state), the 1σ region by a white line. Comparison between the experimental γ-ray energy spectra and the simulated ones inside the 1σ region of the χ^2 map for the decay of the 2779-keV state (b) and with $\tau = 100$ fs and 500 fs in the case of the decay of the 2371-keV state (d).

2584(2) keV was observed in coincidence with ^{19}O ions, while no 2165-keV transition populating this state from the 4943-keV level observed in Ref. [11] was seen. The feeding of the 2779-keV level from the state at 5363(3) keV is measured to be equal to 13(2)%. However, as reported in Table 1 of Ref. [11], the width Γ_γ of the 5363-keV state is 0.15 eV, which corresponds to a lifetime of 4.4 fs. Thus, the systematic error due to the feeding should be less than 1 fs. The very short lifetime of the 5363-keV state can be confirmed by the very broad 2584-keV γ-ray line (see Fig. 1).

Regarding the 2371 keV state in ^{19}O, no minimum was visible in the χ^2 map (see Fig. 7 (c)). In contrast, a valley is observed, extending from $\tau > 400$ fs. This is consistent with the literature value of $\tau > 3.5$ ps [10, 13], and also the measured transition energy $2370.0^{+0.5}_{-3}$ keV agrees well with the known value.

An additional test of the method was performed by considering the $1/2^-$ state in ^{17}O, at 3055 keV, depopulated by the 2184-keV γ ray. With the same method, we obtain: $E = 2184.3^{+0.3}_{-0.2}$ keV, and $\tau = 159^{+40}_{-20}$ fs. This result is consistent with the only existing literature value of $\tau = 115^{+87}_{-58}$ fs reported in NNDC, which is taken from Ref. [17].

4. Conclusions

A brief description was presented of a novel implementation of a Monte-Carlo technique, which allows to obtain lifetimes, in the range from tens to hundreds of femtoseconds, of excited states populated in a deep-inelastic process. As an example, the method was applied to two excited states in ^{19}O: the $9/2^+$ level at 2371 keV and the $7/2^+$ level at 2779 keV. The measured lifetimes of $\tau > 400$ fs and $\tau = 140^{+50}_{-40}$ fs are, respectively, in agreement with the values quoted in literature. The same method has been applied to measure the lifetimes of the second 2^+ states in ^{20}O and ^{16}C [5]. In the future, using radioactive ion beams for transfer and deep-inelastic reactions, this method can be used to investigate excited level lifetimes in the most exotic neutron-rich regions of the nuclear chart.

REFERENCES

[1] S. Akkoyun *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **668**, 26 (2012).

[2] E. Clément *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **855**, 1 (2017).

[3] M. Rejmund *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **646**, 184 (2011).

[4] A. Maj *et al.*, *Acta Phys. Pol. B* **40**, 565 (2009).

[5] M. Ciemała *et al.*, *Phys. Rev. C* **101**, 021303(R) (2020).

[6] S. Ziliani *et al.*, *Acta Phys. Pol. B* **51**, 709 (2020), this issue.

[7] S. Ziliani *et al.*, *Acta Phys. Pol. B* **50**, 625 (2019).

[8] S. Ziliani, Master Thesis, Milano University, 2018.

[9] M. Ciemała *et al.*, *Acta Phys. Pol. B* **50**, 615 (2019).

[10] National Nuclear Data Center, https://www.nndc.bnl.gov/

[11] R. Dungan *et al.*, *Phys. Rev. C* **93**, 021302(R) (2016).

[12] F. Hibou *et al.*, *Nucl. Phys. A* **171**, 603 (1971).

[13] C. Broude *et al.*, *Nucl. Phys. A* **161**, 241 (1971).

[14] M. Labiche *et al.*, AGATA Geant4 Simulations for AGATA@GANIL.

[15] J.F. Ziegler *et al.*, *The Stopping and Range of Ions in Solids*, Pergamon Press, New York 1985.

[16] A. Lopez-Martens *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **533**, 454 (2004).

[17] T.K. Alexander *et al.*, *Nucl. Phys.* **53**, 593 (1964).