ISOMER SPECTROSCOPY AND SUB-NANOSECOND HALF-LIVE DETERMINATION IN ^{178}W USING THE NuBALL ARRAY*

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(Received January 7, 2019)

The reaction of a pulsed ^{18}O beam on a ^{164}Dy target was studied in the first experiment with the NuBall array at the IPN Orsay, France. Excited state half-lives were measured using the fast timing method with 20 $LaBr_3$(Ce) detectors. The timing characteristics of the fully digital acquisition system is briefly discussed. A value for the previously unknown half-life of the first excited 4^+ state in ^{178}W is presented.

DOI:10.5506/APhysPolB.50.661

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

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1. Introduction

The NuBALL array at IPN Orsay is a hybrid HPGe-$LaBr_3$ coincident γ-ray spectrometer. Contributions to this conference by Lebois [1] and Jovančević [2] go into detail about the capabilities of this array. It comprises 24 Compton suppressed HPGe Clover detectors, 10 Compton suppressed coaxial HPGe detectors, and 20 $LaBr_3$(Ce) scintillator detectors supplied by the FATIMA Collaboration. Compton suppression was achieved by BGO detectors surrounding the Ge crystals. The BGO detectors were not shielded towards the target position, giving the advantage of enhance calorimetry capabilities of the setup. In the first in-beam experiment with NuBall, in November 2017, radioactive nuclei were produced by accelerating an ^{18}O ion beam on a ^{164}Dy target (6.3 mg/cm^2 enriched ^{164}Dy, 1 mg/cm^2 Au backing). The measurement was taken at three different beam energies, 71, 76, and 80 MeV, using a pulsed beam provided by the ALTO accelerator. The beam packages were 2 ns long with 400 ns between pulses. The main reaction channel, apart from Coulomb excitation of the target, was the $^{164}\mathrm{Dy}(^{18}\mathrm{O}, 4n)^{178}\mathrm{W}$ fusion–evaporation reaction. The $LaBr_3$ detectors allow for the determination of excited states half-lives by means of delayed coincidence fast timing that were previously unaccessible using standard Ge detectors. The main goal of the first experiment was to determine half-lives of low-lying excited states in ^{166}Dy after two-neutron transfer.

In this contribution, the performance of the NuBall array in terms of isomer spectroscopy of ^{178}W will be discussed. Sub-nanosecond half-life determination was possible using the centroid shift method. First results of this part of the analysis will be presented. This includes the time walk characteristics of the setup, which featured a fully digital data acquisition system, and the determination of the previously unknown half-life of the first excited 4^+ state of ^{178}W.

2. Isomer spectroscopy in ^{178}W

The nucleus ^{178}W is situated in a region of the nuclear chart where isomers are very abundant. Isomers with half-lives larger than 30 ns are studied well [3, 4]. However, shorter lived isomers in the nanosecond range and below have not been easily accessible in previous studies, as these were out of range of the germanium detectors used in these experiments.

Herein lies a big opportunity for arrays like NuBall, which, in addition to a larger number of HPGe detectors, are also equipped with fast $LaBr_3$(Ce) scintillator detectors. States above and below the isomers can be studied using the information of the beam pulse. The γ–γ time resolution (FWHM) of the Ge detectors was about 20 ns, while that of the $LaBr_3$ detectors was about 320 ps, measured with a ^{60}Co source. However, γ-beam pulse timing with the $LaBr_3$ detectors is found to be impractical, except in the case of the strongest transitions, for which the quality of γ–γ timing is superior. For long-lived isomers with half-lives above 100 ns, γ-beam pulse timing with the Ge detectors is superior, as the energy resolution of the Ge detectors yields a much better peak-to-background ratio compared to the $LaBr_3$ detectors while the time resolution is sufficient for these time ranges. However, it is possible to use the beam pulse information with the $LaBr_3$ detectors by defining an out-of-beam coincidence window. This way, it is possible to select the population of levels below isomers, cleaning up the spectrum for fast γ–γ delayed coincidence measurements. Additionally, a gate on a prompt transition can be selected in the Ge detectors to restrict the observed decay path even more. This makes the half-lives of many short-lived isomers in ^{178}W accessible experimentally for the first time.

As an example with a known half-life, the case of the 6^+ state at 1665 keV is shown in Fig. 1. On the left-hand side, a fit to the energy spectrum is shown in grey. The contributions of the three single peaks are shown as solid lines below the spectrum to estimate a region for clean gating. The result agrees within the uncertainty with an earlier measurement by Canty *et al.* [5].

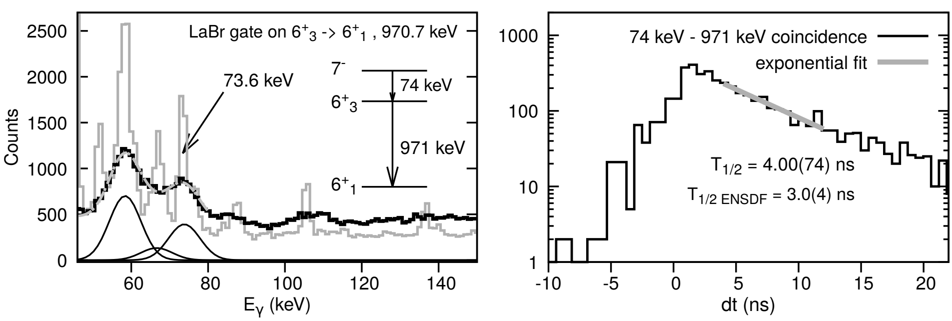

Fig. 1. Examples of a short-lived isomer half-life measured in ^{178}W using a $LaBr_3$–$LaBr_3$ coincidence gate out of beam, 150 ns after the pulse. The left shows a $LaBr_3$ γ-coincidence spectrum gated on the 971 keV transition depopulating the 6^+ isomer at 1664 keV. A Ge spectrum with the same conditions applied is shown in grey. The right shows the corresponding $LaBr_3$–$LaBr_3$ time difference spectra (background subtracted) with an exponential fit.

3. Half-life measurements of excited states in the ground state band of ^{178}W

Half-lives below the time resolution of the $LaBr_3$ detectors are accessible by employing the centroid shift method [6]. This gives access to half-lives down to about 8 ps. For the first time, fully digital timing was used for a large $LaBr_3$ array. Digitisers and software of the FASTER system, developed by Etasse *et al.* at the LPC Caen, France [7], were used for all detectors in the experiment. For the $LaBr_3$ detectors, as well as the BGO detectors, 12 bit digitisers with 500 MHz sampling rate were used. A digital CFD algorithm, using a second order polynomial to interpolate the zero crossing of the discriminator signal, runs on the FPGA and delivers a time stamp with sub-nanosecond precision.

The energy-dependent time walk of the total $LaBr_3$ array was measured using coincident γ rays from a ^{152}Eu source. The result is shown in Fig. 2 (for a reference energy of 344 keV). The time walk is below 50 ps for energies above 200 keV, which is quite low. The uncertainty of the calibration was estimated to be 5 ps above 200 keV. As a test case, the half-lives of the first excited states in the ground band of ^{164}Dy were measured after (prompt) Coulomb excitation.

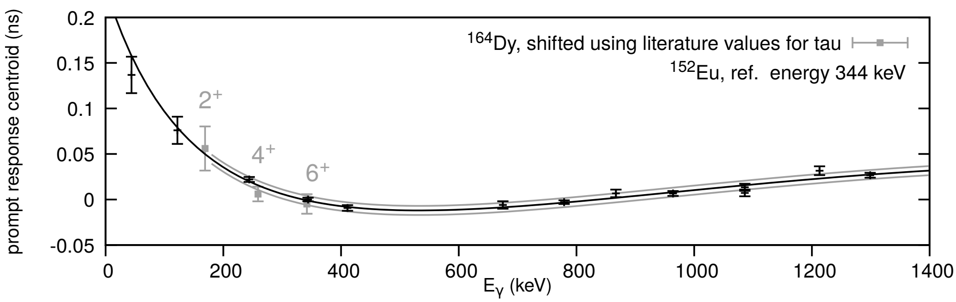

Fig. 2. Mean amplitude time walk for the $LaBr_3$ detector array for a reference energy of 344 keV. The time walk was measured using coincident γ rays from a ^{152}Eu source at the target position and it is below 50 ps for energies above 200 keV. The centroid measurements of the first three excited states of the ground state band in ^{164}Dy, corrected for background contribution and for the known half-lives [8], are shown in grey. They nicely fall onto the curve measured with the source, which confirms the calibration holds for the data taken in beam.

We also measured half-lives in the ground state band of ^{178}W. Prompt coincidence data from runs with energy $E = 76$ MeV and $E = 80$ MeV was used. The half-life of the first 2^+ state was extracted via convolution fit, which yielded $T_{1/2}(2_1^+) = 1.16(6)$ ns. The fit is shown in Fig. 3. It agrees within the uncertainty with the only previous measurement [9]. Those of the 4_1^+ and 6_1^+ were extracted using the centorid shift method (Figs. 3 and 4). These half-lives were measured for the first time. The results after background corrections are $T_{1/2}(4_1^+) = 45(4)$ ps, and $T_{1/2}(6_1^+) < 10$ ps. The results are summarised in Table I.

The respective B(E2) values are then $B(\mathrm{E2}; 4^+ \to 2^+) = 238^{+24}_{-18}$ W.u. and $B(\mathrm{E2}; 6^+ \to 4^+) > 170$ W.u.

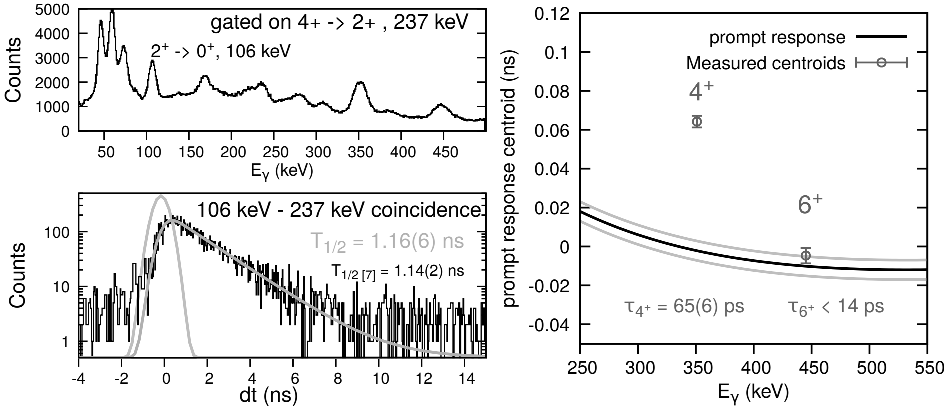

Fig. 3. (Left) Determination of the 2_1^+ half-life of ^{178}W. Background has been subtracted from the time spectrum. The FWHM of the prompt distribution (shown in grey) is 840 ps. (Right) Centroid values, corrected for background and reference energy, of the first excited 4^+ and 6^+ state in ^{178}W. The time walk curve is shown for a reference energy of 344 keV as comparison. The centroid difference from the point to the curve is the lifetime $\tau = T_{1/2}\,\frac{1}{\ln(2)}$.

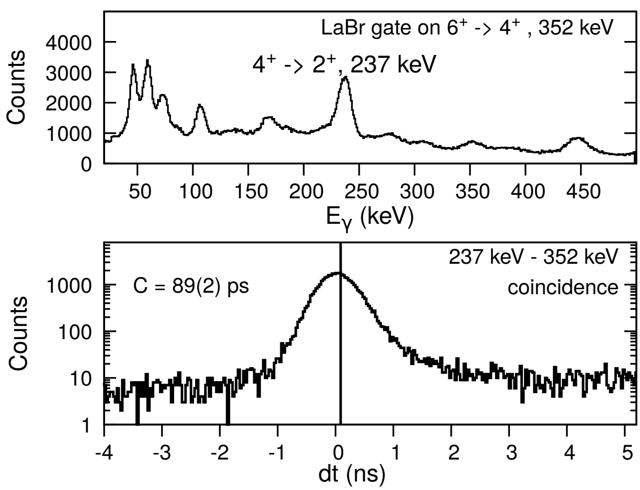

Fig. 4. Half-life determination of the 4^+ state in the ground state band of ^{178}W. A gated energy spectrum is shown in the top panel. The bottom panel shows the corresponding γ–γ time difference spectrum. The centroid of the bare distribution is at 89(2) ps. Background contribution was determined by interpolation with gates close to the peak. In total, a correction of 47.8(26) ps has to be applied. The resulting value of 41.2(33) ps, shifted by 23 ps for a reference energy of 344 keV, is shown in Fig. 3. The same procedure was applied to find the upper limit for the half-life of the 6^+ state.

TABLE I

Results from this work on states from the ground-state band of ^{178}W. Internal conversion coefficients for the calculation of B(E2)s were taken from BrICC [10]. Under the assumption of a rigid rotor, the intrinsic quadrupole moment (in units eb) was deduced via $Q_0 = \sqrt{\frac{16\pi}{5}\frac{\mathrm{B}(E2;J_\mathrm{i}\to J_\mathrm{f})}{<J_\mathrm{i}020|J_\mathrm{f}0>^2}}$

J^π	$E(J \to J-2)$ [keV]	$T_{1/2}$ [ps]	$B(\mathrm{E2};\, J \to J-2)$ [W.u.]	Q_0 [eb]
2_1^+	106	1160(60)	149(8)	2.81(7)
4_1^+	237	45(4)	238^{+24}_{-18}	3.0(2)
6_1^+	351	< 10	> 170	> 2.4

For a rigid rotor, the ratio $B_{4/2} = B(\mathrm{E2};\, 4^+ \to 2^+)/B(\mathrm{E2};\, 2^+ \to 0^+)$ can be calculated directly using the ratio of Clebsch–Gordan coefficents, which is predicted to be $\frac{10}{7} \approx 1.42$. Using the value for $B(\mathrm{E2};\, 4^+ \to 2^+)$ from this work and the more precise value of $B(\mathrm{E2};\, 2^+ \to 0^+) = 153(2)$ W.u. from [9], we get $B_{4/2} = 1.56(16)$ which is in good agreement with the prediction for a rigid rotor.

4. Conclusion

The capabilities of the NuBall array for the determination of isomer half-lives down to the nanosecond regime have been demonstrated with in-beam data taken at the first NuBall campaign in November 2017. Using the delayed coincidence γ–γ method with $LaBr_3$ detectors gated out of beam shows great promise to determine the half-lives of many of the short-lived isomers in ^{178}W.

The digital timing characteristics of the FASTER data acquisition system have been discussed briefly. They are comparable to systems using analogue TACs and CFDs. Especially, the flat time walk for γ rays above 200 keV makes the system a good choice for fast timing measurements with $LaBr_3$ detectors.

The half-lives of the first excited 4^+ and 6^+ state in ^{178}W were measured for the first time.

This research was partially funded by NuSTAR DA BMBF 05P15RDFN1.

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