TPEN

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TPEN: A Triple-foil differential Plunger for lifetime measurements of excited states in Exotic Nuclei.

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Abstract

A Triple-foil differential Plunger for Exotic Nuclei (TPEN) has been developed to measure the lifetimes of excited states in nuclei with small production cross-sections. TPEN utilises one target foil and two degrader foils to make differential lifetime measurements: directly determining the decay function and its derivative at a single plunger distance setting. The direct measurement of the decay function and its derivative removes the requirement to measure γ -ray intensities at several target-to-degrader distances, thereby reducing the beam-time required relative to a conventional plunger with a single-degrader foil. This paper describes the commissioning of TPEN in the lifetime measurement of the first excited 4^+ state in ^{156}Dy using this differential lifetime technique. The 46(2) ps measured lifetime was found to be in good agreement with the 45.6(5) ps deduced from a previous high-statistics experiment using a conventional two-foil plunger. A comparison between the differential mode with TPEN, and that using TPEN as a conventional two-foil plunger reveals that it achieves the same statistical accuracy with a ~ 4 -fold reduction in beam-time in the differential mode, for the reaction and experimental setup used in this work. TPEN opens up new opportunities to study exotic nuclei with lower production cross-sections that were previously not accessible.

Keywords: Plunger, Triple-foil plunger, Excited-state lifetimes, ^{156}Dy , RDDS, DDCM

1. Introduction

Experimental studies of nuclei at the limits of existence will form a major part of international research programs at radioactive ion beam facilities. Determining the lifetimes of excited states in these exotic nuclei can reveal subtle properties of the nuclear force which are masked in the more strongly bound nuclei near to the valley of stability. As the electromagnetic (EM) operator is extremely well understood, transition rates between excited nuclear states provide useful knowledge of the wave functions of the states involved. For example, the lifetimes of nuclear states are particularly sensitive to a variety of nuclear structure features including changes in conventional shell gaps, shape co-existence, isospin symmetry, proton-neutron coupling and the coupling between discrete levels and the continuum [1–5].

The main obstacle in performing experiments on exotic nuclei far from stability is their small production cross-sections. For example, conventional plunger devices such as the Differential Plunger for Unbound Nuclear States, (DPUNS) [6] are limited to measuring lifetimes in nuclei with production cross-section greater than $10 - 20 \mu\text{b}$ [7–11]. In order to study nuclei with smaller production cross-sections, the Triple-foil differential Plunger for Exotic Nuclei (TPEN) was developed at The University of Manchester. TPEN is more efficient than traditional two-foil plungers as it utilises the differential mode of the differential-decay curve method (DDCM) to directly determine the decay function and its derivative at a single plunger distance setting [12].

TPEN was commissioned at the Accelerator Laboratory of the University of Jyväskylä (JYFL), Finland. This paper presents the results of this commissioning experiment in which the lifetime of the first excited 4^+ state in ^{156}Dy was measured. The lifetime measured with TPEN was found to be in agreement with that determined from a conven-

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37 tional plunger experiment [13]. A comparison between the
 38 differential mode of TPEN and TPEN acting as a conven-
 39 tional plunger reveals that it achieves the same statistical
 40 accuracy with approximately 4-fold reduction in beam-
 41 time with this $^{24}\text{Mg}(^{136}\text{Xe}, 4n)$ reaction. The improved
 42 beam-time efficiency will allow lifetime measurements in
 43 more exotic nuclei. As an example, TPEN could be used
 44 to study: (a) proton-emitting nuclei in fusion-evaporation
 45 reactions with the Jurogam III setup at the University of
 46 Jyväskylä, (JYFL) Finland; (b) neutron-rich exotic nuclei
 47 with COULEX-plunger experiments or multi-nucleon trans-
 48 fer reactions at the MINIBALL setup at HIE-ISOLDE, CERN
 49 [14, 15].

50 2. Method

51 2.1. Differential lifetime measurement

52 The Recoil Distance Doppler-Shift method (RDDS) pro-
 53 vides a method of studying the lifetimes of excited states
 54 in nuclei [12, 16]. In a typical RDDS experiment, a heavy
 55 ion beam impinges a target foil to produce recoiling nuclei
 56 in high-spin states. A stopper foil is placed close to the
 57 target foil to stop the recoils. The γ rays emitted from the
 58 recoiling nucleus will experience a different Doppler shift in
 59 energy depending on whether the recoiling nucleus decays
 60 before or after the degrader foil. The intensities of the
 61 fully-shifted and degraded components of the γ -ray transi-
 62 tion are measured at several target-to-degrader distances
 63 and are used to extract the lifetime of the state of inter-
 64 est. The Differential Decay Curve Method (DDCM) is an
 65 analysis technique within the RDDS method. The DDCM
 66 and RDDS methods are described in depth in Refs. [12, 16],
 67 respectively.

68 Reference [12] also presents the idea of a three-foil dif-
 69 ferential plunger which comprises of one target foil and
 70 two degrader foils. A three-foil plunger utilises the DDCM
 71 but directly measures the decay function and its derivative
 72 with a single set of plunger distances, eliminating the re-
 73 quirement to measure γ -ray intensities at multiple distance
 74 settings. Figure 1(a) shows a schematic illustration of the
 75 target, degrader and stopper foils used in the new three-foil
 76 plunger TPEN.

77 As shown in Fig. 1(a), the incoming beam is directed
 78 onto a target foil, producing excited nuclei which subse-
 79 quently decay via γ -ray emission. These nuclei recoil out
 80 of the target foil and travel towards the degrader foil with
 81 a velocity v , taking a time $t = x/v$ to reach the degrader
 82 foil, where x is the target-to-degrader foil distance. As
 83 the recoils pass through the degrader foil their velocity is
 84 reduced to v' and they continue towards the stopper foil
 85 where they are stopped. The time taken from leaving the
 86 degrader foil to reaching the stopper foil is $\Delta t = \Delta x/v'$
 87 where Δx is the degrader-to-stopper foil distance. If the
 88 excited state is short lived compared with t , then the γ -ray
 89 decay is likely to occur between the target and degrader foil
 90 and the emitted γ rays will be observed fully-shifted (fs)

Figure 1: (a) A schematic illustration of the TPEN target, degrader and stopper foils along with (b) the three Doppler shifted γ -rays and their energies. The Doppler shifts shown are for backward angled detectors such as those used in this experiment.

and the observed γ -ray energy is γ_{fs} . Alternatively, if the
 excited states decay after the degrader foil but before the
 stopper foil, then the γ -rays are observed with a smaller
 Doppler shift in energy and are said to be degraded (d)
 with γ -ray energy γ_d . Finally, if the nuclei decay in the
 stopper foil, no Doppler shift in energy is experienced and
 the observed γ -energy is unshifted (us), γ_{us} . Therefore, by
 varying the target-to-degrader distance, x , and degrader-to-
 stopper distance, Δx , and measuring the intensities of γ_{fs} ,
 γ_d and γ_{us} , the lifetimes of excited states in the recoiling
 nucleus can be accurately measured. It should be noted
 that a second degrader foil can replace the stopper foil
 allowing the recoiling nucleus to pass into a recoil separator
 for subsequent tagging as has been used with a conventional
 two-foil plunger [6–8, 17–22].

The normalised probability for a decay to occur after
 the recoil has been implanted into the stopper foil as a
 function of flight time, is known as the decay curve, $R(t)$.
 Both the decay curve, and the derivative of the decay
 curve must be known in order to measure a lifetime [23].
 The decay curve is directly measured by measuring the
 intensity, I^{us} , of γ_{us} . In a two-foil plunger, the derivative
 of the decay curve must be inferred from the shape of
 the decay curve, which requires measurements at several
 target-to-degrader distances (see Ref. [23] for more details).
 The third foil in TPEN allows for a direct measure of both
 the decay function and the derivative of the decay function.
 This direct measure of the derivative of the decay function
 eliminates the need for measuring $R(t)$ at several target-
 to-degrader distances. In order to accurately infer the
 derivative $\frac{d}{dt}R(t)$ from the measured quantity $R(t)$, the
 typical number of target-to-degrader distances required
 in a two-foil plunger experiment is 6 – 10. Hence using
 TPEN there is a potential reduction in the total number
 of γ -ray events required for a lifetime measurement of
 a factor of $\sim 6 - 10$ [12, 23]. However, this advantage
 is somewhat reduced because the additional foil creates
 additional scattering and the observed γ -ray decays are now

distributed over three component peaks with TPEN instead of two component peaks from a conventional plunger. This is further discussed in Sec. 6. This reduction in beam-time requirement is one of the main advantages of TPEN as the precision of lifetime measurements in RDDS is mostly limited by the number of γ -ray events observed [23].

When measuring nuclear lifetimes, it is often favorable to use coincidence gates in order to remove the effects of side-feeding. In the situation where a γ -ray coincidence gate is placed on the Doppler-shifted components of a γ -ray energy directly feeding a state of interest, the lifetime of that state can be measured directly from the three intensity components using a single distance measurement [12]. The lifetime of the state is given by Eqn. 1 [12],

$$\tau = \frac{I^{us}}{I^d} \frac{\Delta x}{v'}, \quad (1)$$

where I^d is the intensity component of the degraded peak.

Alternatively, if a coincidence gate on the Doppler-shifted components of a γ -ray not directly feeding a state of interest is used, then the lifetime of the state of interest is given by [12]:

$$\tau_i = \frac{I^{us} - b_{ij} \sum_h \frac{\alpha_{hi}}{\alpha_{ij}} I_{hi}^{us}}{I^d} \frac{\Delta x}{v'}. \quad (2)$$

Here, b_{ij} is the normalised branching ratio of the state of interest, L_i , to the state L_j , α_{hi} and α_{ij} reflect any difference in the intensity between feeding and depopulating transitions and is defined in Ref [23], and I_{hi}^{us} is the intensity of the unshifted peaks of the transition L_h to L_i . Derivations of Eqns. 1 and 2 are given in Ref. [12] and show that the equations only hold under the condition that Δt is small compared with τ . A correction factor $C(\tau, \Delta t)$, discussed in Ref. [24], is used to account for any difference between the measured quantity I^d and $\frac{d}{dt}R(t)$ and is given by:

$$C(\tau, \Delta t) = \frac{\exp(\Delta t/\tau) - 1}{\Delta t/\tau}. \quad (3)$$

For measurements where the decay curve can be approximated as a simple exponential decay, the correction factor should be applied iteratively to the lifetime calculated from Eqns. 1 and 2.

3. Design

TPEN consists of three foils mounted onto stretching cones. Computer-aided-drawings of the stretching cones are shown in Fig. 2. Figure 3 shows a photograph of a degrader foil stretched over one of these cones. The foil stretching cones are connected to foil mounts using three hard springs placed 120° apart which are compressed using screws. The cones are arranged inside TPEN, typically with the flat faces (the face that can be seen in Fig. 3) of the target foil and the flat face of the degrader foil facing each other, and the stopper foil nested in the degrader.

cone. TPEN can also be arranged with the flat faces of the degrader foil and stopper foil facing each other, with the target nested inside the degrader cone. This paper uses the first arrangement, which is seen in Fig. 4. The compression of the springs between the stretching cones and the foil mount allows for the alignment of the foils. The screws that vary the compression of the springs sit inside Boron Nitride (BN) insulating blocks. These BN blocks were used to electrically isolate the cones from the foil-mounts and allow heat to dissipate into the mounts, preventing heat build up when TPEN is used under vacuum conditions.

Figure 2: Computer-aided-drawing of the target (left), degrader (center) and stopper (right) stretching cones used to mount the foils in TPEN. The cones are all 88 mm in diameter and 3 mm thick and made from aluminium.

Figure 3: Photograph of a degrader foil stretched over a degrader cone.

Figure 4(a) shows a schematic diagram of the TPEN central chamber and Fig. 4(b) details the online feedback system used to control and monitor the distances between the three foils. The stopper, degrader and target stretching cones are shown in Fig. 4(a). The target foil is at a fixed position, whereas the degrader and stopper foils are mounted on Physik Instrumente (PI) [25] Linear Piezo Positioning Stage-45 (LPS-45) piezoelectric motors (Fig. 4), which can change the target-to-degrader and degrader-to-stopper distances independently. The LPS-45s each have a total travel range of 26 mm and have a position resolution of 1 nm. These motors utilise a constant negative-feedback system which keeps the target-to-degrader and

degrader-to-stopper distances at the set value throughout the experiment. A BNC model PB-5 pulser is used to apply a voltage pulse to the degrader foil. The induced voltage on the target and stopper foils is used for feedback see Fig. 4(b). A 16-Bit National Instruments [26] USB 6251 data acquisition (DAQ) card was used to sample the induced voltage at a rate of 1.25×10^6 samples per second. If the induced voltage moves outside an accepted range, then the feedback system acts to move the motors accordingly. Two TESA [27] GT43 axial miniature probes and a TESA TT20 electronic micrometer were used to calibrate the induced voltage against target-to-degrader and degrader-to-stopper distance. A modified version of the Köln plunger control software, adapted for Windows 10, was used to run the constant feedback system independently from the data acquisition system. The software was originally developed for the Köln plunger [23].

4. Commissioning

TPEN was commissioned at the Accelerator Laboratory of the University of Jyväskylä, Finland, by measuring the known 45.6(5) ps lifetime of the first 4^+ excited state in ^{156}Dy [13]. The $^{24}\text{Mg}(^{136}\text{Xe}, 4n)^{156}\text{Dy}$ fusion-evaporation reaction was used at a beam energy of 590 MeV with a cross-section of ~ 100 mb. The 4^+ lifetime in ^{156}Dy was originally measured with a conventional two-foil plunger using the $^{124}\text{Sn}(^{36}\text{S}, 4n)$ reaction at 155 MeV [13]. Figure 5 shows the partial level scheme of ^{156}Dy , taken from Ref [28]

Figure 5: Partial level scheme of ^{156}Dy according to Ref. [28]. The lifetimes of the known states from Ref. [13] are given for the rotational band built upon the ground state.

Our commissioning experiment tested the differential mode of TPEN and compared the lifetime obtained with

that of the previous measurement [13]. In the present experiment, a ~ 1 pA $^{136}\text{Xe}^{25+}$ beam from the K130 cyclotron was used for 6 days to bombard a 1 mg/cm^2 natural magnesium target foil placed inside TPEN. The reaction produced ^{156}Dy nuclei with a measured average recoil velocity of $6.99(10)\%c$. Two 6.6 mg/cm^2 ^{56}Ni foils were placed downstream from the target position to degrade and stop the produced recoils, respectively. The degraded recoil velocity was measured to be $v' = 2.86(6)\%c$.

Four Compton-suppressed Jurogam Phase-1 [29, 30] germanium detectors were placed at an angle of 157.5° with respect to the beam axis around TPEN in order to measure the γ -ray intensities. The detectors were placed at a distance of 12.5 cm from the target position on a specially constructed table, where their combined absolute efficiency was measured to be $\sim 0.2\%$ at 1.3 MeV. Figure 6 shows TPEN installed inside the target vacuum chamber and the four germanium detectors used in the measurement. The central vacuum housing of TPEN is an aluminium ball, 176 mm in diameter with a wall thickness of 2 mm. The foils are arranged inside TPEN such that γ -rays detected in the germanium detectors pass through only the 2 mm aluminium wall.

The total data readout (TDR) [31] data acquisition system was employed to record the events from all four germanium detectors. The GRAIN software package was used to perform offline analysis and construct 2D γ - γ matrices [32] where the two γ rays were detected within 100 ns of each other. A total of five sets of distances, $(x, \Delta x) = (700 \mu\text{m}, 31 \mu\text{m}), (700 \mu\text{m}, 51 \mu\text{m}), (400 \mu\text{m}, 31 \mu\text{m}), (400 \mu\text{m}, 51 \mu\text{m}), (400 \mu\text{m}, 71 \mu\text{m})$, were used for differential lifetime analysis. The three intensity components of the 266-keV γ -ray were measured at each of these plunger distances and Eqn. 1 was used to extract the lifetime of the 4^+ state in ^{156}Dy . The components were measured at several distances to ensure the differential technique was valid across a range of distances but the lifetime of the state was measured independently at each of these distances.

5. Results

5.1. Differential mode

Figure 7 shows the three-foil system inside the central TPEN chamber.

The three foils were aligned in order to achieve small foil separations. The alignment of the foils was performed in two steps. Firstly, the degrader foil-mount was rotated through 180° , relative to that shown in Fig. 4, so that the flat faces of the stopper and degrader foils were facing each other. The stopper foil was optically aligned with the degrader foil by varying the compression on the springs with the screws. The degrader foil was then rotated back through 180° to its original position so that the flat faces of the target and degrader foils were facing each other and the stopper foil was nested inside the degrader, as shown in Fig. 4. Using the optical alignment as a starting position,

Figure 4: (a) A diagram showing TPEN and (b) the electronic modules used to control the constant feedback system. If required the target cone can be replaced with a stopper cone the degrader foil can be rotated through 180° to allow for very small degrader-to-stopper distances.

Figure 6: A photograph of the TPEN vacuum housing surrounded by the 4 backward facing germanium detectors, two of which can be seen. RITU [33] can also be seen downstream from the central chamber, although this was not used in the present experiment.

Figure 7: A photograph of the TPEN. The stopper foil can be seen mounted on a LPS-45 motor on the right of the image. The foil mounts for the degrader and target foils can also be seen.

the degrader and stopper foils were aligned using the capacitance measurement, again by varying the compression on the springs. Once the degrader and stopper foils were aligned, the target foil was aligned with the degrader foil by adjusting the springs on the target mount only. The alignment was performed optically and then fine tuned with the capacitance measurement. After the alignment was completed, a distance calibration was performed in order to determine the offset between electrical contact between the foils and the zero separation distance. The calibration curve for the target-to-degrader distance is shown in Fig. 8 and the calibration curve for the degrader-to-stopper distance is shown in Fig. 9. The calibration curves were compared to parallel-plate capacitors to determine the off-

sets. The offset between the target and degrader was found to be $90(20) \mu\text{m}$ and the offset between the degrader and stopper foils was found to be $8(1) \mu\text{m}$. For lifetimes measurements using a single set of distances with TPEN, this offset is required for the lifetime analysis and contributes to the overall systematic error in the lifetime measurement. For high-statistics plunger experiments, this systematic error in the absolute distance can be large compared to the statistical uncertainty. Therefore, for high-statistics

experiments several plunger distances in differential mode should be used to remove this systematic uncertainty.

Figure 8: The target to degrader calibration curve showing induced voltage versus distance.

Figure 9: The degrader to stopper calibration curve showing induced voltage versus distance.

Figure 10(a) shows the total projection of the 2D γ - γ coincidence matrix for any of the four germanium detectors versus any other detector. This spectrum contains the data from all distances combined in order to illustrate the quality of our data. As a natural magnesium target was used, several contaminants were produced with a significant cross-section of ~ 30 mb, estimated from gated projections of the γ - γ coincidence matrix. These are highlighted with symbols in Fig. 10(a). To select the γ rays originating from ^{156}Dy , and to remove the effects of side-feeding, a γ -ray coincidence gate was placed on the fully-shifted and degraded components of the 366-keV γ ray, which directly feeds the 4^+ state in ^{156}Dy . Figure 10(b) shows a background subtracted spectrum of γ rays in coincidence with the fully shifted and degraded components of the 366-keV γ -rays.

Two dimensional γ - γ matrices were produced for each of the plunger distance settings collected in the experiment. In order to analyse the lifetime of the 4^+ state in ^{156}Dy , a γ -ray coincidence gate was placed on fully shifted and degraded components of the 366 keV, 6^+ to 4^+ , transition in each of these γ - γ matrices. Figure 11 shows the resultant gated spectra on a logarithmic scale, zoomed in on the 4^+ to 2^+ transition for each distance setting. Gaussian fits to the fully-shifted

Figure 10: (a) Spectrum showing the total projection of a 2D γ - γ coincidence matrix for any detector versus any detector, for all distances combined. The γ -rays from transitions in ^{156}Dy are labeled with their initial and final states and the main contaminants are labeled with symbols. (b) Spectrum showing γ -rays in coincidence with the fully-shifted and degraded components of the $6^+ \rightarrow 4^+$ transition in ^{156}Dy , for all distances combined.

(green), degraded (orange) and stopped (red) intensity components of the 266-keV γ ray transition were made in order to extract the component intensities. Table 1 shows these intensities at the five plunger distances.

Table 1: The target-to-degrader, x , and degrader-to-stopper distances, Δx used during the commissioning experiment. The distances given are relative to the electrical contact point between the foils. The intensities of the unshifted (I^{us}), degraded (I^d) and fully-shifted (I^{fs}) components of the 266-keV transition are given for different x and Δx combinations, along with the lifetimes, τ , calculated with Eqn. 1.

x (μm)	Δx (μm)	I^{us}	I^d	I^{fs}	τ (ps)
700	31	1337(40)	140(20)	1149(40)	44(5)
700	51	1824(47)	275(27)	1827(49)	47(4)
400	31	786(30)	82(13)	395(23)	44(6)
400	51	1460(41)	222(22)	781(33)	47(4)
400	71	1048(34)	209(18)	520(26)	49(4)

The lifetime of the 4^+ state was then calculated from Eqn. 1 at each of the plunger distances, and these are also given in Table 1. The correction factor, from Eqn. 3, was applied iteratively to the lifetime calculated from Eqn. 1 and accounted for a $\sim 3\%$ change in the measured lifetime. The average and standard deviation for these lifetime values is 46(1) ps. As our lifetime measurements at each distance setting were independent, no normalisation of the measured γ -ray intensities was required. This removes one source of error associated with conventional two-foil

Figure 11: Spectra gated on the fully-shifted and degraded components of the 6^+ to 4^+ transition in ^{156}Dy for different target-to-degrader and degrader-to-stopper distances, showing the fully-shifted (green-dashed), degraded (orange-solid) and stopped (red-dotted) intensity components of the 266-keV γ ray.

plungers which require normalisation of γ -ray intensities across ~ 6 -10 distance settings. Therefore, a weighted average of $\tau = 46(2)$ ps was calculated from the five distances used in our differential analysis. This $46(2)$ ps lifetime is in good agreement with the $45.6(5)$ ps measured in Ref. [13] from a high-statistics, two-foil plunger experiment, demonstrating that TPEN works with differential lifetime measurements.

In order to understand the performance of TPEN in the limit of low statistics, a subset of higher-fold, multiplicity 3 events were used to perform a similar lifetime analysis. At a plunger distance of $x = 700 \mu\text{m}$, $\Delta x = 51 \mu\text{m}$, a 2D γ - γ matrix was produced which only included events with multiplicity 3 or above. A coincidence gate was set on the fully shifted and degraded components of the 366 keV, 6^+ to 4^+ transition in ^{156}Dy . Figure 12 shows a zoomed in spectrum of the 4^+ to 2^+ transition with two histogram channel widths (a) 1 keV per channel and (b) 2 keV per channel. Gaussian fits to the fully-shifted (green), degraded (orange) and stopped (red) intensity components of the 266-keV γ ray transition are shown. The number of counts recorded in the fully shifted, degraded and stopped components of the 266-keV γ ray, were 210(20), 28(9) and 200(16), respectively. Using Eqn. 1 and the component intensities, the lifetime of the 4^+ state in ^{156}Dy was found to be $50(13)$ ps, which is in good agreement with the literature value [13]. This low-statistics analysis demonstrates that TPEN can be used in differential mode for lifetime measurements in

nuclei with small production cross sections.

Figure 12: Spectra gated on the 4^+ state in ^{156}Dy using multiplicity three events at $x = 700 \mu\text{m}$, $\Delta x = 51 \mu\text{m}$. The fully-shifted (green), degraded (orange) and stopped (red) intensity components of the 266-keV γ ray are shown. The data is shown using histogram channel widths of 1 (a) and 2 keV (b).

5.2. Using TPEN as a standard two-foil plunger

The lifetime of the 4^+ state in ^{156}Dy was also measured using TPEN as a standard plunger to allow a direct comparison of the precision of results using the two different techniques. The intensities of γ -ray decays before and after the first degrader foil were measured in coincidence with the fully-shifted component of the 366-keV transition at target-to-degrader distances of $48 \mu\text{m}$, $76 \mu\text{m}$, $109 \mu\text{m}$, $140 \mu\text{m}$, $195 \mu\text{m}$, $257 \mu\text{m}$, $300 \mu\text{m}$, $400 \mu\text{m}$, $500 \mu\text{m}$ and $700 \mu\text{m}$. These data are shown in Fig. 13. Gaussian fits to the data were made in order to extract the component intensities. The measured intensities were normalised to the total number of counts in the gated projection, to correct for different number of beam particles between runs.

The degraded and stopped components of the 266-keV were combined to form the decay curve, i.e. the intensity of decays after the first degrader foil. Combining the stopped and degraded components effectively allows TPEN to be used as a standard two-foil plunger. In this way the decay curve is measured at various distances and the differential of the decay curve is inferred from the shape of the decay curve, as in the standard DDCM [12].

Figure 14 shows the lifetime of the 4^+ state in ^{156}Dy calculated using the standard DDCM analysis using the NAPATAU computer program. The normalised intensities of the fully-shifted components the 266-keV transition in coincidence with the fully-shifted component of the 366-keV transition is shown as a function of distance in Fig. 14(b). The combined normalised intensities of the degraded and stopped components the 266-keV transition in coincidence with the fully-shifted component of the 366-keV transition, as a function of distance are also shown in Fig. 14(c). A piece-wise second order polynomial is fitted to the fully-shifted component (red-dashed), the uncertainty on this

Figure 13: The background subtracted spectra showing the three intensity components of the 266-keV transition in ^{156}Dy , in coincidence with the fully-shifted component of the 366-keV transition at 10 plunger distances. Gaussian fits to the decays occurring before the first degrader foil are shown in red-dashed and Gaussian fits to the decays occurring after the first-degrader foil are shown in blue-solid.

fit is shown in red-shaded. The red-shaded area shows the change to the fit given by increasing the total χ^2 by 1, i.e. increasing the average variance by 1. The derivative of this second-order polynomial, multiplied by the lifetime of the state, is fitted to the intensity of decays after the degrader foil (blue-solid), with the uncertainty in blue-shaded. The normalised intensities of the decays before and after the degrader foil are given in Table. 2. The lifetime of the state is calculated at each of the 10 target-to-degrader distances and is shown in Fig. 14(a) along with the uncertainty on the average lifetime, taking into account the uncertainty on the fit to the data.

6. Discussion

6.1. Beam-time improvement with TPEN

This commissioning experiment has demonstrated that the newly constructed TPEN is capable of performing differential lifetime measurements in the limit of low statistics. The main advantage of a triple-foil differential plunger is the reduced beam-time required for a lifetime measurement,

Figure 14: The intensity of the 266-keV transition in ^{156}Dy before and after a degrader foil, in coincidence with the fully-shifted component of the 366-keV transition at 10 plunger distances. (a) the calculated lifetime at each of the plunger distances and the average lifetime, (b) the fully-shifted component of the 266-keV transition and a piecewise polynomial fit to the data (red-dashed) along with the uncertainty on the fit (red-shaded), (c) the derivative of the fit to (b) multiplied by τ (blue-solid) and the uncertainty on this (blue-shaded). The uncertainty on the derivative is of the same order as the line thickness.

compared to that of a conventional two-foil plunger. In the present work, a total of 7×10^7 γ - γ events were collected using TPEN for the differential lifetime measurements performed at five sets of target-to-degrader and degrader-to-stopper distances. This resulted in a 13 000(200) events in the three components of the 266-keV γ -ray transition for the differential lifetime analysis, yielding a lifetime value with a 4% uncertainty, seen in Fig. 11.

When using the standard DDCM analysis by using TPEN as a standard plunger, 10 000(100) counts were used across all distances to yield a lifetime value with a 12% uncertainty, seen in Fig. 14. From this, it is estimated that $\sim 50\,000(1\,000)$ counts would provide a measurement with a 4% uncertainty using TPEN as a two-foil plunger. Directly taking the ratio of the statistics required in the two modes of TPEN, with identical detector set-ups, it can be concluded that TPEN in differential mode requires a factor of 3.8(1) less in statistics or in beam time compared to a standard plunger with the reaction used in this work.

6.2. Future use of TPEN

For lifetime measurements in nuclei produced with small production cross-sections, it is often essential to use tag-

Table 2: The target-to-degrader, x , and the normalised measured intensities of the 266-keV γ -ray transition before and after the degrader. The distances given are relative to the electrical contact point between the foils.

$x(\mu\text{m})$	I^{fs}	$I^{us} + I^d$
48	122(20)	480(55)
76	106(20)	500(60)
109	155(20)	500(50)
140	150(25)	450(50)
195	200(21)	350(35)
257	250(25)	430(45)
300	290(40)	450(70)
400	240(20)	360(50)
500	270(25)	340(30)
700	305(25)	270(40)

beam-time requirements of a factor of ~ 4 for measurements with no tagging, and a factor of ~ 2 for experiments when tagging is employed.

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ging techniques in order to select the nuclei of interest from the overwhelming background from the less exotic reaction products [17–21]. These tagging techniques are often performed using recoil separators such as RITU [33] at JYFL. The overall transmission efficiency of separators is reduced by any material in the beam’s path. Hence, the extra foil in TPEN will reduce the tagging efficiency compared with a conventional two-foil plunger and therefore reduce the beam-time improvement estimated above. In this case with the $^{24}\text{Mg}(^{136}\text{Xe}, 4n)$ reaction, simulations show that with the RITU separator [33] the addition of a 1 mg/cm^2 Mg degrader foil reduces the overall transmission efficiency by $\sim 33\%$. Simulations specific to the reaction should be performed for reliable values. Therefore, if recoil tagging techniques were employed for the reaction described in this work, then the overall beam-time improvement using TPEN would be a factor of $\sim 3.5 \times 0.66 = 2.3$ relative to using a two-foil conventional plunger. As two-foil plungers have performed tagged lifetime measurements in nuclei with production cross-sections of $10 - 20\mu\text{b}$ [7, 22], TPEN would therefore be capable of performing tagged lifetime measurements in nuclei with production cross-sections down to $\sim 4 - 8\mu\text{b}$.

7. Conclusions

A new triple foil plunger, TPEN, has been developed in order to study nuclei with production cross-section of the order of a few microbarn. A commissioning experiment at the accelerator laboratory of the University of Jyväskylä, Finland, has been performed. The first 4^+ excited state in ^{156}Dy was measured at five distances independently. All of the measurements were in good agreement with the current literature value of $45.6(5)\text{ ps}$ [13], with an average lifetime from all distances being $46(2)\text{ ps}$. This measurement demonstrated the capability of TPEN to measure lifetimes using a single set of distances and showed a reduction in

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