A NEW PLUNGER DEVICE FOR INVESTIGATING THE EFFECTS OF DEFORMATION ON PROTON EMISSION RATES VIA LIFETIME MEASUREMENTS

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A new plunger device has been designed and built to measure the lifetimes of unbound states in exotic nuclei beyond the proton drip-line. The device is designed to work in both vacuum and dilute-gas environments made possible through the introduction of a low-voltage piezoelectric motors. The differential plunger for unbound nuclear states, DPUNS, will be used in conjunction with the gas-filled separator RITU and the vacuum separator MARA at the accelerator laboratory of the University of Jyväskylä, Finland, to measure the lifetimes of excited states with low population cross-sections. This is achieved by eliminating the need for a carbon foil to isolate the helium gas of RITU from the beam line thus reducing the background from beam-foil reactions. The plunger will be used to address many key facets of nuclear structure physics with particular emphasis on the effect of deformation on proton emission rates.

1. Introduction

The study of proton emission is key to the understanding of drip-line nuclei far from the valley of stability. Structure information on these exotic proton-emitting nuclei is usually extracted from a comparison between the measured half-life and that determined theoretically. Decay lifetimes calculated within simple barrier penetration models [1] agree fairly well with those measured in near-spherical nuclei but more sophisticated models are required for deformed nuclei [2,3]. Proton emission rates are highly sensitive to nuclear deformation but in all known cases the deformation has never been experimentally determined. Currently, proton emission calculations rely on theoretically determined deformations [4] making experimentally determined values highly sought after for these theoretical models. To address this logical weakness a new plunger device, DPUNS (Differential Plunger for Unbound Nuclear States) [5], has been developed to measure the lifetimes of low-lying excited states in proton emitting nuclei. The accurate determination of excited-state lifetimes above proton emitting states can be used to evaluate the extent of deformation in the system. With the aid of state-of-the-art theoretical models [2,6-10], decay half-lives can be calculated for the measured deformation and compared with those determined experimentally. This study will, therefore, test and improve current models and help shed light on the effect of deformation on proton emission rates

2. DPUNS Technical Details

DPUNS, like the majority of plunger devices, utilises the recoil distance Doppler shift (RDDS) method [11]. Accelerated nuclei impinge on a reaction target producing the nuclei of interest. Downstream from the target resides a degrader foil, usually Mg, which acts to reduce the velocity of the reaction products leaving the target foil. A degrader foil is required for tagging techniques, otherwise, a thick stopper foil can be used. The target and degrader foils are stretched and optically aligned so that extremely short target-to-degrader distances can be achieved in order to measure picosecond lifetimes. A voltage pulse, supplied by a high-precision BNC Model PB-5 pulser, is applied to the degrader foil and the induced voltage on the target foil is used as a feedback signal. The induced target signal is sampled by a 1.25 MS/s, 16 Bit, National Instruments PCI-6251 M Series data acquisition (DAQ) card. A PC running a modified version of the Köln plunger control software, developed under the National Instruments LabView [12] framework, employs negative feedback to maintain the target-to-degrader distance during beam bombardment. DPUNS was designed to be used primarily at the accelerator laboratory of the University of Jyväskylä, Finland (JYFL) in conjunction with the Jurogam-II Ge detector array [13], the gas-filled separator RITU [14,15] and the GREAT focal plane detector system [16]. The high transmission efficiency and selectivity of RITU combined with the high detection efficiency of Jurogam-II and GREAT is necessary to study exotic nuclei with low production rates. The basic mechanical design of DPUNS (Fig. 1) is based on the very successful Köln plunger device [17]; however, DPUNS encompasses a number of technical improvements to facilitate lifetime measurements in nuclei produced with relatively low cross-sections compared to those previously measured using the RDDS technique. Firstly, DPUNS utilises differential pumping to eradicate the need for a carbon foil to isolate the helium gas of RITU from piezoelectric motors. This reduces the background recorded by the Jurogam-II Ge detectors from nuclei produced in beam reactions on the carbon foil. For example, calculations show that for the reaction used in the commissioning experiment, discussed in section 3, that the fusion-evaporation reaction yield for a 0.1 μm carbon foil would constitute around 30% of the total yield for both beam-foil and beam-target reactions (using a 0.8 mg/cm^2 ^{98}Mo target). The removal of the associated γ-ray background is crucial for low cross-section measurements. To remove the helium gas from the beam line an

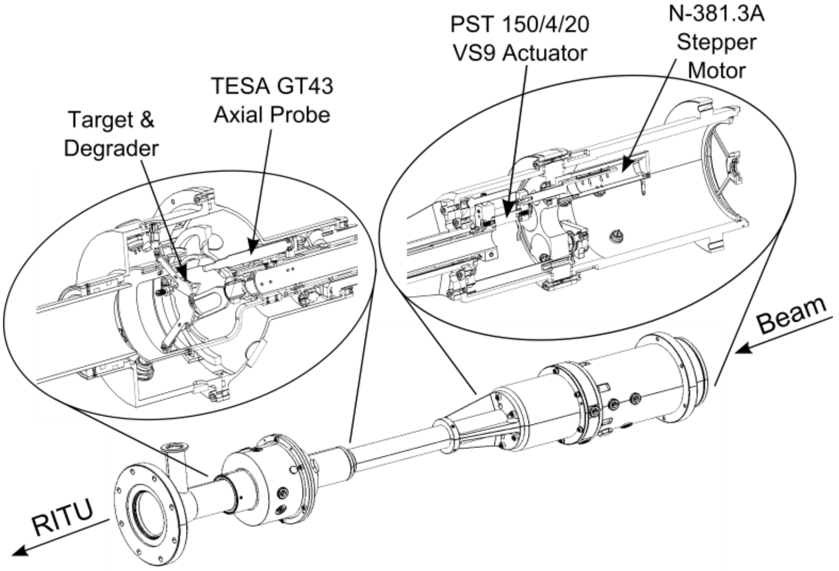

Figure 1: Computer aided drawing of the new DPUNS plunger device showing the external geometry and cross-sections of the upstream and downstream ends that house the piezoelectric drive system and distance measurement device, respectively

Edwards EH1200 Roots pump [18] is located directly upstream from DPUNS. Differential pumping requires low-voltage motors that would not discharge in the dilute gas environment of RITU. DPUNS incorporates a Physik Instrumente (PI) [19] 45 V, high-precision, N-381.3A linear piezoelectric stepping motor as well as a 150 V Piezomechanik [20] PST 150/4/20 VS9 piezoelectric actuator. The stepping motor boasts a 30 mm travelling range allowing the measurement of lifetimes as long as 2 ns (based on a typical recoil velocity v/c = 4%). The motor utilises piezo bending elements allowing a movement accuracy of around 20 nm. It was envisaged that the stepper motor would be used to set the target-to-degrader distance and the actuator would keep this value constant during beam bombardment. The excellent movement resolution of the stepper motor, however, means that both tasks can be performed solely by the one component if required. The induced target voltage is calibrated using a TESA [21] GT43 axial miniature probe coupled to a TT20 electronic micrometer. Although the stepper motor has an internal distance-measurement system a measurement probe, located in the downstream chamber (Fig. 1), is required as the motor axis differs from the target axis. The efficiency of the setup is augmented further through improvements to the ancillary apparatus at JYFL. For example, a thinner than usual (<300 μm) double-sided silicon strip detector (DSSD) will be utilised for proton-tagging experiments to reduce the background from escaping α particles. The recent implementation of digital electronics for the Jurogam-II detectors increases the maximum detector counting rates to 60 kHz (from 10 kHz with analogue electronics) which allows higher beam currents to be used. There is also a plan to use digital electronics with the DSSDs so that proton decays can be discriminated from recoil implantations via pulse shape analysis [22]. All of the detailed improvements have been/will be implemented to enable the measurement of excited-state lifetimes in exotic.

3. DPUNS Commissioning

A DPUNS commissioning experiment was performed at the accelerator laboratory of the University of Jyväskylä measuring the lifetimes of the first excited 2^+ and 4^+ states in ^{134}Nd. The decision for this particular experiment was based on: (i) the lifetimes were already established with small uncertainties, (ii) ^{134}Nd had the largest cross-section in data taken from a previous experiment [23], (iii) the data, for which, showed that clean γ gates could be achieved, (iv) the reaction utilises a Mo target which could be stretched making it an ideal plunger target and (v) the reaction products would have enough energy after the degrader foil to reach the focal plane of RITU. Excited states in ^{134}Nd were populated via the fusion-evaporation reaction ^{98}Mo(^{40}Ar,4n). The K130 cyclotron was used to accelerate the $^{40}Ar^{7+}$ beam to 165 MeV and the beam current averaged ~3 pnA over an approximate running time of 4 days. The reaction target housed in DPUNS was located at the centre of the Jurogam-II γ-ray spectrometer [13] which recorded prompt γ rays following the reactions. For this work Jurogam-II comprised of 39 Compton-suppressed germanium detectors; 15 Eurogam Phase-1 type detectors and 24 Clover detectors and had a total photo-peak efficiency of ~6% at 1332 keV. The Jurogam-II detectors form rings with detector midpoint angles ranging from 158° (ring 1) to 76° (ring 4) defined with respect to the beam direction. All events were time-stamped by a 100 MHz clock through the triggerless Total Data Readout (TDR) acquisition system [24]. One of the primary functions of RITU [14,15] is to reduce the background arising from scattered, unreacted beam nuclei through correlations with recoils detected at the focal plane. Unfortunately, this was not possible in this experiment as the purchased target foil was ~4 times thicker than requested. This meant that the recoils left the target-degrader system with insufficient energy to be recorded at the focal plane of RITU. Data for the lifetime analysis was recorded by the single-crystal Phase-1 type detectors at a backward angle of 158° (ring 1). The remaining detectors were used for gating above the state of interest to remove the contributions from feeding states. Nominal target-to-degrader distances of 5 to 1400 μm were used to track the shifting of prompt ^{134}Nd γ-ray transitions from fully degraded (at the shortest distances), to fully shifted (at the largest distances). The lifetime value was then calculated using the differential decay curve method (DDCM) [25] in γ-ray coincidence mode. The final lifetime is extracted from a weighted mean of values determined at each target-to-degrader distance. It should be noted, that in the DDC method only relative target-to-degrader distances are important and not absolute values.

4. Results

Figure 2 shows γ rays recorded by the ring 1 detectors in coincidence with the shifted component of the $4^+ \rightarrow 2^+$ transition in ^{134}Nd. The coincident yrast transitions can clearly be seen along with transitions that directly and indirectly feed into the 4^+ state. This gating condition was used to produce similar spectra for all of the measurement distances ranging from 5 to 1400 μm. Due to the aforementioned larger-than-expected target thickness the shifted and degraded components of the 2^+ decay were not cleanly separated by the ring 1 detectors.

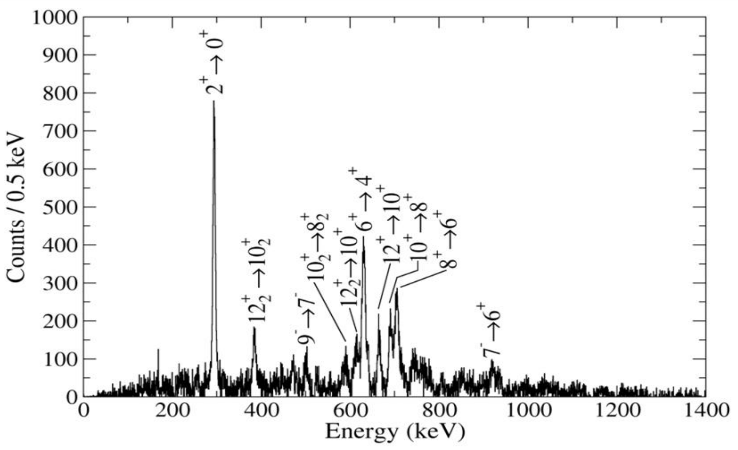

Figure 2: Spectrum showing γ rays in coincidence with the shifted component of the 494 keV $4^+ \rightarrow 2^+$ transition in ^{134}Nd. The data was recorded by the ring 1 detectors for a target-to-degrader distance of 1400 μm at which most of the transitions shown are fully shifted

Figure 3 shows the $2^+ \rightarrow 0^+$ photopeak for six target-to-degrader distances.

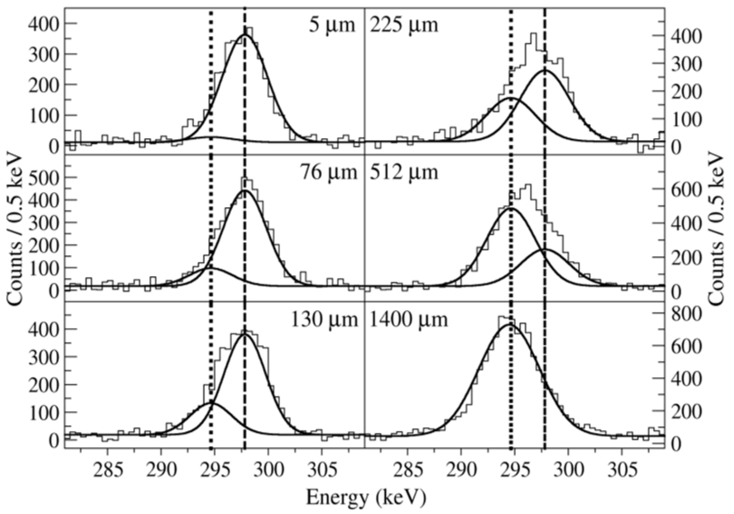

Figure 3: Spectra showing the 292 keV $2^+ \rightarrow 0^+$ transition for six measurement distances along with the centroids of the shifted (dotted) and degraded (dashed) components. The shifted and degraded components, reproduced from the two-Gaussian fit parameters, are also shown. A Doppler correction was applied to the data with *v/c* = 1.62(7)%.

A two component Gaussian fit was used to extract the shifted and degraded intensities using fixed centroids for the fully shifted and fully degraded photopeaks determined from the shortest (5 μm) and longest (1400 μm) distance spectra. The measured intensities were normalised using the sum of the shifted and degraded intensities (I_s+I_d). A simultaneous least squares fit, using a second order polynomial, to the normalised shifted and degraded intensities was performed. Figure 4b shows the normalised shifted intensities for the $2^+\rightarrow0^+$ decay along with the result of the least squares fit (line) which had a χ^2 of 1.12.

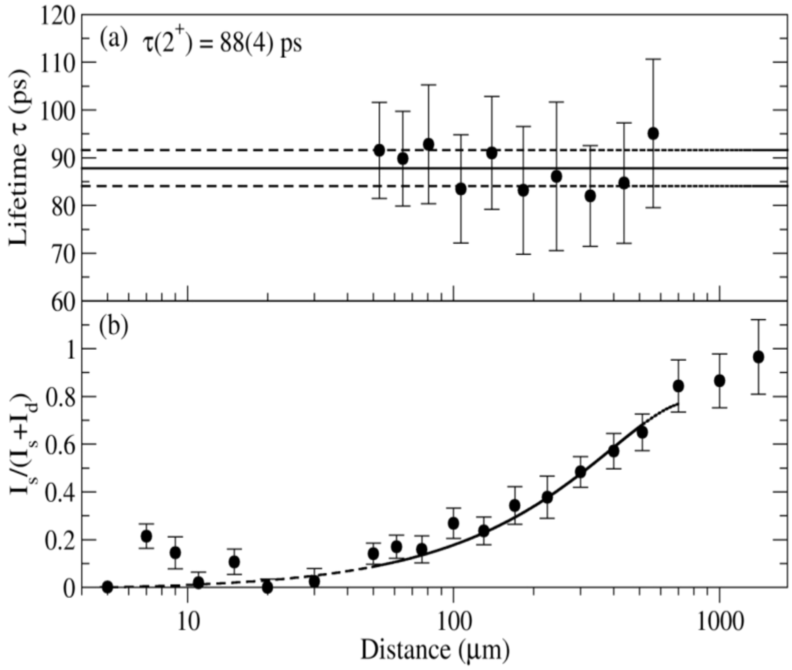

Figure 4: (a) The lifetime of the 2^+ state evaluated, using a recoil velocity of v/c = 1.62(7)%, for each distance covering the region-of-sensitivity along with the weighted mean of 88(4) ps (solid line) and its uncertainty (dashed lines). (b) Normalised shifted intensities for the $2^+\rightarrow0^+$ decay ^{134}Nd along with the results of a least-squares fit (dashed line). The portion of the fit covering the region-of-sensitivity used to determine the state lifetime is denoted by the solid line.

The lifetime of the 2^+ state was then determined using this fit for each distance that resides in the so called “region of sensitivity”; a range of distances where the data is most sensitive to the lifetime of the decaying state. A mean recoil velocity, v/c = 1.62(7)%, was determined from a Doppler shift analysis using data collected by the Jurogam-II detector rings at the largest target-to-degrader distance. The portion of the fit covering the region-of-sensitivity is denoted by the solid line. Figure 4a shows the evaluated lifetimes for the region-of-sensitivity spanning 50 – 512 μm along with the weighted mean of 88(4) ps (solid line) which was adopted as the state lifetime. The dashed lines in Fig. 4a indicate the uncertainty on the mean lifetime. The data used for the lifetime evaluation was taken with DPUNS running in gas mode with a He gas pressure of 0.6 mbar. The measured 2^+ state lifetime is in good agreement with the current literature value of 93(3) ps [26] which is a weighted mean dominated by the measurement of Klemme et al. [27]. Klemme and co-workers measured the lifetime of the 2^+ state in ^{134}Nd using the plunger technique but with a stopper foil after the reaction target. They deduced a lifetime of 94(3) ps using data collected for target-to-stopper distances ranging from 50 to 500 μm. A lifetime for the 4^+ state of 5.1(3) ps was also determined in good agreement with the current literature value of 4.9(1) ps [26]. These results confirm the validity of the new device.

5. Summary

A new plunger device has been developed to measure the lifetimes of excited states in exotic nuclei approaching the proton drip-line. Named the differential plunger for unbound nuclear states (DPUNS) the device was designed to work in conjunction with the gas-filled separator RITU and the vacuum separator MARA at the accelerator laboratory of the University of Jyväskylä, Finland. DPUNS can operate in vacuum or dilute gas environments due to the introduction of low-voltage piezoelectric motion driving components. A commissioning experiment, measuring the lifetimes of the first excited 2^+ and 4^+ states in ^{134}Nd, was performed. The measured values of 88(4) and 5.1(3) ps for the 2^+ and 4^+ state lifetimes, respectively, are in good agreement with the current literature values of 93(3) and 4.9(1) ps [26] and demonstrates that the device can accurately measure excited-state lifetimes.

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