A new plunger device to measure lifetimes of unbound states in tagged exotic nuclei

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Abstract. A new plunger device has been designed and is being built at the University of Manchester to measure lifetimes of unbound states in exotic nuclei approaching the proton drip-line. The device is designed to work in both vacuum and gas environments and will be used in conjunction with the gas filled separator RITU and the vacuum-mode separator MARA at the University of Jyväskylä, Finland. This will enable the accurate measurement of excited state lifetimes identified via isomer and charged-particle tagging. 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 our understanding of drip-line nuclei far from the valley of stability. Structure information on these exotic proton-emitting nuclei is usually extracted through the comparison of the measured half life with various model predictions. 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] therefore experimentally determined values are crucial input parameters to the theoretical models.

To this end, a new plunger device, DPUNS (Differential Plunger for Unbound Nuclear States), is being developed to measure the lifetimes of unbound states in proton-dripline nuclei. With the aid of state-of-the-art theoretical models [2, 5, 6, 7, 8, 9], accurate state lifetime measurements above proton emitting states can be used to determine the extent of deformation in the system and thus the effect this has on the proton emission rate. The basic design of DPUNS (figure 1) is based on the very successful Köln plunger device [10] but with various technical improvements which are outlined in section 2. The basic operation of DPUNS is the same as the Köln and many other plunger devices in that a reaction target along with degrader and stopper foils are used at a number of separation distances to ascertain excited state lifetimes via the Recoil Distance Doppler Shift (RDDS) technique. However, DPUNS has been designed with flexibility in mind and can be used in three-foil differential, two-foil recoil and two-foil stopped modes as well as being able to operate in both gas and vacuum environments.

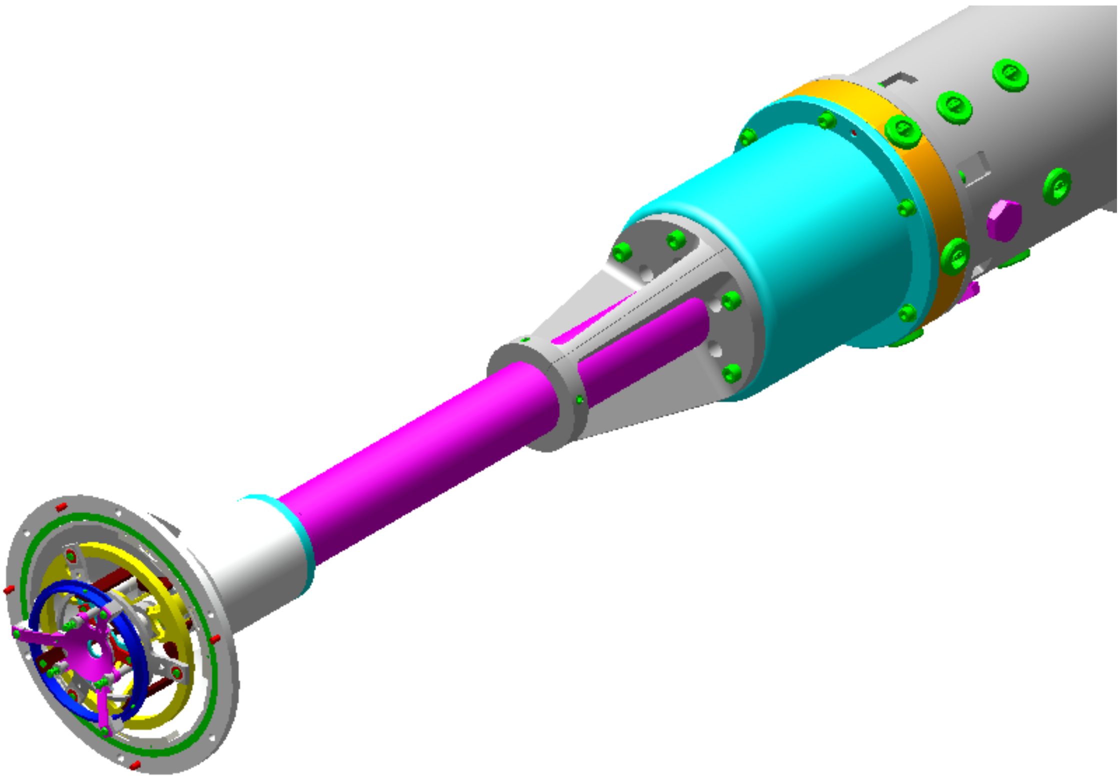

Figure 1. Schematic representation of the new DPUNS device for which the overall design is based on the Köln plunger device [10].

2. Technical Details

DPUNS will be used at the accelerator laboratory of the University of Jyväskylä, Finland (JYFL) in conjunction with the gas-filled separator RITU and with the future vacuum-mode separator MARA [11]. Use of the Köln plunger at JYFL requires it to be isolated from the RITU gas with carbon foils as the device uses 1 kV stepping motors to set the target-degrader distance which were intended for use solely in a vacuum environment. DPUNS incorporates a low voltage, 45 V, stepping motor along with a low voltage, 150 V, piezoelectric actuator (see figure 2) which are manufactured by Physik Instrumente (PI) GmbH [12]. These low-voltage motors allow DPUNS to be used in the helium gas environment of RITU thus alleviating the need for carbon isolating foils. DPUNS also incorporates an improved inner plunger design and it is envisaged that a new in-situ optical telescope will be installed to improve the accuracy with which the target and degrader foils are aligned. It is hoped that these modifications will increase the measurement efficiency over the Köln plunger. This efficiency increase will be 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 β and escaping α particles. The use of digital electronics will significantly increase (up to ~ 60 kHz) the maximum counting rate of the JUROGAM-II detectors allowing larger beam currents to used. This will be an improvement beneficial for studies where the proton decay half lives are on the order of a ms or less as this will result in a much improved tagging efficiency compared to what is achievable with conventional analogue electronics (maximum 10 kHz counting rate). Also one side of the DSSD will use digital electronics so that proton decays can be discriminated from recoil implantations via pulse shape analysis. All of the detailed improvements coupled with the high efficiency of

Figure 2. The new low-voltage stepper motor and piezoelectric actuator, along with supports, being used in the DPUNS device.

RITU are intended to enable the measurement of the lifetimes of unbound states in exotic nuclei produced with sub-microbarn cross-sections.

2.1. Testing

The plunger and it's individual components have been tested at various points of the assembly to ensure that the device as a whole will perform as desired. The outer shell of DPUNS was assembled and a vacuum test yielded a vacuum of 1.7×10^{-8} bar which is well below that required for attachment to the JYFL beam line. The stepper motor and micrometer were tested for linearity and a fit to the resulting data yielded a linear regression coefficient $R^2 = 0.9999$. The inner mechanism, which allows the distance between the target and degrader foils to be set, was tested and showed that for a transit of approximately 2 cm a divergence of less than 0.2 mm was recorded over a projected measurement distance of 6 m. It is envisaged that once fully assembled DPUNS will undergo in-beam feedback tests at the University of Köln before being shipped to JYFL for commissioning.

3. Experimental Programme

The first DPUNS (commissioning) experiment will investigate the low-energy structure of ^{98}Ru via the measurement of excited state lifetimes. The basic low-energy structure of the Ru isotopes and in particular ^{98}Ru is still not fully understood. Figure 3a shows the low-energy level scheme for ^{98}Ru which at first glance resembles a structure that one may observe for a harmonic vibrator. The transition widths in figure 3a represent the reduced quadrupole transition probabilities which disagree with that expected for a harmonic vibrator. Indeed, lifetime [13], excitation energy [13], transition probability [14] and g-factor measurements [15] have all raised conflicting ideas as to the true nature of the low-lying excitations. In particular, anomalous B(E2:$4_1^+ \to 2_1^+$) / B(E2:$2_1^+ \to 0_1^+$) < 1 and B(E2:$6_1^+ \to 4_1^+$) / B(E2:$2_1^+ \to 0_1^+$) < 1 ratios [16] have been observed in contradiction to the predictions of collective models. Although the B(E2:$4_1^+ \to 2_1^+$) / B(E2:$2_1^+ \to 0_1^+$) < 1 anomaly has been addressed to some extent by Williams et al. [17], large uncertainties (the currently adopted 4_1^+ state lifetime has a 20% uncertainty) inhibit clarification of the type and degree of collectivity in ^{98}Ru. A choice of reactions are available to populate the excited states of interest, all with large ^{98}Ru production cross-sections. The reaction kinematics will yield a large energy separation between the shifted and degraded components for decays recorded by the Jurogam-II detectors at angles of 157° (ring 1) and 133° (ring 2) (see Ref [18] for more details on the Differential Decay Curve Method (DDCM) for lifetime determination).

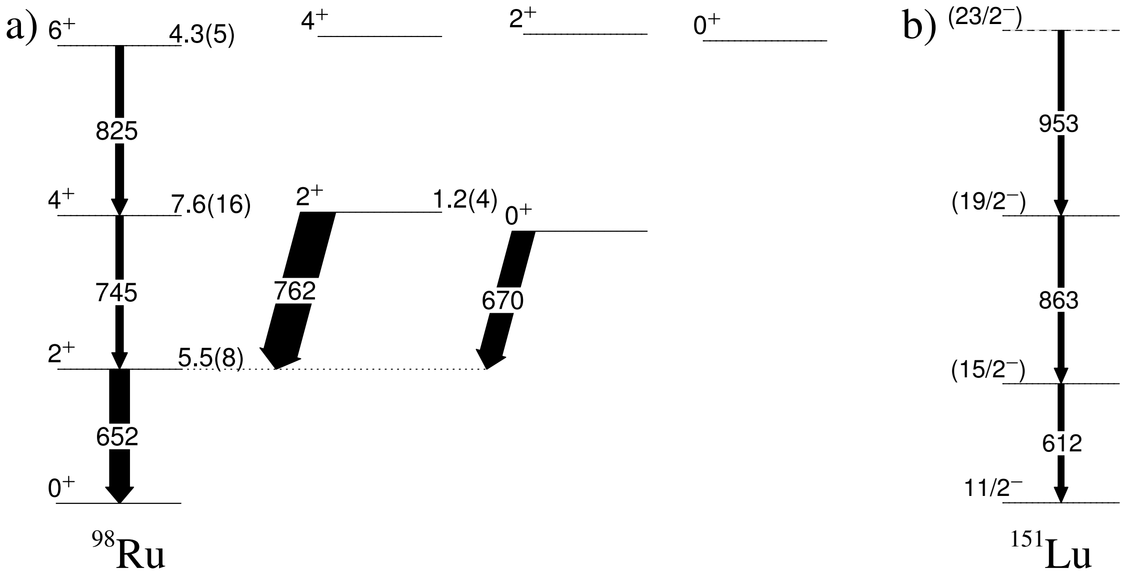

Figure 3. a) The low-energy structure of ^{98}Ru from [13] with transition widths representing the reduced transition probabilities. b) Tentative level scheme for ^{151}Lu deduced from [19] highlighting the excited states to be measured by DPUNS.

This large separation along with the large cross-section will enable the performance of DPUNS to be easily evaluated.

The second experiment will measure, for the first time, the lifetimes of the proton-unbound states in ^{151}Lu [19] (see figure 3b). There is a long standing issue as to whether the proton emission from the ground state in ^{151}Lu [20] arises from a spherical [21] or deformed [3] nuclear system. The measurement of excited-state lifetimes in ^{151}Lu will shed light on the degree of deformation in the system and therefore aid in the resolution of this debate. The work of Liu et al., [19] showed evidence for proton emission from an isomeric state with a half life of 16(1) μs but a level scheme based on this was not established. It is therefore hoped that this will also be addressed in the measurement. Furthermore, these measurements will allow an investigation into the possible role of these unbound states coupling to the continuum. Excited states in ^{151}Lu will be populated in the reaction ^{96}Ru(^{58}Ni,$p2n$)^{151}Lu with an estimated cross-section of $\sim 70\mu$b. This experiment will therefore test DPUNS in a low cross-section, proton-tagging environment for which the device is primarily designed.

Other studies include the lifetime measurement of excited states in the neutron deficient nuclei ^{111,113}I. This experiment would build upon previous work performed in this region [22] (and references therein) which revealed evidence for an increase in collectivity in the low-lying $\pi h_{11/2}$ band compared to the heavier isotopes and a reduced collectivity in the $11/2^-$ ground-state state when compared to theoretical calculations. Therefore measurement of the lifetimes of states above and below the $\pi h_{11/2}$ band-head in neighbouring ^{111}I and ^{113}I would allow a systematic comparison of the competing trends in collectivity for increasing valence neutron number.

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References

[1] Hofmann S 1966 *Nuclear Decay Models*, ed D N Poenaru (Bristol: IOP) p 143-203
[2] Maglione E, Ferreira L S and Liotta R J 1998 *Phys. Rev. Lett.* **81** 538
[3] Ferreira L S and Maglione E 2000 *Phys. Rev. C* **61** 021304(R)
[4] Möller P *et al.* 2006 *Phys. Rev. Lett.* **97** 162502
[5] Arumugam P, Ferreira L S and Maglione E 2008 *Phys. Rev. C* **78** 041305(R)
[6] Maglione E, Ferreira L S and Liotta R J 1999 *Phys. Rev. C* **59** 589(R)
[7] Ferreira L S and Maglione E 2001 *Phys. Rev. Lett.* **86** 1721
[8] Ferreira L S and Maglione E 2005 *Nucl. Phys. A* **752** 223
[9] Delion D S, Liotta R J and Wyss R 2006 *Physics Reports* **424** 113
[10] Cleemann L, Eberth J, Neumann W, Wiehl N and Zobel V 1978 *Nucl. Instr. & Meth.* **156** 477
[11] Sarén J *et al.* 2008 *Nucl. Instr. & Meth. B* **266** 4196
[12] *Physik Instrumente (PI) GmbH & Co.* `http://www.pi.ws`
[13] Singh B and Hu Z 2003 *Nucl. Data Sheets* **98** 335
[14] Landsberger S *et al.* 1980 *Phys. Rev. C* **21** 588
[15] Taylor M J *et al.* 2011 *Phys. Rev. C* **83** 044315
[16] Cakirli R B *et al.* 2004 *Phys. Rev. C* **70** 047302
[17] Williams E *et al.* 2006 *Phys. Rev. C* **74** 024302
[18] Dewald A, Harissopulos S and von Brentano P 1989 *Z. Phys. A* **334** 163
[19] Liu Z 2007 *Proceedings of PROCON Conference, A.I.P.* **961** 34
[20] Hofmann S *et al.* 1982 *Z. Phys A* **305** 111
[21] Bingham C *et al.* 1999 *Phys. Rev. C* **59** R2984
[22] Procter M G *et al.* 2011 *Phys. Lett. B* **704** 118