Lifetime measurements of unbound nuclear states

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Abstract. A Differential Plunger device for measuring the lifetimes of Unbound Nuclear States (DPUNS) is currently being built at the University of Manchester. The plunger has been designed to be able to work with the proton-, alpha-, beta- and isomer-tagging methods using the JUROGAM II – RITU – GREAT setup at the University of Jyväskylä, Finland. Valuable nuclear-structure information can be investigated from the measurement of lifetimes in proton- and alpha-unbound nuclei. To date, nuclear structure information from proton emission has been obtained from a comparison of the experimentally measured half-life with that predicted from various tunnelling calculations. A crucial parameter required to perform these calculations is the deformation of the parent nucleus involved in the decay, which in all cases to date, has only ever been estimated or calculated from theory. DPUNS aims to address this logical weakness through the measurement of the lifetimes of excited states in these unbound nuclei. The first measurement of a lifetime in a proton-unbound nucleus was recently obtained for ^{109}I. The results from this measurement were discussed along with the future physics programme that can be performed with DPUNS.

1. Motivation

The lifetimes of states in exotic nuclei are neither well established nor understood. This results from the subtle interplay between *microscopic* single-particle and *macroscopic* collective effects, which are difficult to model at such extremes of existence. Near the proton drip line, the half-lives for proton emission heavily depend upon the shape and coulomb barrier of the parent nucleus involved in the decay. Theoretical models aimed at reproducing the observed decay half-lives for proton emitters require the deformation of the nucleus as an input parameter. However, it has not been until recently that lifetime measurements of excited states in proton-unbound nuclei have allowed the deformation of these proton emitters to be experimentally determined [1].

The Differential Plunger for Unbound Nuclear States (DPUNS) aims to address this key issue by measuring the lifetimes of excited states within a range of proton-unbound nuclei. A recent experiment with the Köln plunger [2] allowed the first measurement of a lifetime in the proton-unbound nucleus ^{109}I [1]. The design of DPUNS is largely based upon that of the Köln plunger, but with additional improvements [3], optimised for the Jyväskylä setup, that will allow for the measurement of nuclei with cross sections down to ~ 1 μb.

2. Methodology

In order to study the lifetimes of excited states in nuclei beyond the drip line a high experimental selectivity is required. Unbound nuclear states are produced with cross sections of the order of $0.1 - 40$ μb out of a total fusion cross section of ~ 1 mb. One method of isolating the nuclei of interest uses the recoil-decay tagging (RDT) technique, which can be performed at the University of Jyväskylä in conjunction with the Total Data Readout (TDR) acquisition system. In this method, nuclei are first associated with the products of their decay and then, with the knowledge of both the energy and half-life of this decay, correlated with prompt transitions that feed the decaying state. More recently, these selection techniques have been complemented by the addition of the Köln plunger device. The plunger facilitates the collection of Recoil distance Doppler-shifted (RDDS) data which allows the extraction of the lifetimes of weakly populated levels above proton-unbound states, see Fig. 1.
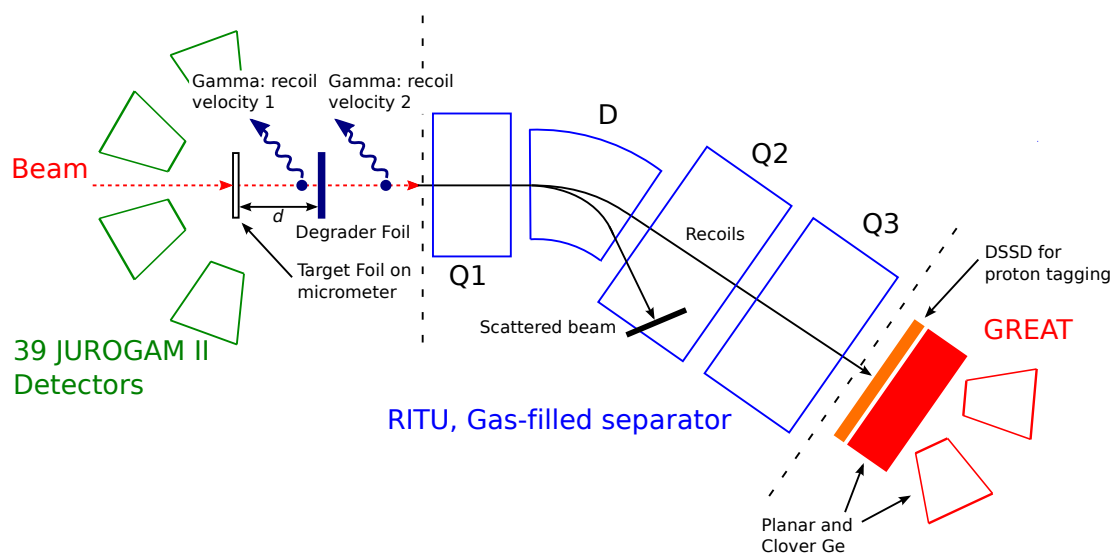

Figure 1. Schematic diagram of the experimental setup used to determine lifetimes of unbound nuclear states at the University of Jyväskylä, Finland. Recoiling nuclei are associated with their proton decay at the focal plane of RITU and correlated with previously detected prompt transitions at the target position. The plunger, located at the centre of the JUROGAM II array, houses both the target and degrader foils. The relative intensities of both the fully Doppler-shifted and degraded components of the full photo-peak are measured as a function of target-to-degrader distance in order to extract the lifetime value [4, 5].

The use of the new plunger device, DPUNS will provide several improvements compared with the Köln plunger at the University of Jyväskylä. The most significant improvement will be the ability to use DPUNS within the helium gas of RITU by using low voltage stepper motors. This precludes the need to use carbon foils to isolate the gas from the high-voltage motors used with the Köln plunger [3]. The removal of the carbon foils will reduce the amount of scattered beam around the target area, allowing for the use of higher beam intensities. The effects of this are immediately evident in the derivation of the final lifetime measurements, where the main contribution towards the uncertainties of each lifetime arise from the statistical errors in the peak intensity measurements.

3. ^{109}I results

Recent measurements by Procter *et al.* have shown the state-of-the-art results which can currently be achieved using the Köln plunger with proton tagging in ^{109}I at the University of Jyväskylä [1]. Excited states in ^{109}I were populated using the ^{58}Ni(^{54}Fe,$p2n$) reaction at a beam energy of 206 MeV. The cross-section for ^{109}I in this reaction was measured to be $\sim$40 μb. With an average beam current of 2.5 pnA, data were collected at eight target-to-degrader distances over an approximate total running time of 245 hours. Prompt transitions were observed in Ring 2 of the PRE-JUROGAM II spectrometer [6], comprising 10 single-crystal Ge detectors located at a backward angle of 134° to the beam line. The recoiling reaction products passed through a 1 mg/cm^2 Mg degrader foil housed in the Köln plunger device [2] downstream from the target. The degrader foil reduced the full velocity of the recoils from v/c=0.036(3) to 0.027(4). The fusion reaction products were separated from beam-like nuclei by the recoil ion transport unit (RITU) [7, 8] and implanted into a pair of double-sided silicon strip (DSSD) detectors in the GREAT focal plane spectrometer [9, 10]. The subsequent proton decays were detected and correlated with ^{109}I recoils. Employing a proton-decay search time of 300 μs, delayed protons were associated with prompt γ-ray transitions at the focal plane. Figure 2(a) shows spectra obtained for four target-to-degrader distances for the 594-keV transition in ^{109}I. The lifetime of the $(11/2^+)$ state was determined using the Differential decay curve method (DDCM) [4, 5] (see Ref. [1] for more details). Figure 2(b) shows the decay curve for the 594-keV transition in ^{109}I. The final lifetime value of 15.4(19) ps was determined from a weighted average of values obtained within the so-called "region of interest" [1]. The experimentally
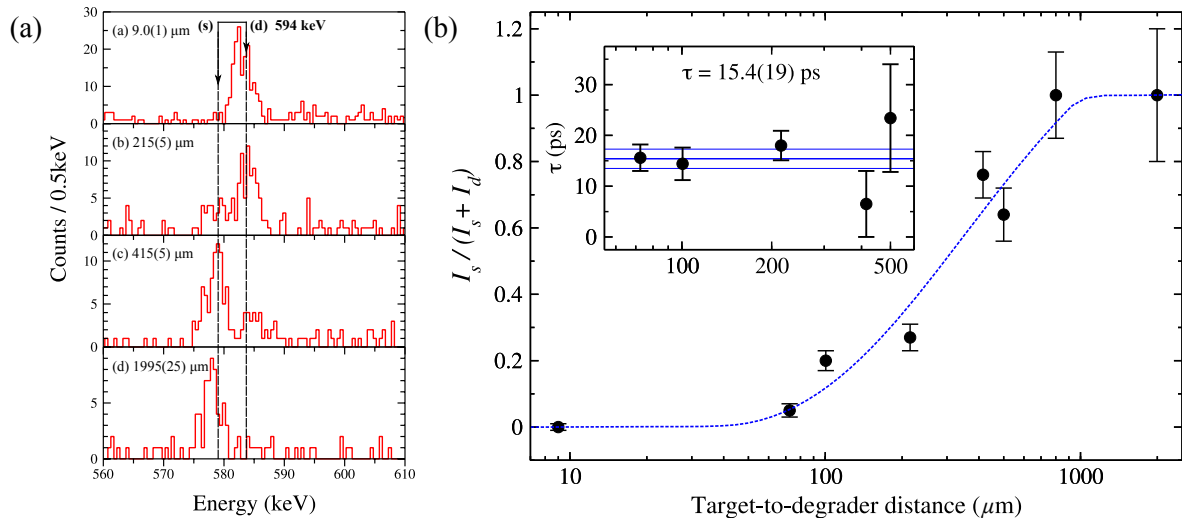
Figure 2. (a) Example of recoil-proton-tagged spectra for four target-to-degrader distances for the 594-transition in ^{109}I. The splitting of the fully Doppler-shifted (s) and degraded (d) components is highlighted. No Doppler correction has been applied to the data. (b) Normalised shifted intensities for the $(11/2^+) \rightarrow (7/2^+)$ transition in ^{109}I. The dashed curve is drawn to guide the eye. The inset shows the individual lifetimes from five target-to-degrader distances used in the weighted average calculation of the final lifetime [1].

deduced $B(E2)$ value was compared with theoretical shell-model calculations using the realistic CD-Bonn nucleon-nucleon potential, shown in Fig. 3. The theoretical calculations were observed to largely overestimate the experimental reduced transition probability. A comparison with the experimental measurements and theoretical predictions of the lower mass nuclei ^{109}Te and ^{108}Te,

shown in Fig. 3, suggested that the discrepancy observed in ^{109}I was due to the inability of the shell model calculations to correctly account for the unbound nature of the last valence proton.
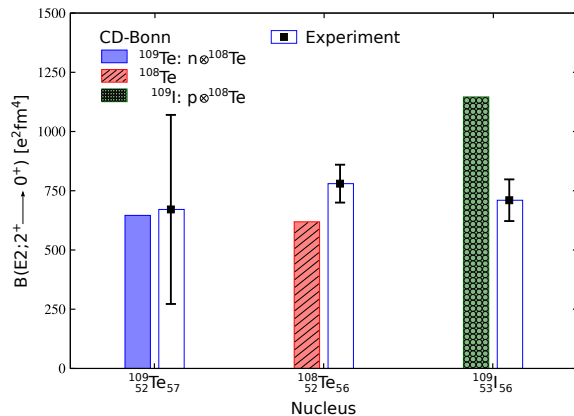
Figure 3. Comparison of theoretical $B(E2)$ values, calculated with the CD-Bonn interaction, with experimentally measured values for the ground-state transitions in ^{109}Te and ^{108}Te, and the assumed ground-state transition in ^{109}I. The theoretical $B(E2)$ values were calculated with proton and neutron effective charges of e_p=1.5 e and e_n=0.5 e, respectively. Figure taken from Ref. [1].

This measurement highlights the need for further experimental lifetime measurements of excited states in proton-unbound nuclei which DPUNS will address.

4. Experimental programme

The first lifetime measurements in a proton-unbound nucleus using DPUNS will focus on the nucleus ^{151}Lu [11]. The measurement of lifetimes in this nucleus will help to resolve the current issue as to whether the proton decay of the ground-state proceeds via a deformed [12] or spherical [13] nuclear shape. In conjunction with addressing this particular issue, the results will also allow an investigation into the possible role of coupling to the nuclear continuum of the unbound system. Due to the small separation energies at the proton-drip line, the effects of coupling to the continuum are expected to modify the energies of the excited states within the nucleus. The experiment will utilise a combination of the RDDS and RDT techniques at the University of Jyväskylä, in a similar way to the ^{109}I measurement. The experiment will use the established ^{96}Ru(^{58}Ni,$p2n$) reaction at a beam energy of 290 MeV in order to populate ^{151}Lu. The predicted cross section for this reaction is ∼70 μb. The experiment is to be performed over a period of 14 days, collecting data at eight separate target-to-degrader distances.

A second experiment aims to build upon the recent lifetime measurement in ^{109}I through the measurement of the lifetimes of excited states in ^{111}I and ^{113}I. Although this experiment will not utilise the proton-tagging technique outlined above, the results will be compared with those from the proton-unbound nucleus ^{109}I in order to better understand the discrepancies observed in that work between the experimental measurement and theoretical calculations.

Acknowledgments

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