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Proton emission from an oblate nucleus ^{151}Lu

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ABSTRACT

Excited states in the proton-unbound nucleus ^{151}Lu have been established using γ-ray coincidence techniques. The lifetime of the first excited state above the proton-emitting ground state has been measured using the recoil-distance Doppler-shift method combined with recoil-decay tagging. The experimental level scheme and extracted lifetime have been compared with state-of-the-art theoretical calculations based upon a non-adiabatic deformed Woods–Saxon potential. This comparison suggests that the proton-emitting ground state in ^{151}Lu is mildly oblate with a deformation $\beta = -0.11^{+0.02}_{-0.05}$ and represents the best evidence to date for proton emission from an oblate nucleus.

Proton emission from nuclei was first observed in ^{151}Lu in 1982 [1] where the half-life for proton emission from the ground state was established as 85(10) ms. In order to interpret this proton emission, WKB theoretical tunnelling calculations were performed based upon a spherical nuclear potential [2]. In the tunnelling model, proton emission rates are dependent upon the angular momentum and energy of the proton [3]. The use of a spherical potential was at that time justified by the close proximity of ^{151}Lu to the $N = 82$ shell closure. These spherical calculations were indeed able to provide a satisfactory agreement with the experimental half-life based upon a proton with angular momentum $\ell = 5$, originating from the spherical $h_{11/2}$ single-particle state [2]. Several years later in 1999, proton emission was also observed from a 16 µs low-lying isomeric state in ^{151}Lu [4]. Using calculations based upon a spherical potential, proton decay from the isomeric state was described as an $\ell = 2$ decay from a spherical $d_{3/2}$ single-particle state [4]. However, in that work, it was acknowledged that larger than expected spectroscopic factors were required in order to obtain agreement with the experimental emission rates [4]. The discrepancy of the spherical WKB tunnelling model prediction was explained as either due to possible shifts in the relative energies of the $d_{3/2}$ and $h_{11/2}$ states, or from the effects of core excitations from the coupling of the single-particle states to the 2^+ state of ^{150}Yb [4].

In separate developments, calculations based on the microscopic–macroscopic model of Möller and Nix, suggested that ^{151}Lu [5,6] may have a slightly oblate nuclear deformation, $\beta = -0.156$. The influence of deformation on the proton decay rate was first discussed for ^{151}Lu in Ref. [7]. In that work, a deformed Woods–Saxon plus spin–orbit potential was used and the wave function of the parent nucleus was taken from the particle-rotor model using the adiabatic strong-coupling limit [7]. These calculations were,

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for the first time, able to consistently describe the experimental half-lives and spectroscopic factors for proton emission from both the ground state and the isomeric state in ^{151}Lu with an oblate deformation, $-0.18 < \beta < -0.14$ [7]. Although these adiabatic calculations gave the first theoretical indication that ^{151}Lu may have a small deformation, they should ideally only be used where the deformation is large and the rotational core has an infinite moment of inertia which may not be strictly true for ^{151}Lu.

The motivation for the present work described in this Letter, was the need to provide both a better experimental and theoretical understanding of proton emission from mildly deformed nuclei such as ^{151}Lu. The determination of nuclear deformation in proton-emitting nuclei [8,9] is in itself a *tour-de-force* of experimental physics and is reliant on a firm knowledge of the low-lying level structure. It is inevitably difficult to examine the structure of very proton-rich nuclei due to the small production cross section. Prior to the present work, only the first two excited states in ^{151}Lu had been tentatively placed [10], based upon a systematic comparison with the lighter-mass $N = 80$ isotones. In the present work, an RDT experiment has been performed to examine the prompt level structure of ^{151}Lu above the proton-emitting state. In addition, the lifetime of the first excited state was measured by combining the recoil-decay tagging RDT technique with the Recoil-Distance Doppler-Shift (RDDS) method [11]. In order to explain these experimental results, a new theoretical code has been developed. The full details of this model, which can account for the non-adiabatic influence of the non-rotational core on the odd proton, will be published later [12]. However, the significant contribution to this work is that, along with calculating the deformation of the proton-emitting states, this code additionally calculates the lifetime of the first excited state, which decays by an electromagnetic γ-ray transition, as a function of deformation. The unique combination of the deformation extracted from both the proton- and electromagnetic-transition rates, along with the newly established excited state level scheme, reveals that ^{151}Lu is best described with a small oblate deformation, $\beta = -0.11^{+0.02}_{-0.05}$. This result represents the best evidence to date for proton emission from an oblate nucleus.

The experiment was performed at the Accelerator Laboratory of the University of Jyvaskyla, Finland. A beam of $^{58}Ni^{8+}$ ions at 290 MeV was accelerated onto a 550 μg cm^{-2} ^{96}Ru target, mounted on an upstream-facing 2 mg cm^{-2} Au foil. Prompt γ-ray transitions were measured in the JUROGAM-II spectrometer positioned around the target [13]. Recoiling fusion-evaporation residues were separated in-flight from scattered beam by RITU, the gas-filled separator [14]. RITU was operational under a helium gas pressure of 0.6 mbar and was partitioned from the vacuum of the beam line with a roots differential pumping system. Recoils were transported to the GREAT focal-plane spectrometer where they were implanted into a pair of double-sided silicon strip detectors (DSSD) [15]. The high granularity of the DSSD allowed recoiling fusion-evaporation products to be identified with ^{151}Lu through the use of Recoil-Decay Tagging (RDT). In this work, the RDT technique was based upon the requirement that a delayed proton event was registered in the same pixel as the proceeding recoil event with an energy of ∼1.23 MeV and within a search time of 300 ms ($\sim 3 \times T_{1/2}$). The Differential Plunger for Unbound Nuclear States (DPUNS) [16–18] was located at the target position to facilitate the collection of RDDS data. The plunger housed both the target foil as well as a 1 mg cm^{-2} Mg degrader foil. DPUNS incorporated a low voltage, 45 V stepping motor along with a low voltage, 150 V piezoelectric attenuator allowing it to operate within the helium gas environment of the target chamber, alleviating the use of carbon isolating foils. The degrader foil acted to reduce the full velocity of the recoiling reaction products from $v/c = 0.035(2)$ to 0.024(2). In typical plunger experiments, both the target and de-

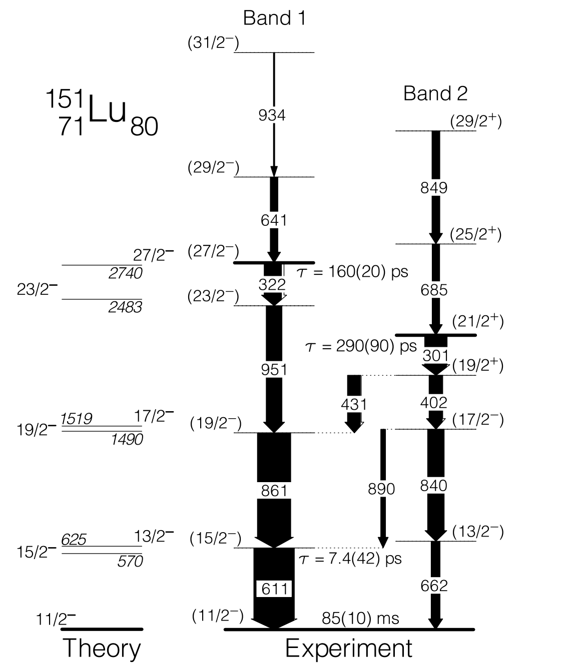

Fig. 1. (Right) Excited levels in ^{151}Lu assigned in this work. The widths of the arrows correspond to the intensities of each transition, with the white component of each arrow indicating the calculated internal conversion component. The lifetimes of the states measured in this work are also shown. (Left) Theoretical level scheme calculated at an oblate deformation of $\beta = -0.03$, where the theoretical and experimental energy separations of the $(17/2^-)$ and $(19/2^-)$ states are equal to 30 keV (see later).

grader foils are stretched in order to allow the collection of RDDS data at the smallest of target-to-degrader separations. The only rhenium target available for this experiment had already been mounted on a small target frame and used in a previous experiment. As a consequence, there was no possibility to remount the target on a plunger frame and therefore, this target could not be stretched in the usual manner for plunger experiments. As such, it was estimated that the minimum target-to-degrader separation achievable (optical contact) in this setup was ⩾200 μm. It should be noted that, within the analysis of the lifetime data (see later), it is only the relative and not the absolute target-to-degrader distances that are required.

For the spectroscopic analysis of ^{151}Lu, coincident Doppler-shifted γ-rays were collected in the combined rings 3 and 4 of the JUROGAM-II spectrometer, located at 104.5° and 75.5° with respect to the beam direction, respectively. Lifetime data were collected in ring 2 at a backward angle of 134° to the beam line for 8 different target-to-degrader distances of optical contact plus 2.2 μm to 10 mm. Data were time stamped by a 100 MHz clock from the Total Data Readout (TDR) acquisition system [19] and collected on-line using the GRAIN software package [20]. The data were sorted into one-dimensional histograms and two-dimensional symmetric matrices to be analyzed with the RADWARE software suite [21].

Fig. 1 shows the level scheme for ^{151}Lu deduced from data collected in the present work. γ-ray coincidences and energy summations have been firmly assigned for many of the low-spin states for the first time. Table 1 summarizes the energies and intensities of the γ-ray transitions associated with ^{151}Lu decays in this work.

Fig. 2 shows a set of prompt spectra obtained from setting gates in the recoil-proton-tagged prompt–prompt γ–γ matrix from data collected in the combined rings 3 and 4 of the JUROGAM-II spectrometer located at 75.5° and 104.5° to the beam line, respec-

Table 1
Energies, relative intensities, corrected for efficiency and assumed transition assignments for the γ-rays correlated with ^{151}Lu proton decays in this work. The errors on the energy measurements are derived purely from Gaussian fits to the photo-peaks measure in detectors at 75.5° and 104.5° to the beam line.

E_γ (keV)[a]	Transition assignment	Intensity (%)
301.4(2)	$(21/2^+ \rightarrow 19/2^+)$	55(2)
321.8(2)	$(27/2^- \rightarrow 23/2^-)$	43(2)
402.1(2)	$(19/2^+ \rightarrow 17/2^-)$	33(2)
431.2(4)	$(19/2^+ \rightarrow 19/2^-)$	32(2)
611.0(1)	$(15/2^- \rightarrow 11/2^-)$	100(4)
641.4(1)	$(29/2^- \rightarrow 27/2^-)$	19(1)
662.3(1)	$(13/2^- \rightarrow 11/2^-)$	22(2)
684.8(2)	$(25/2^+ \rightarrow 21/2^+)$	19(2)
840.0(1)	$(17/2^- \rightarrow 13/2^-)$	41(2)
848.7(2)	$(29/2^+ \rightarrow 25/2^+)$	19(2)
860.6(1)	$(19/2^- \rightarrow 15/2^-)$	83(3)
890.4(2)	$(17/2^- \rightarrow 15/2^-)$	12(1)
934.1(3)	$(31/2^- \rightarrow 29/2^-)$	3(1)
951.1(1)	$(23/2^- \rightarrow 19/2^-)$	39(2)

[a] An additional contribution to the uncertainties on the measured energies of 0.2 keV for $E_\gamma < 500$ keV and 0.3 keV for $E_\gamma > 500$ keV is added from the average Doppler-shift correction applied to the combined data from detector rings 3 and 4.

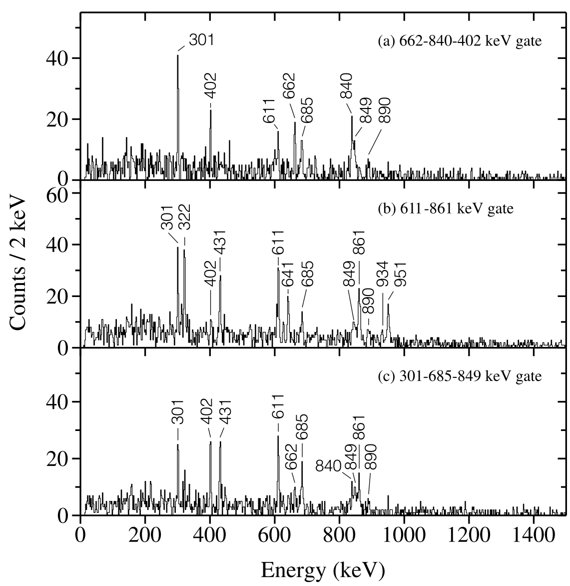

Fig. 2. Prompt γ–γ spectra from a recoil-proton-tagged matrix of ^{151}Lu recorded with the clover germanium detectors in the JUROGAM-II array at 104.5° and 75.5°. Figure (a) shows a summation of gates on the 662-, 840- and 402-keV transitions, (b) a summation of gates on the 611- and 861-keV transitions and (c) a summation of gates on the 301-, 685- and 839-keV transitions.

tively. A Doppler-shift correction of $v/c = 0.03$ has been applied to the data, in order to best align the photo-peaks observed in rings 3 and 4, which suffer opposing Doppler shifts due to their distribution either side of 90° to the beam line. Fig. 2(a) shows the spectrum resulting from a summation of gates on the low-energy (662-, 840- and 402-keV) γ-ray transitions in Band 2. The lack of observation of the 861-, 951-, 322-, 641- and 934-keV transitions confirms the placement of these gated γ-rays as parallel to Band 1. Fig. 2(b) shows a summation of gates on the 611- and 861-keV transitions in Band 1. The spectrum confirms the placement of γ-rays in Fig. 1 through the non-observation of the parallel 662- and 840-keV γ-rays and shows the presence of a 431-keV transition which links Band 1 to the higher-lying states in Band 2. The presence of the 951-, 322-, 641- and 934-keV transitions (which were absent in Fig. 2(a)) confirms their placement at higher spin in Band 1 and shows that there are no higher-lying linking transitions between Bands 1 and 2. Finally, Fig. 2(c) shows a summation of gates on the 301-, 685- and 849-keV transitions in Band 2. This spectrum further corroborates the placement of the 431-keV transition as linking high-spin states in Band 2 with lower-spin states in Band 1 through the presence of the 861- and 611-keV transitions. None of the transitions placed above the $(19/2^-)$ state in Band 1 are present, confirming that no further transitions exist between these bands. The ordering of the 840- and 662-keV γ-ray transitions was determined from the non-observation of a 229-keV transition that would be expected to link the $(13/2^-)$ and $(15/2^-)$ states if the order was reversed compared to that shown in Fig. 1. The presence of a ≈50 keV converted transition between the $15/2^-$ and $13/2^-$ states is also ruled out by the lack of presence of an 840-keV transition in Fig. 2(b).

Lifetime data were analyzed with the Differential Decay Curve Method (DDCM) [22,23] using γ-ray singles data collected in ring 2 only, at a backward angle of 134° to the beam line. In this method the lifetime of the first excited state was determined at each target-to-degrader distance, d from a χ^2 minimization fit of three third-order polynomials to the normalized fully Doppler-shifted component, I_s of the transition depopulating the state. The contribution towards the observed lifetime from higher-lying states was accounted for by the inclusion of the measured intensities of both the 861- and 890-keV feeding transitions. Within the DDCM the lifetime of the state under investigation is determined at each target-to-degrader distance. However, it is only where the difference between the feeding and depopulating intensities is maximized, the so-called 'region of sensitivity', that the lifetime values are derived with the smallest systematic and statistical uncertainties [22,23]. As a result, a weighted average of the individual lifetime measurements that lie within the region of sensitivity are used in the final result. The DDCM requires Doppler-shifted data to be collected at target-to-degrader separations that best exhibit the changing intensity of both components (fully Doppler-shifted and degraded) of the photo-peak. These distances are dependent upon both the lifetime of the state being measured and the recoil velocity of the reaction products. The inability to collect data at small, <200 μm, distances in this work originally suggested that it might not have been possible to measure states with lifetimes <50 ps. However, the presence of longer-lived states at higher excitation energy allowed the measurement of the short-lived transition to the ground state using larger than anticipated target-to-degrader separations. Fig. 3 shows representative RDDS spectra for the 611-keV γ-ray depopulating the $(15/2^-)$ state in ^{151}Lu. The presence of longer-lived feeding transitions is evident in the data because even at a target-to-degrader distance of 200 μm a large fraction of the full photo-peak remains in the degraded component. Fig. 4(c) shows the normalized shifted intensities of the 611-keV photo-peak. The individual lifetime measurements of the $(15/2^-)$ state are shown in Fig. 4(d), along with the weighted-average value, 7.4(42) ps. In addition, the effective lifetimes of the longer-lived higher-lying $(27/2^-)$ and $(21/2^+)$ states were also measured from a simple exponential fit plus background to the normalized decay curve and were found to be 160(20) and 290(90) ps, respectively, see Fig. 4(a) and (b). The lifetime measurements for the $(27/2^-)$ and $(21/2^+)$ states were only possible because of their long-lived nature, compared with the transitions feeding them which were fully Doppler-shifted at the shortest target-to-degrader distances.

In order to determine the magnitude and sign of the deformation of the proton-emitting state in ^{151}Lu from the experimental results, new non-adiabatic theoretical calculations have been performed in this work [12]. In order to account for the mild deformation and the non-adiabatic effects resulting from the influence of the core on the odd proton, the Hamiltonian presented

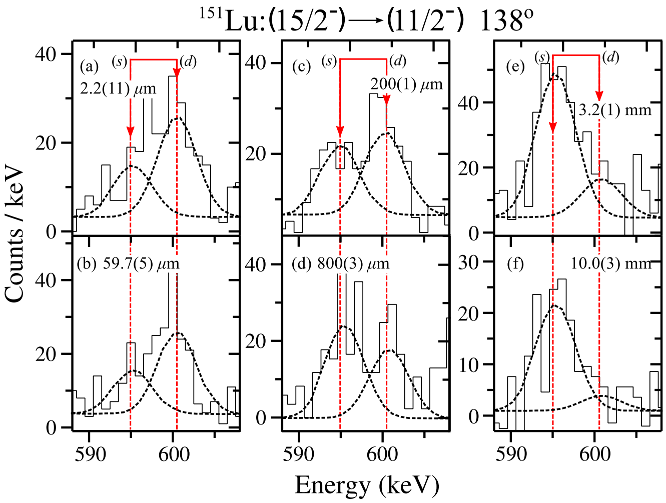

Fig. 3. (Color online.) Recoil-proton-tagged prompt spectra for the 611-keV transition depopulating the $(15/2^-)$ state in ^{151}Lu collected at six target-to-degrader distances (a)–(f) in ring 2 at 134°. The distances are offset by the optical-contact distance of ≈200 μm (see text for details). The shifted and degraded components of the photo-peaks are highlighted for each target-to-degrader distance. No Doppler correction has been applied to these spectra.

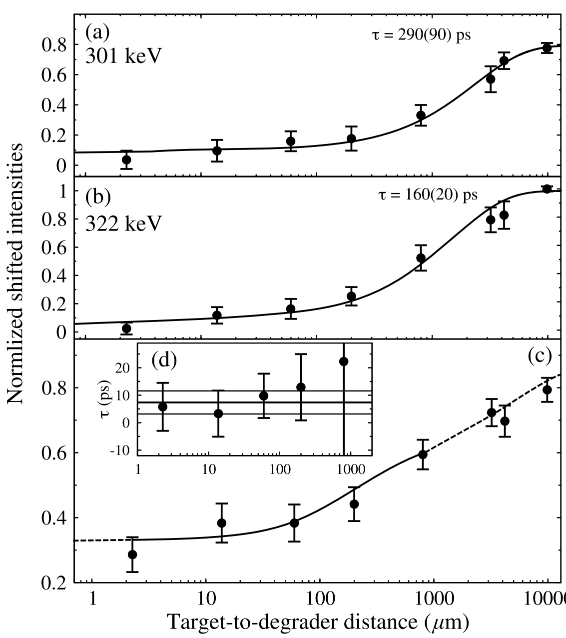

Fig. 4. (a) Decay curve for the 301-keV transition established to depopulate the $(21/2^+)$ state in ^{151}Lu. (b) Decay curve for the 322-keV transition established to depopulate the $(27/2^-)$ state in ^{151}Lu in this work. (c) Decay curve for the 611-keV transition established to feed the ground state in ^{151}Lu in this work. The dashed curves correspond to regions of extrapolation from the fit. (d) Shows the individual lifetimes from five of the target to degrader distances used in the weighted-average calculation of the final lifetime.

in Ref. [24] has been used. This Hamiltonian allows the model to account for the experimental non-rotational spectrum of the core instead of a purely adiabatic rotational core. The nucleus ^{148}Er was used as the core as there is no experimental information available for ^{150}Yb. ^{148}Er displays an yrast band that is not quite rotational. To overcome the problem of the inclusion of the pairing interaction, the Hamiltonian was diagonalized in the intrinsic system within a basis of quasi-particle states as validated in Ref. [25]. The predicted excitation energies of the negative-parity states in ^{151}Lu from this model are shown in Fig. 5(a). For deformations $|\beta_2| \leqslant 0.3$ the $J = 11/2^-$ level is predicted to be the ground state. Fig. 5(b) shows the half-life for proton emission from the $11/2^-$ state as a function of the deformation parameter, β. The half-life is proportional to the inverse of the probability that the $h_{11/2}$ single particle is empty in the daughter nucleus. For ^{151}Lu this quantity is small, and depends strongly on the pairing gap and on the relative positions of the other single-particle levels. Since some of these states are not well known, an uncertainty has been added to the theoretical half-lives, corresponding to a shift (up or down) of the Fermi energy by 200 keV, in order to account for it. From the theoretical results presented in Fig. 5(b), one can exclude a prolate deformation larger than $\beta = 0.2$ for the proton-emitting state, as the half-life is too long compared with the experimental value of 85(10) ms [1]. However, the comparison of the experimental excitation energies in Fig. 1 with the theoretical excitation energies in Fig. 5(a), allows the sign of the deformation to be determined. Only for an oblate deformation does the theoretical $13/2^-$ state reside above the $15/2^-$ state and the $17/2^-$ state reside above the $19/2^-$ state, as observed in the experimental data, see Fig. 1. The energy separation of the $(17/2^-)$ and $(19/2^-)$ states is measured experimentally to be 30 keV. According to Fig. 5(a) the same theoretical $17/2^-$ and $19/2^-$ splitting occurs at $\beta = -0.03$ (dashed red line) suggesting that the ground state of ^{151}Lu has a mild oblate deformation. The theoretical excitation energy spectrum corresponding to $\beta = -0.03$ is shown to the left in Fig. 1 and is found to be in good agreement with the experimentally deduced level scheme. Since the spacing between the theoretical $13/2^-$ and $15/2^-$ states is quite small and depends upon several parameters within the theoretical code, this level scheme comparison is solely used to determine the sign of the deformation. The absolute value is instead determined from the RDDS lifetime value outlined below.

Using the same non-adiabatic strongly-coupled model [25], theoretical calculations have been used to convert the RDDS lifetime value to a quadrupole deformation. The calculated lifetime as a function of deformation is shown for the $(15/2^-)$ state in Fig. 6. The deformation deduced from the 7.4(42) ps experimental RDDS lifetime is determined to be $\beta = -0.11^{+0.02}_{-0.05}$. Relating the experimentally measured deformation for the $(15/2^-)$ state to the ground-state deformation in ^{151}Lu requires the assumption that the nucleus does not undergo a drastic change in shape between the two states. Any large changes would manifest themselves in a much larger theoretical lifetime value for the $15/2^-$ state due to the reduced overlap of the wave functions for this state and the ground state. This longer theoretical lifetime would imply that a larger deformation would be required to reproduce the experimental lifetime. However, with a larger theoretical deformation the level splitting between the $15/2^-$ and $13/2^-$ states shown in Fig. 5(a) would not match the experimental splitting shown in Fig. 1. Hence we assume no change in deformation between the $(11/2^-)$ and $(15/2^-)$ states. The theoretical and experimental results presented in this Letter therefore provide the best evidence to date that the deformation of the proton-emitting ground state in ^{151}Lu is mildly oblate with $\beta = -0.11^{+0.02}_{-0.05}$.

In summary, the low-lying excited states in ^{151}Lu have been firmly placed for the first time using recoil-proton tagging. In addition, the lifetime of the first excited state, as well as higher-lying longer-lived states have been measured using the recoil-distance Doppler-shift method. The results have been compared with theoretical calculations using the non-adiabatic strong-coupling model. A comparison of the experimental and theoretical results suggest that the proton-emitting ground state of ^{151}Lu has a mildly oblate deformation of $\beta = -0.11^{+0.02}_{-0.05}$. This work presents the best evidence to date for proton emission from an oblate nucleus.

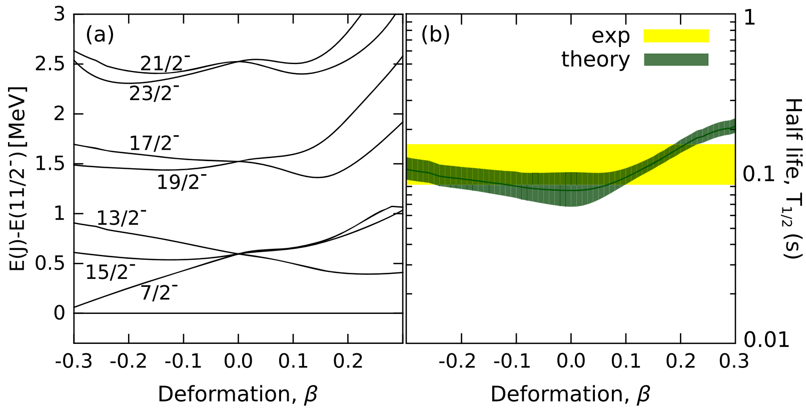

Fig. 5. (Color online.) (a) Non-adiabatic theoretical excitation energies of the negative-parity states in ^{151}Lu as a function of deformation. The dashed red line corresponds to the deformation where the $19/2^-$ and $17/2^-$ splitting matches the experimental separation of ≈30 keV. (b) Experimental half-life (yellow) and theoretical half-life (green), as a function of deformation, of the proton-emitting $h_{11/2}$ ground state in ^{151}Lu. Positive (negative) values of β correspond to prolate (oblate) nuclear deformation.

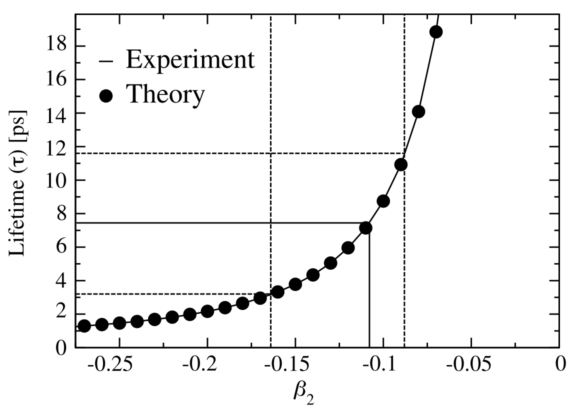

Fig. 6. Theoretical non-adiabatic calculations (circles) of the change in the deformation parameter, β as a function of the lifetime of the $(15/2^-)$ state in ^{151}Lu. The region bound by the dashed lines corresponds to the limits on β from the experimental RDDS lifetime measurement of 7.4(42) ps made in this work.

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