Spectroscopic factor and proton formation probability for the $d_{3/2}$ proton emitter ^{151m}Lu

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The quenching of the experimental spectroscopic factor for the proton decay of ^{151m}Lu from the short-lived $d_{3/2}$ isomeric state has been a long standing problem. In the present work, the proton energy value and half-life of this isomer were remeasured to be 1295(5) keV and 15.4±0.8 μs, respectively, in an experiment at the Accelerator Laboratory of the University of Jyväskylä. The refined experimental data can resolve the discrepancy in the spectroscopic factor with the WKB approximation. It is also found that the proton formation probability extracted from the present measurements is much larger than that from the adopted data before, indicating no significant hindrance for the proton decay of ^{151m}Lu.

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I. INTRODUCTION

Proton emission is a quantum tunneling process in which the escaping proton penetrates through a potential barrier consisting of Coulomb and centrifugal potentials. The study of proton decay provides critical spectroscopic information on the proton emitters and the ordering of quantum states of nuclei lying beyond the proton drip line [1–4]. As a measure for the purity of the single-particle configuration in the initial wave function, the spectroscopic factor is conventionally employed.

The experimental spectroscopic factor (S_p^{exp}) is usually defined as the ratio between experimental half-life and the calculated one based on single-particle models. It provides a measure of the amplitude of the single particle (n, l, j) component in the proton emitting nucleus. The calculated proton half-life $t^p_{1/2}(\text{calc})$ can be obtained using the WKB approximation and has a very strong dependence on the proton-decay energy and the orbital angular momentum. No nuclear structure information other than the angular momentum of the proton is assumed in the WKB approach.

The experimental spectroscopic factor (S_p^{exp}) may be compared with theoretical one S_p^{th}. The latter is model dependent and very sensitive to nuclear structure in-

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volved, including the single particle energies, which are much affected by the nuclear potential used and the excitation modes. Within the BCS theory the spectroscopic factor is given by $S_p^{\rm th} = u_j^2$, where the vacancy factor u^2 is the probability that the spherical shell-model orbital with (n, l, j) quantum numbers is empty in the daughter nucleus. The agreement between experimental and theoretical spectroscopic factors has been used to indicate that the correct assumption about the initial wave function has been taken.

Proton emitters in the region with $A \approx 150 - 170$, $69 \leq Z \leq 79$ are spherical or nearly spherical. They are of particular interest as the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ proton orbitals are almost degenerate. This leads to the presence of low-spin and high-spin states in close proximity, one of which is isomeric. Systematic analysis of the experimental data [5–8], shows good agreement of the theoretical spectroscopic factors with the experimental ones for $h_{11/2}$ and $s_{1/2}$ emitters. In contrast, for $d_{3/2}$ states the observed spectroscopic factors are systematically lower than those predicted by, e.g., a low-seniority shell model calculation [5] or BCS calculations [6]. One such case is ^{151m}Lu [9, 10], the heaviest odd-A proton emitter found in an isomeric state that has a $d_{3/2}$ proton decay. This isomer was interpreted as a proton decay from the $d_{3/2}$ state by WKB penetration calculations, but the observed decay half-life is much longer than that obtained from the WKB calculations, and the extracted $S_p^{\rm exp}$ of $0.26^{+0.14}_{-0.08}$ using the WKB approximation [9] is much reduced compared to the calculated $S_p^{\rm th}$ of 0.73 [11] or 0.67 [5].

More recent calculations of the spectroscopic factors, e.g., within a generalized liquid drop model [12], using the self-consistent approach based on covariant density functional theory [13–16] or a deformed density-dependent model [17], do not show the apparent systematic trends as predicted by the low-seniority shell model [5] or BCS calculations [6]. In fact, all these calculated spectroscopic factors are rather interaction or model dependent.

In order to address the discrepancies between experimental and theoretical spectroscopic factors for $d_{3/2}$ proton emitters, sophisticated models have been developed to take into account the role of dynamical particle-vibration coupling [18, 19], or the effect of non-negligible deformation for the $d_{3/2}$ orbital in ^{151m}Lu [20, 21]. A nonadiabatic quasiparticle calculations [10] was able to reproduce the experimental data, provided that ^{151m}Lu has a deformation of $\beta_2 \approx$ -0.12. This value is comparable to the corresponding β_2 value deduced for the ground state of ^{151}Lu using the same formalism [22]. These calculations were also able to reproduce properties of excited levels built upon the proton-emitting states.

Here we report on the reinvestigation of ^{151m}Lu in an independent recoil-decay tagging (RDT) experiment performed at the University of Jyväskylä. With our new results, we present the experimental and theoretical spectroscopic factor for ^{151m}Lu assuming a spherical shape with the WKB approximation [8]. Considering the fact of missing nuclear structure effects in the WKB barrier transmission approximation and model-dependent theoretical spectroscopic factors, we introduce the proton formation probability as a more proper description of the proton decay process [23]. The proton formation probability extracted from the present results indicates no significant hindrance for the proton decay of ^{151m}Lu.

II. EXPERIMENTAL DETAILS AND RESULTS

The experimental setup consisted of the JUROGAM Ge-detector array [24] at the target position, the gas-filled recoil separator RITU [25, 26] and the GREAT spectrometer at the focal plane of RITU. In this experiment, excited states of ^{151}Lu were populated by bombarding a self-supporting 500 μg/cm^2 isotropically enriched ^{96}Ru target with a ^{58}Ni beam at 266 MeV and 274 MeV delivered by the K130 cyclotron. A 50 μg/cm^2 C charge reset foil was placed behind the target. The average beam current on the target was 3 particle nA for 110 hours. After a time of flight of about 0.6 μs in RITU, the evaporation residues passed through a gas-filled multiwire proportional chamber (MWPC), and then were implanted into a pair of 300 μm thick double-sided silicon strip detectors (DSSDs) of the GREAT spectrometer. This spectrometer registers the recoiling evaporation residues, proton and α decays, β rays, conversion electrons as well as X and γ rays. Each DSSD is segmented into 40 horizontal strips in the front and 60 vertical strips at the back, providing a total of 4800 pixels. To minimize the interference from scattered electrons and light ions in the DSSDs, a pin-diode detector array surrounding the DSSDs in GREAT can be used as a veto. Prompt γ rays emitted in the fusion-evaporation reactions were detected by the JUROGAM array. More details of the setup can be found in Refs. [25, 27].

For each event, all signals induced in the JUROGAM, MWPC and GREAT were recorded by a triggerless data acquisition system TDR [28]. In this system, all channels are running independently and each registered signal was time stamped by a 100 MHz clock. Thus the prompt γ rays at the target position, the impinging time and position of the evaporation residues, as well as the energy, time and position of subsequent decays, could be measured and stored. A position-energy-time-correlation analysis of the event chains allowed one to make detailed deductions with implantation rates of several hundred evaporation residues per second. In other words, decays within a given pixel of DSSDs can be correlated with the previous implant in the same pixel. In this way it is possible to determine the decay time of the radioactivity.

In total, 1500 full energy protons were registered for the $d_{3/2}$ isomeric decays, 80 percent of which are from the setting with beam energy of 266 MeV. Half-lives in the range of microseconds to about a few hundreds of milliseconds could be measured by observing the decay of the activity. The data were analyzed with the GRAIN [29] and RADWARE [30] software packages.

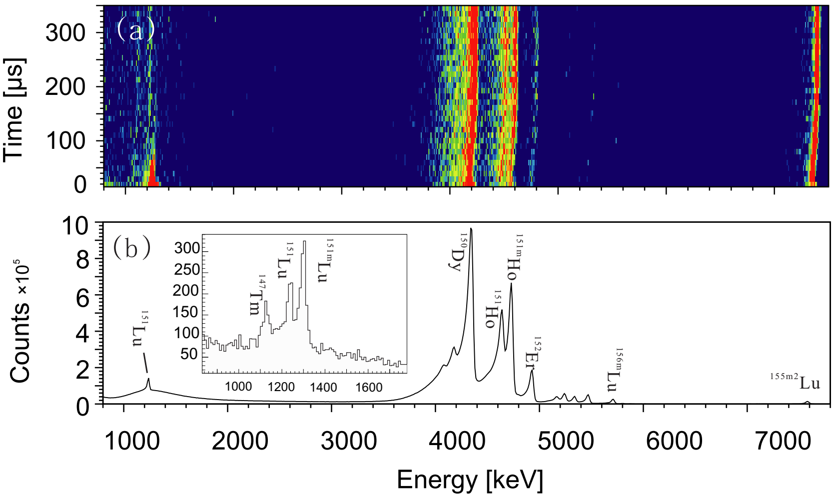

FIG. 1: (a) PIN-vetoed decay spectrum of DSSDs as a function of time after implantation. (b) Projection of the decay spectrum within 500 ms after the implantation. The inset is the projection between 30 - 400 μs, where both proton lines from ^{151g,m}Lu are clearly visible.

TABLE I: Energies and relative intensities for γ-ray transitions assigned to ^{151m}Lu. The relative intensities are normalized to that of the 675 keV transition.

E_γ/keV	$I_\gamma/\%$
675	100(28)
429	35(14)
360	33(15)
551	30(15)

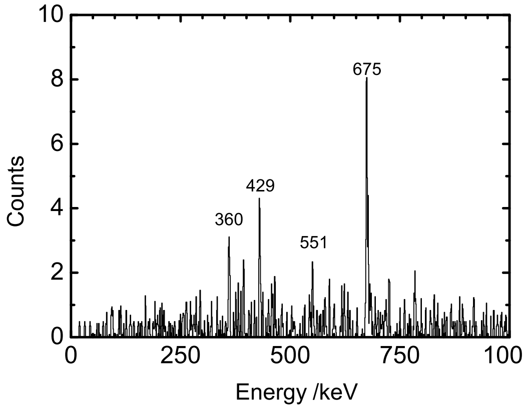

FIG. 2: Prompt γ-ray spectrum tagged with proton decay from the ^{151m}Lu. A background spectrum of decays between 300-400 μs has been subtracted.

The energy-time spectrum of the charged particle decay is shown in Fig. 1(a) with a bin size of 10 μs in time. A few α particle peaks are clearly resolved. It can be seen that the peak energies increase with time in the first 200 μs after the implantation, and then remain constant for decays thereafter, causing the energy resolution to be degraded for fast decays. This is due to the residual pulse height in the associated amplifiers caused by the implant at the time of decay. Such energy resolution degradation was also observed in Refs. [9, 31], and the correction is necessary for life times up to a few milliseconds.

The energy projection of the decay spectrum within 500 ms after implantation is presented in Fig. 1(b). One proton peak is visible in the low-energy region. Peaks above 4 MeV are assigned to the known α-decaying nuclei. The most intense α particle peaks between 4 and 5 MeV are from the decays of the $N = 84$ isotones (^{150}Dy, ^{151}Ho, ^{152}Er). The higher energy α lines, including the isomeric transition of ^{155m2}Lu, are due to the isotopic impurities of heavier Ru isotopes in the target.

The kinetic energies of these α particles and the proton from the ground state (g.s.) of ^{151}Lu [32] were used for the energy calibration of the DSSDs. Corrections [33, 34] were applied to take into account the pulse height defect for protons and α particles in silicon [35], the contribution of the recoiling daughter nucleus to the energy signal [36] and the non-linear response of silicon detectors for low-Z ions [37, 38]. As shown in the inset in Fig. 1(b), the ^{151m}Lu proton-decay peak is clearly resolved from the g.s. proton-decay line with an energy difference of 62 keV, producing an E_p of 1295(5) keV for the isomeric state. The new value is basically consistent with 1310(10) keV obtained in Ref. [9] and 1285(4) keV in Ref. [10] in one standard deviation, but the centroid value is somehow in between. The corresponding proton-decay energy Q_p was calculated to be 1317(5) keV taking into account the recoiling energy of the daughter nucleus and (electron) screening correction [39]. The proton-decay half-life associated with the isomer is 15.4 ± 0.8 μs, which compares with the value of 16(1) μs [9] and 17(1) μs [10].

By tagging on the protons emitted from ^{151m}Lu, four prompt γ-ray transitions feeding the d$_{3/2}$ isomer are identified at 675, 551, 429 and 360 keV as shown in Fig. 2. The first three of these were also observed in Ref. [10], but the 369 and 283 keV transitions reported there are not confirmed in this work. The relative intensities of these four transitions are also listed in Table I. Although the 675 keV transition is the strongest γ ray in the spectrum, no γ-γ coincidences could be established due to

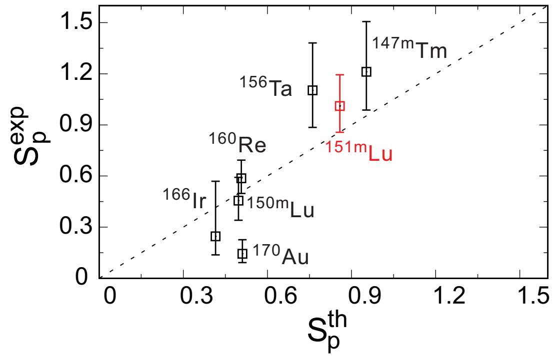

FIG. 3: Experimental spectroscopic factors vs. theoretical ones obtained in the RMF+BCS theory for the region with $64 \leq Z \leq 82$ for $d_{3/2}$ states. The new result from this work is indicated by red color. The symbol (m) denotes an isomeric state.

the low statistics. Consequently it was not possible to propose a level scheme on the basis of the present data.

III. DISCUSSION

The experimental spectroscopic factor provides an estimate of the amplitude of the single particle (n, l, j) component in the proton-emitting nucleus. One can assert that this is an effective theory since one has to introduce an effective single-proton potential to mimic the motion of the decaying proton inside the nucleus. The calculated penetration probability and the extracted experimental spectroscopic factor are sensitive to that potential, as already indicated in various calculations [5–7, 12–17].

The slight decrease in Q_p from the adopted value [9] increases the theoretical proton half-life within the WKB approximation. Together with the reduced experimental half-life, this will thus give a larger experimental spectroscopic factor S_p^{exp}, and can therefore help to resolve the discrepancy found in previous works [9].

To illustrate the effect of present refined data, we have calculated the theoretical spectroscopic factor using the relativistic mean field theory (RMF) combined with the BCS method as described in Ref. [8]. The experimental and theoretical spectroscopic factors based on the up-to-date data are plotted in Fig. 3 for the $d_{3/2}$ proton emitters in the subshell between Z = 64 and 82. The error bars have taken into account the experimental error on the half-life and the theoretical error induced by the uncertainty in Q_p.

With the refined data, the experimental spectroscopic factor S_p^{exp} of ^{151m}Lu is much enhanced from 0.58 [8] to $1.01^{+0.12}_{-0.11}$. This value should be compared with S_p^{theo} of 0.86. Thus the present refined measurements can resolve the long-standing discrepancy in the spectroscopic factor of ^{151m}Lu, without introducing the deformation effect or particle-vibration coupling. This shows the importance of precision measurements in short-lived proton decay.

However, the calculated spectroscopic factor is rather interaction or model dependent as mentioned before, making it not an “ideal” quantity to describe the proton decay process. An alternative description of the proton decay process is given by the R-matrix approach [4], which provides a microscopic scheme to extract experimental proton formation amplitude at the nuclear surface in a model independent way [23]. Shown in Fig. 4 is a schematic plot for the R-matrix description of the proton emission process, where one divides the decay process into two regions: the inner and outer region. Here the value R defines a radius of the nuclear surface outside of which the nuclear potential vanishes. In the outer region, the nuclear attraction vanishes and the proton escapes the nucleus with a rate solely determined by the Q_p value, the Coulomb and centrifugal barriers. In the inner region, the dynamic motion of the proton determines the proton-decay formation property that describes the influence of nuclear structure on the proton decay [23].

In this scheme, the proton formation amplitude reflects the overlap between the parent and daughter wave functions from which one can distinguish the role played by deformation and pairing on the decay process. It avoids the ambiguities of the deduced spectroscopic factor in relation to the surface effects and quantifying in a more precise manner the nuclear many-body structure effects. It is worth noting that, if a smooth potential is used in calculating the spectroscopic factor, the proton formation amplitude and the effective spectroscopic factor may show a similar systematic pattern. However, the WKB calculation on the total penetrability is also influenced by the surface part and the inner part through the effective single-proton potential.

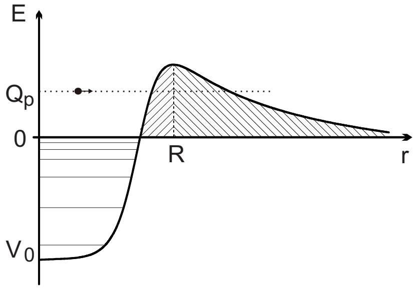

FIG. 4: Schematic view of the proton emission process in the R-matrix approach with no contribution from the centrifugal barrier (i.e. zero orbital angular momentum). For details please refer to the text.

The formation amplitudes $\log_{10}|RF(R)|^2$ extracted from experimental data, as shown in Fig. 2 in Ref. [23], are clearly divided into two distinct groups characterized by deformation: the decays of well-deformed nuclei for lighter isotopes and the decays of spherical orbitals. ^{151m}Lu falls basically in the spherical group but is slightly below the overall trend.

Using the data obtained in the present work the proton formation probability of ^{151m}Lu $|RF_l(R)|^2$ is recal-

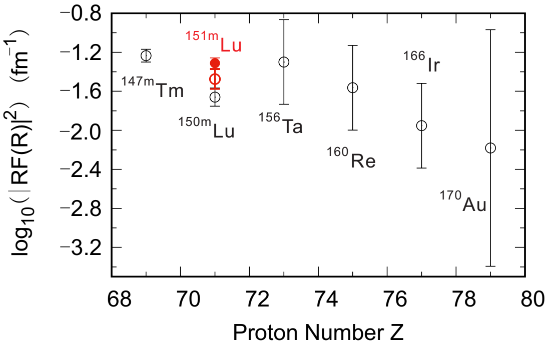

FIG. 5: Proton-decay formation amplitudes $\log_{10}|RF(R)|^2$ extracted from experimental data as a function of Z for the $d_{3/2}$ states. The results for ^{151m}Lu are illustrated by unfilled red circle (previous result) and filled red circle (this work).

culated to be 0.049(3) fm^{-1}. This is 48% larger than that obtained from the adopted data [2] and is nearly identical to those of the d$_{3/2}$ states in neighboring nuclei, e.g. ^{147}Tm and ^{156}Ta [23]. The proton formation probabilities for the six $d_{3/2}$ proton emitters are shown in Fig. 5. This new proton formation probability fits well in the group of spherical proton emitters. The level scheme built on the proton decaying ground state of ^{151}Lu can be well described in terms of the coupling between valence protons (above Z=64 subshell closure) and the neutron-hole pair (below N=82 shell closure) by large-scale shell model calculations. Detailed analysis of the experimental spectrum and theoretical calculations will be presented elsewhere. It is also noticed in Fig. 5 that the formation probability of the d$_{3/2}$ state in ^{150m}Lu is still obviously lower than those of the neighboring nuclei. The reason is unclear and a new precision experiment is called for to clarify this.

IV. SUMMARY

In the present work, the $d_{3/2}$ proton emitter ^{151m}Lu, has been reinvestigated in an RDT experiment. With the decay energy and half-life values measured in the present work, the spectroscopic factor for ^{151m}Lu is increased from 0.58 to about 1 in the WKB approach. This can solve the long-standing quenching problem in spherical shell-model calculations, without the need to include either deformation or particle-vibration coupling effects. Meanwhile, in comparison with the WKB approach, the proton formation probabilities have been discussed in detail as a more proper and microscopic quantity to describe the proton decay. The newly extracted proton formation probability is close to those of neighboring nuclei, following well the general trend of proton emitters in the spherical group .

Acknowledgments

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