Physics Letters B 770 (2017) 83–87

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

F. Wang [a], B.H. Sun [a,*], Z. Liu [b,c,**], R.D. Page [d], C. Qi [e], C. Scholey [f], S.F. Ashley [c], L. Bianco [d], I.J. Cullen [c], I.G. Darby [g], S. Eeckhaudt [f], A.B. Garnsworthy [h], W. Gelletly [c], M.B. Gomez-Hornillos [i], T. Grahn [f], P.T. Greenlees [f], D.G. Jenkins [j], G.A. Jones [c], P. Jones [k], D.T. Joss [d], R. Julin [f], S. Juutinen [f], S. Ketelhut [f], S. Khan [l], A. Kishada [l], M. Leino [f], M. Niikura [m], M. Nyman [n], J. Pakarinen [d], S. Pietri [o], Z. Podolyak [c], P. Rahkila [f], S. Rigby [d], J. Saren [f], T. Shizuma [p], J. Sorri [f], S. Steer [c], J. Thomson [d], N.J. Thompson [c], J. Uusitalo [f], P.M. Walker [c], S. Williams [q], H.F. Zhang [r], W.Q. Zhang [b], L.H. Zhu [a]

[a] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China*
[b] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[c] *Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK*
[d] *Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK*
[e] *KTH, Alba Nova University Center, SE-10691 Stockholm, Sweden*
[f] *University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland*
[g] *Department of Nuclear Sciences and Applications, International Atomic Energy Agency, A-1400 Vienna, Austria*
[h] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[i] *Universitat Politécnica de Catalunya (UPC), 08034 Barcelona, Spain*
[j] *Department of Physics, University of York, Heslington, York, UK YO10 5DD, UK*
[k] *iThemba LABS, National Research Foundation, PO Box 722, Somerset West, South Africa*
[l] *Schuster Building, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK*
[m] *CNS, University of Tokyo, Tokyo 351-0100, Japan*
[n] *European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium*
[o] *GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*
[p] *Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[q] *Nikhef National Institute for Subatomic Physics, University of Amsterdam, Amsterdam, Netherlands*
[r] *School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 7 April 2017
Accepted 17 April 2017
Available online 20 April 2017
Editor: V. Metag

Keywords:
Proton emitter
Recoil-decay tagging
Spectroscopic factor
Proton formation probability
WKB approximation
$A = 151$

ABSTRACT

The quenching of the experimental spectroscopic factor for proton emission from the short-lived $d_{3/2}$ isomeric state in ^{151m}Lu was a long-standing problem. In the present work, proton emission from this isomer has been reinvestigated in an experiment at the Accelerator Laboratory of the University of Jyväskylä. The proton-decay energy and half-life of this isomer were measured to be 1295(5) keV and 15.4(8) μs, respectively, in agreement with another recent study. These new experimental data can resolve the discrepancy in the spectroscopic factor calculated using the spherical WKB approximation. Using the R-matrix approach it is found that the proton formation probability indicates no significant hindrance for the proton decay of ^{151m}Lu.

---

* Corresponding author.
** Corresponding author at: Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail addresses: bhsun@buaa.edu.cn (B.H. Sun), liuzhong@impcas.ac.cn (Z. Liu).

http://dx.doi.org/10.1016/j.physletb.2017.04.034

1. 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]. The spectroscopic factor is conventionally employed as a measure of the purity of the single-particle configuration of the initial wave function.

The experimental spectroscopic factor (S_p^{exp}) is usually defined as the ratio between the 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 $t_{1/2}^p$ (calc) can be obtained using the WKB approximation and has a very strong dependence on the proton-decay energy, the orbital angular momentum carried by the emitting proton as well as the effective single-particle potential and the corresponding initial single-proton wave function used in the calculation. One can assert that the way one extracts the experimental spectroscopic factor 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 [5–14].

The experimental spectroscopic factor (S_p^{exp}) may be compared with the theoretical one S_p^{th}. The latter is model dependent and very sensitive to the nuclear structure involved, 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 $S_p^{\text{th}} = u_j^2$, 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 can be a good indication that a reasonable and consistent initial wave function for the outgoing proton has been taken. Considering the large uncertainties mentioned above, however, one may not be able to draw a firm conclusion.

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. 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 spherical shell model calculation [5] or BCS calculations [6].

In order to address the discrepancies between experimental and theoretical spectroscopic factors, sophisticated models have been developed to evaluate the role of dynamical particle-vibration coupling [15,16], or the effect of non-negligible deformation.

More recent calculations of the spectroscopic factors, e.g., within a generalized liquid drop model [9], using the covariant density functional theory [10–13] or a deformed density-dependent model [14], do not show the apparent systematic trends as predicted by the low-seniority shell model [5] or BCS calculations [6].

An alternative description of the proton-decay process is given by the R-matrix approach [4]. It provides a microscopic scheme to extract the experimental proton formation amplitude at the nuclear surface in a model independent way [17]. In this scheme, as will be illustrated in the Discussion Section, the proton decay process can be evaluated in two steps: the inner process which describes the dynamic motion of the proton inside the nucleus and the possibility for it to be emitted, and the outer process which describes the penetration of the proton through the barrier. The latter part of the inner process corresponds to the proton formation amplitude that 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. This scheme avoids the ambiguities of the deduced spectroscopic factor in relation to the surface effects and quantifies in a more precise manner the nuclear many-body structure effects. It is also valid for all charged particle decays. It is worth noting that, if a smooth effective single-proton potential is used in calculating the spectroscopic factor, the proton formation amplitude and the effective spectroscopic factor may show a similar systematic pattern.

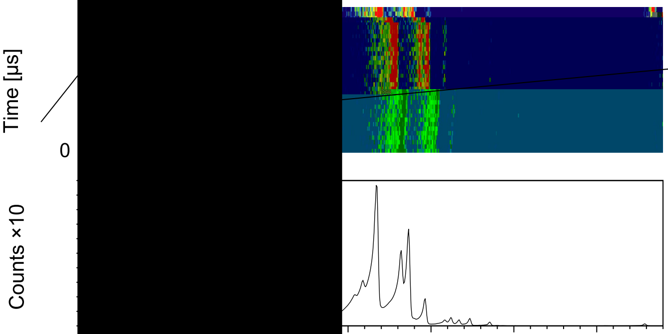
An important case is ^{151m}Lu [18], the heaviest odd-A nuclide for which proton emission has been observed from a $d_{3/2}$ isomeric state. However, the observed half-life was much longer than that predicted by spherical WKB calculations and the extracted S_p^{exp} of $0.26^{+0.14}_{-0.08}$ using the WKB approximation [18] is lower than the predicted values of S_p^{th} of 0.73 [19] or 0.67 [5]. However, a recent study by Taylor et al. [20] reported a lower value for the proton-decay energy, which could potentially resolve the discrepancy. In that work, nonadiabatic quasiparticle calculations were also performed, which were able to reproduce the improved 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 (g.s.) of ^{151}Lu using the same formalism [21]. In addition, these calculations were able to reproduce properties of excited levels built upon the proton-emitting states.

Here we report on a reinvestigation of ^{151m}Lu in an independent recoil-decay tagging (RDT) experiment performed at the University of Jyväskylä. Our new results are consistent with those of Ref. [20] and we discuss the experimental and theoretical spectroscopic factor for ^{151m}Lu assuming a spherical shape with the WKB approximation [8]. Considering that nuclear structure effects are not included in the WKB barrier transmission approximation and the model dependence of theoretical spectroscopic factors, we introduce the proton formation probability as a more proper description of the proton-decay process [17], which defines the possibility of finding the decaying proton at the nuclear surface. The proton formation probability extracted from the present results indicates no significant hindrance for the proton decay of ^{151m}Lu.

2. Experimental details and results

The experimental setup consisted of the JUROGAM Ge-detector array [22] at the target position, the gas-filled recoil separator RITU [23,24] 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 isotopically 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.

[redacted]



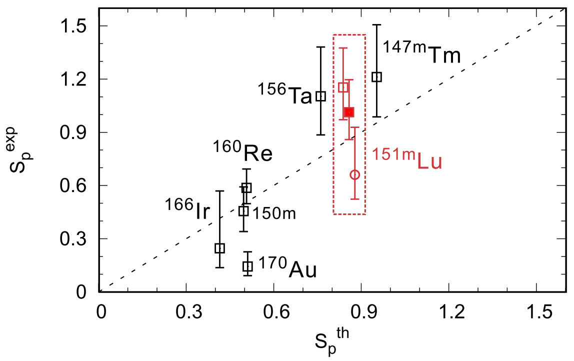


Fig. 3. Experimental spectroscopic factors vs. theoretical ones obtained in the RMF+BCS theory for the region with $64 \leq Z \leq 82$ for $d_{3/2}$ states. The results of ^{151m}Lu (in red color) deduced from the present work, Refs. [18] and [20], are indicated by the solid square, open circle and open square, respectively. The $S_p^{\rm th}$ of ^{151m}Lu are shifted slightly for a better view. The symbol (m) denotes an isomeric state. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The decay of the $d_{3/2}$ proton emitters was also discussed in terms of the proton formation probability, a more proper and microscopic quantity to describe the proton-decay process. The extracted proton formation probability for ^{151m}Lu is compared to those in neighboring nuclei, and is found to follow well the general trend of spherical proton emitters.

Acknowledgements

This work has been supported by the National Natural Science Foundation of China under Nos. 11475014, 11435014, 11405224, 11205208, 11675225, 11675066, U1632144 and the National key research and development program (2016YFA0400500), the “100 Talented Project” of the Chinese Academy of Sciences, the EU 6th Framework programme “Integrating Infrastructure Initiative – Transnational Access”, Contract Number: 506065 (EURONS) and by the Academy of Finland under the Finnish Centre of Excellence Programme 2006–2011 (Nuclear and Accelerator Based Physics Programme at JYFL), and United Kingdom Science and Technology Facilities Council. CS (209430) and PTG (111965) acknowledge the support of the Academy of Finland. CQ is supported by the Swedish Research Council (VR) under grant Nos. 621-2012-3805, and 621-2013-4323 and the Göran Gustafsson foundation. The computations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at PDC, KTH, Stockholm. We would also like to thank Bao-An Bian, Cary Davids, Lang Liu, and Zheng-Hua Zhang for valuable discussions.

References

[1] P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 (1) (1997) 541–590.
[2] B. Blank, M. Borge, Prog. Part. Nucl. Phys. 60 (2) (2008) 403–483.
[3] M. Pfützner, M. Karny, L.V. Grigorenko, K. Riisager, Rev. Mod. Phys. 84 (2012) 567–619.
[4] D. Delion, R. Liotta, R. Wyss, Phys. Rep. 424 (3) (2006) 113–174.
[5] C.N. Davids, P.J. Woods, J.C. Batchelder, C.R. Bingham, D.J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, T. Davinson, S.J. Freeman, D.J. Henderson, R.J. Irvine, R.D. Page, H.T. Penttilä, D. Seweryniak, K.S. Toth, W.B. Walters, B.E. Zimmerman, Phys. Rev. C 55 (1997) 2255–2266.
[6] S. Åberg, P.B. Semmes, W. Nazarewicz, Phys. Rev. C 56 (1997) 1762–1773.
[7] A.P. Robinson, C.N. Davids, G. Mukherjee, D. Seweryniak, S. Sinha, P. Wilt, P.J. Woods, Phys. Rev. C 68 (2003) 054301.
[8] H.F. Zhang, Y.J. Wang, J.M. Dong, J.Q. Li, W. Scheid, J. Phys. G, Nucl. Part. Phys. 37 (8) (2010) 085107.
[9] J.M. Dong, H.F. Zhang, G. Royer, Phys. Rev. C 79 (2009) 054330.
[10] M. Bhattacharya, G. Gangopadhyay, Phys. Lett. B 651 (2–C3) (2007) 263–267.
[11] L. Ferreira, E. Maglione, P. Ring, Phys. Lett. B 701 (4) (2011) 508–511.
[12] Q. Zhao, J.M. Dong, J.L. Song, W.H. Long, Phys. Rev. C 90 (2014) 054326.
[13] Y. Lim, X. Xia, Y. Kim, Phys. Rev. C 93 (2016) 014314.
[14] Y. Qian, Z. Ren, Eur. Phys. J. A 52 (3) (2016) 1–7.
[15] C.N. Davids, H. Esbensen, Phys. Rev. C 64 (2001) 034317.
[16] K. Hagino, Phys. Rev. C 64 (2001) 041304.
[17] C. Qi, D.S. Delion, R.J. Liotta, R. Wyss, Phys. Rev. C 85 (2012) 011303.
[18] C.R. Bingham, J.C. Batchelder, K. Rykaczewski, K.S. Toth, C.-H. Yu, T.N. Ginter, C.J. Gross, R. Grzywacz, M. Karny, S.H. Kim, B.D. MacDonald, J. Mas, J.W. McConnell, P.B. Semmes, J. Szerypo, W. Weintraub, E.F. Zganjar, Phys. Rev. C 59 (1999) R2984–R2988.
[19] S. Cwiok, J. Dudek, W. Nazarewicz, J. Skalski, T. Werner, Comput. Phys. Commun. 46 (3) (1987) 379–399.
[20] M.J. Taylor, D.M. Cullen, M.G. Procter, A.J. Smith, A. McFarlane, V. Twist, G.A. Alharshan, L.S. Ferreira, E. Maglione, K. Auranen, T. Grahn, P.T. Greenlees, K. Hauschild, A. Herzan, U. Jakobsson, R. Julin, S. Juutinen, S. Ketelhut, J. Konki, M. Leino, A. Lopez-Martens, J. Pakarinen, J. Partanen, P. Peura, P. Rahkila, S. Rinta-Antila, P. Ruotsalainen, M. Sandzelius, J. Saren, C. Scholey, J. Sorri, S. Stolze, J. Uusitalo, M. Doncel, Phys. Rev. C 91 (2015) 044322.
[21] M. Procter, D. Cullen, M. Taylor, G. Alharshan, L. Ferreira, E. Maglione, K. Auranen, T. Grahn, P. Greenlees, U. Jakobsson, R. Julin, A. Herzan, J. Konki, M. Leino, J. Pakarinen, J. Partanen, P. Peura, P. Rahkila, P. Ruotsalainen, M. Sandzelius, J. Sarn, S. Stolze, C. Scholey, J. Sorri, J. Uusitalo, T. Braunroth, E. Ellinger, A. Dewald, D. Joss, C. McPeake, B. Saygi, Phys. Lett. B 725 (1) (2013) 79–84.
[22] C. Beausang, S. Forbes, P. Fallon, P. Nolan, P. Twin, J. Mo, J. Lisle, M. Bentley, J. Simpson, F. Beck, et al., Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 313 (1–2) (1992) 37–49.
[23] M. Leino, J. Äystö, T. Enqvist, P. Heikkinen, A. Jokinen, M. Nurmia, A. Ostrowski, W. Trzaska, J. Uusitalo, K. Eskola, et al., Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 99 (1) (1995) 653–656.
[24] M. Leino, Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 126 (1) (1997) 320–328.
[25] R. Page, A. Andreyev, D. Appelbe, P. Butler, S. Freeman, P. Greenlees, R.-D. Herzberg, D. Jenkins, G. Jones, P. Jones, D. Joss, R. Julin, H. Kettunen, M. Leino, P. Rahkila, P. Regan, J. Simpson, J. Uusitalo, S. Vincent, R. Wadsworth, in: 14th International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications, Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 204 (2003) 634–637.
[26] I. Lazarus, E.E. Appelbe, P.A. Butler, P.j. Coleman-Smith, J.R. Cresswell, S.J. Freeman, R.D. Herzberg, I. Hibbert, D.T. Joss, S.C. Letts, R.D. Page, V.F.E. Pucknell, P.H. Regan, J. Sampson, J. Simpson, J. Thornhill, R. Wadsworth, IEEE Trans. Nucl. Sci. 48 (3) (2001) 567–569.
[27] P. Rahkila, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 595 (3) (2008) 637–642.
[28] D. Radford, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 361 (1) (1995) 297–305.
[29] J.C. Batchelder, C.R. Bingham, K. Rykaczewski, K.S. Toth, T. Davinson, J.A. McKenzie, P.J. Woods, T.N. Ginter, C.J. Gross, J.W. McConnell, E.F. Zganjar, J.H. Hamilton, W.B. Walters, C. Baktash, J. Greene, J.F. Mas, W.T. Milner, S.D. Paul, D. Shapira, X.J. Xu, C.H. Yu, Phys. Rev. C 57 (1998) R1042–R1046.
[30] S. Hofmann, W. Reisdorf, G. Münzenberg, F.P. Heßberger, J.R.H. Schneider, P. Armbruster, Z. Phys. A 305 (2) (1982) 111–123.
[31] S. Hofmann, W. Faust, G. Münzenberg, W. Reisdorf, P. Armbruster, K. Güttner, H. Ewald, Z. Phys. A 291 (1) (1979) 53–70.
[32] R.D. Page, P.J. Woods, R.A. Cunningham, T. Davinson, N.J. Davis, A.N. James, K. Livingston, P.J. Sellin, A.C. Shotter, Phys. Rev. C 53 (1996) 660–670.
[33] W. Lennard, S. Tong, G. Massoumi, L. Wong, Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 45 (1) (1990) 281–284.
[34] A. Ratkowski, Nucl. Instrum. Methods 130 (2) (1975) 533–538.
[35] W. Lennard, H. Geissel, K. Winterbon, D. Phillips, T. Alexander, J. Forster, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 248 (2) (1986) 454–460.
[36] W. Lennard, G. Massoumi, Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 48 (1) (1990) 47–50.
[37] K.-N. Huang, M. Aoyagi, M.H. Chen, B. Crasemann, H. Mark, At. Data Nucl. Data Tables 18 (3) (1976) 243–291.