CERN-INTC-2024-038 / INTC-I-278
09/04/2024

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

In-source laser spectroscopy of neutron-deficient lutetium and holmium isotopes, towards the proton emitters

April 9, 2024

K. M. Lynch[1], T. E. Cocolios[2], B. Cheal[3] K. Chrysalidis[4], A. de Roubin[5], S. Geldhof[6], R. Heinke[4], A. A. H. Jaradat[1,4], J. Reilly[1,4], M. Reponen[7], L. V. Rodríguez[8,9], J. Wessolek[1,4]

[1]*Department of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK*

[2]*KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*

[3]*Oliver Lodge Laboratory, University of Liverpool, UK*

[4]*Accelerator Systems Department, CERN, CH-1211 Geneva 23, Switzerland*

[5]*Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France*

[6]*GANIL, CEA/DRF-CNRS/IN2P3, BP 55027, Bd Henri Becquerel, F-14076 Caen, France*

[7]*Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL), FI-40014, Finland*

[8]*Experimental Physics Department, CERN, Geneva, Switzerland*

[9]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*

Spokespersons: Kara Marie Lynch [kara.lynch@manchester.ac.uk]
Thomas Elias Cocolios [thomas.cocolios@kuleuven.be]
Contact person: Reinhard Heinke [reinhard.heinke@cern.ch]

Abstract: We would like to obtain updated yield measurements for the neutron-deficient lutetium and holmium isotopes. This is with the hope of proposing in-source laser spectroscopy to measure the charge radii of proton-emitting ^{151}Lu and ^{141}Ho for the first time. Utilising a Ta-foil target coupled to the Laser Ion Source Trap (LIST), the beam time will allow us to investigate two promising laser spectroscopy schemes that have recently been developed for lutetium and holmium. The results will allow us to determine the feasibility of in-source laser spectroscopy measurements at the proton drip line.

Summary of requested shifts: 8 shifts

1 Physics Motivation

At the edge of the neutron-deficient nuclear landscape, the proton drip line marks the region where proton emission from the nucleus becomes energetically possible. As the neutron number decreases, so does the proton separation energy, resulting in nuclei whose protons are no longer bound by the nuclear force. These unstable nuclei have a certain lifetime, however, as the protons can only pass through the Coulomb and centrifugal potential energy barrier by quantum tunnelling. With the proton existing outside the nuclear potential, the proton-unbound nucleus is expected to display an enhanced charge radius due to the larger spatial occupancy of the proton distribution. Experimentally, this has yet to be measured and has become an exciting area of interest in recent years [1, 2, 3].

Since its discovery [4], the study of proton radioactivity by means of emitted proton energies, Q-values and half-lives has been a thriving field in nuclear physics [5]. As the potential energy barrier is strongly influenced by the centrifugal potential experienced by the proton, the rate of proton decay is extremely sensitive to the orbital angular momentum of the proton in the nucleus, so the correct nuclear spin assignment is essential [6]. For many proton emitters, the rate of proton decay can only be explained by the inclusion of nuclear deformation. Located in a region of changing deformation, a rapid transition is predicted between the spherical nuclei around Lu (Z=71) and the highly deformed nuclei of Ho (Z=67) [7]. For ^{150}Lu and ^{151}Lu, the proton decay rates (for the ground and isomeric states) can only be described by the assignment of oblate deformations [8, 9, 10], despite expectation of a spherical shape [7, 10]. Similarly for the proton emitter ^{151}Ho, a highly-deformed prolate model is required to account for its proton decay rate and its quadrupole moment could only be deduced [11]. Unambiguous measurement of the quadrupole moments of the Ho isotopes is therefore needed to help understand what is driving this onset of deformation.

In such cases, it is only by comparison between experimental values (e.g. proton decay rates) and theoretical calculations that assignments of nuclear spin and deformation can be deduced. In order to provide definitive answers to these questions, a direct and nuclear-model independent measurement of the deformation of proton-emitting nuclei is required. Laser spectroscopy provides us with such a technique, allowing us to measure the nuclear spin, the static deformation (by means of the quadrupole moment) and how the dynamic deformation changes (charge radii) as the proton drip line is crossed. Furthermore, measurement of the magnetic moment provides information on the single-particle nature of the nucleus, providing insight into the arrangement of the nucleons in the nucleus, and ultimately the nuclear shell orbital from which the proton is likely emitted. With both proton-emitting isotopes needing a deformed framework to explain the observed properties, direct measurement of the deformation of the Lu and Ho isotopes will provide insights into how the deformation changes as the proton drip line is crossed and the nucleus starts to emit protons.

Previous measurements of the charge radii of the Lu and Ho isotopes are shown in Figure 1. By measuring the charge radii across the proton drip line at ^{155}Lu (N=84) and ^{145}Ho

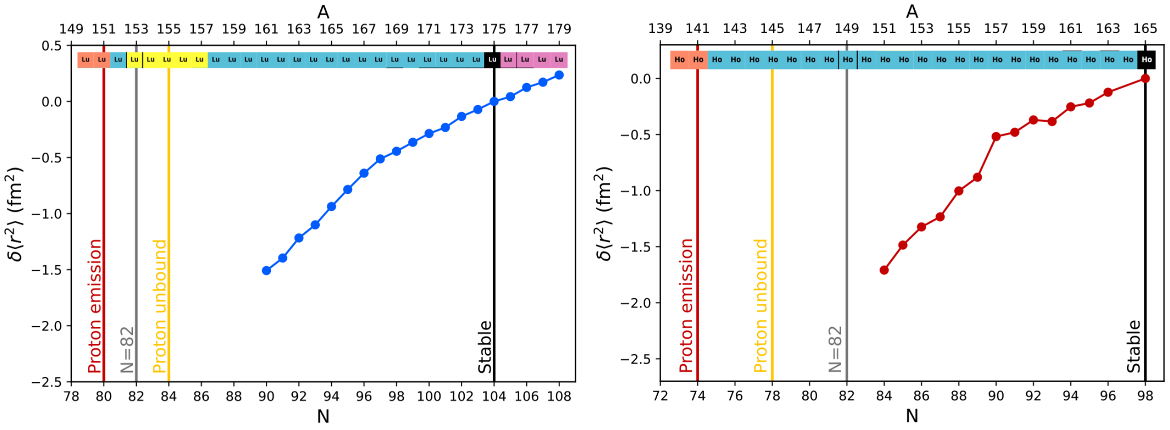

Figure 1: Previous charge-radii measurements of the (left) lutetium isotopes, $^{161-178}$Lu [12] and (right) holmium isotopes, $^{152-165}$Ho [13].

(N=78), and towards the proton emitters ^{151}Lu (N=80) and ^{141}Ho (N=74), the evolution of nuclear deformation can be investigated. Additional insight into the stability of the nuclear structure and shell-effects will be gained from these measurements due to the crossing of the $N = 82$ shell closure. Table 1 provides an overview of the isotopes of interest for future laser-spectroscopy studies, alongside the potential new results.

Lu		
Isotope	Half-life	New results
$^{175-161}$Lu	Stable - 77 s	-
^{160}Lu*	36.1 s	I, μ, Q, $\delta\langle r^2\rangle$
^{159}Lu	12.1 s	I, μ, Q, $\delta\langle r^2\rangle$
^{158}Lu	10.6 s	I, μ, Q, $\delta\langle r^2\rangle$
^{157}Lu*	6.8 s	I, μ, Q, $\delta\langle r^2\rangle$
^{156}Lu*	494 ms	I, μ, Q, $\delta\langle r^2\rangle$
^{155}Lu*	68 ms	μ, Q, $\delta\langle r^2\rangle$
^{154}Lu*	1.12 s	I, μ, Q, $\delta\langle r^2\rangle$
^{153}Lu	0.9 s	μ, Q, $\delta\langle r^2\rangle$
^{152}Lu	0.7 s	I, μ, Q, $\delta\langle r^2\rangle$
^{151}Lu	80.6 ms	μ, Q, $\delta\langle r^2\rangle$

Ho		
Isotope	Half-life	New results
$^{166-152}$Ho	Stable - 161.8 s	-
^{151}Ho*	35.2 s	I, μ, Q, $\delta\langle r^2\rangle$
^{150}Ho*	72 s	I, μ, Q, $\delta\langle r^2\rangle$
^{149}Ho*	21.1 s	I, μ, Q, $\delta\langle r^2\rangle$
^{148}Ho*	2.2 s	I, μ, Q, $\delta\langle r^2\rangle$
^{147}Ho	5.8 s	I, μ, Q, $\delta\langle r^2\rangle$
^{146}Ho	3.32 s	I, μ, Q, $\delta\langle r^2\rangle$
^{145}Ho	2.4 s	I, μ, Q, $\delta\langle r^2\rangle$
^{144}Ho	0.7 s	I, μ, Q, $\delta\langle r^2\rangle$
^{143}Ho*	?	I, μ, Q, $\delta\langle r^2\rangle$
^{142}Ho	0.4 s	I, μ, Q, $\delta\langle r^2\rangle$
^{141}Ho	4.1 ms	I, μ, Q, $\delta\langle r^2\rangle$

Table 1: Isotopes of interest, half-lives and potential new results. Asterisked isotopes have one or more isomeric states.

2 Experimental Method

This Letter of Intent seeks to use a Ta-foil target coupled to the Laser Ion Source Trap (LIST) to measure the yields of neutron-deficient Lu and Ho isotopes. This will allow us to determine the feasibility of performing in-source laser spectroscopy using the

Perpendicularly-Illuminated Laser Ion Source Trap (PI-LIST) setup, across the proton drip line and towards the proton-emitting ^{151}Lu and ^{141}Ho isotopes.

In-source laser spectroscopy using the resonance ionization laser ion source (RILIS) has proven to be a very powerful spectroscopic technique [14], allowing many successful measurements of the nuclear deformation of exotic isotopes [15, 16], with yields down to 0.1 ion/s [17, 18]. With the lasers probing the atoms directly in the ion source, losses due to transportation (i.e. from ion source to experimental beam line) are removed and the highest possible number of atoms are available to be studied. While the resonance-ionization process greatly enhances the selectivity of the isotope of interest, other ionization processes (e.g. surface ionization) may still occur in the target ion source, producing isobaric contamination that can hinder experimental measurements. To overcome this limitation, the Laser Ion Source and Trap (LIST) apparatus was developed [19]. By geometrically decoupling the region in which the laser ionization occurs from the region where surface ionization takes place, the surface-ionized contamination could be suppressed and pure beams of exotic isotopes could be studied for the first time [19]. However, due to the thermal Doppler broadening of the spectral lines inside the ion source, the resolution of the hyperfine spectra is typically limited to around 3 GHz, limiting the sensitivity to the nuclear quadrupole moment. To improve the resolution of the hyperfine structure, the Perpendicularly Illuminated-Laser Ion Source and Trap (PI-LIST) setup has been recently developed [20]. Based on the LIST device, the laser beam is perpendicularly aligned with the atom beam, leading to a significant reduction of thermal Doppler broadening. As a result, hyperfine-spectra linewidths can be reduced to around 100 MHz [21]. Recent online tests performed on the Ac (Z=89) isotopes at ISOLDE have produced linewidths around 200 MHz [20]. Future laser-spectroscopy studies of Lu and Ho isotopes plan to use the PI-LIST setup to benefit from both the suppression of the large surface-ionized contamination (created when producing lanthanides) and the high resolution of the perpendicular laser geometry. The additional loss factor of 3 when going from LIST to PI-LIST will be considered [20].

For the yield measurements, ionization of the isotope of interest will be via resonance ionization with the LIST. Measurement of the production yields of the resonant ions will be with the suite of detection methods available at ISOLDE. Primarily utilising the ISOLDE Fast Tape Station to measure yields, the ISOLDE Faraday cups will also allow for the total beam current to be measured and a Magnetof detector will provide detection of (time-resolved) single ions.

For the Lu isotopes, two resonance ionization schemes will be tested, see Figure 2(left), to determine the most efficient and sensitive scheme for future studies. The 451.86-nm (blue) resonant excitation step was used in previous laser-spectroscopy measurements, which reached ^{161}Lu [12]. Recently, a more efficient scheme has been developed [22], see Figure 2(left), using a 298.93-nm (UV) step followed by a 888.07-nm (red) transition to an auto-ionising (AI) state. Efficiency measurements determined a 52% ionization efficiency for this UV-red scheme, compared to an efficiency of 37% for the blue-blue scheme [22]. While the most efficient scheme is certainly preferred, it is important

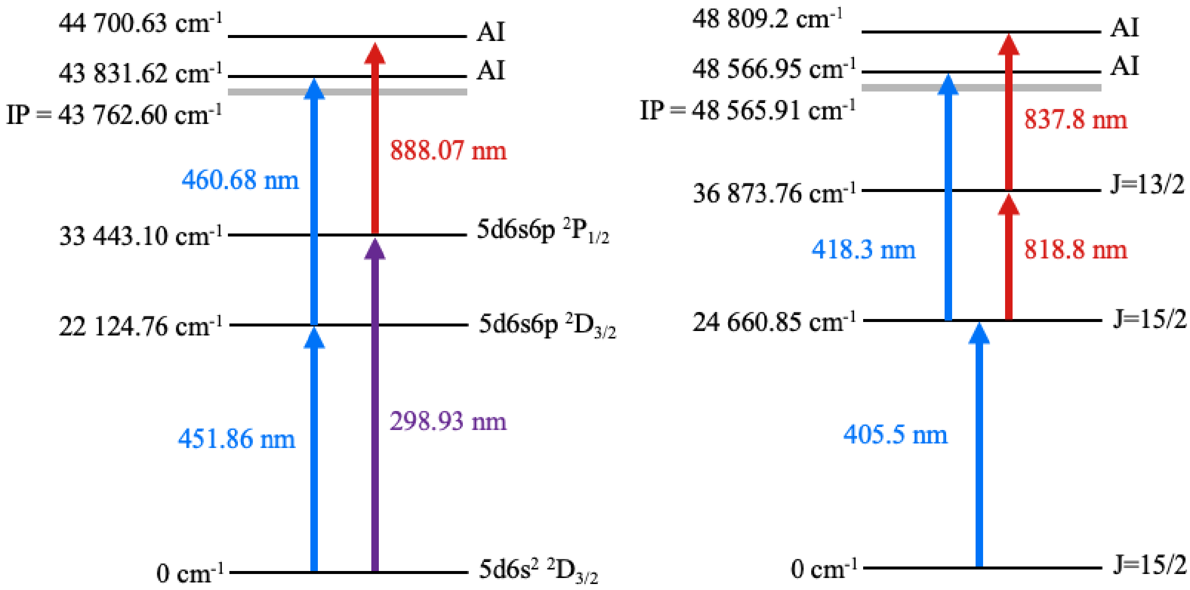

Figure 2: (Left) Resonance ionization schemes for lutetium. The 451.86-nm resonant excitation step was used in previous laser-spectroscopy measurements [12]. Recent ionization scheme developments have found efficient schemes to auto-ionising (AI) states [22]. (Right) Resonance ionization schemes for holmium. A newly-developed two-step scheme [23] will be used for this study, with an increased ionization efficiency of 69% compared to an efficiency of 41% for the previous three-step scheme [24]

that the first step involves an atomic state that has a high degree of sensitivity to the hyperfine parameters (and is thus sensitive to the nuclear observables). As such, the sensitivity of the two transitions to the isotope shift will be investigated, to determine the optimum atomic transition for extraction of the charge radii. In addition to the standard 'narrow-band' laser operation of RILIS, high-resolution laser light can be produced via collaboration with RILIS and CRIS, whereby continuous-wave laser light from the CRIS laser laboratory is used to seed an injection-seeded TiSa system at RILIS. Such a setup has already been successfully demonstrated [25, 26] and will allow the hyperfine structure to be resolved. Investigating the production yields of three Lu isotopes with each resonance ionization scheme will allow us to determine the most appropriate scheme: one that is efficient as well as having good sensitivity to the isotope shifts (and other hyperfine parameters). The chosen scheme will then be used to determine the yields of the rest of the neutron-deficient isotopes.

For the Ho isotopes, a new two-step (blue-blue) scheme has also recently been developed [23], see Figure 2(right). With an increased ionization efficiency of 69%, in comparison to the previous three-step (blue-red-red) scheme with an efficiency of 41% [24], we will use this scheme to determine the production yields of the neutron-deficient Ho isotopes.

3 Beam Time Request

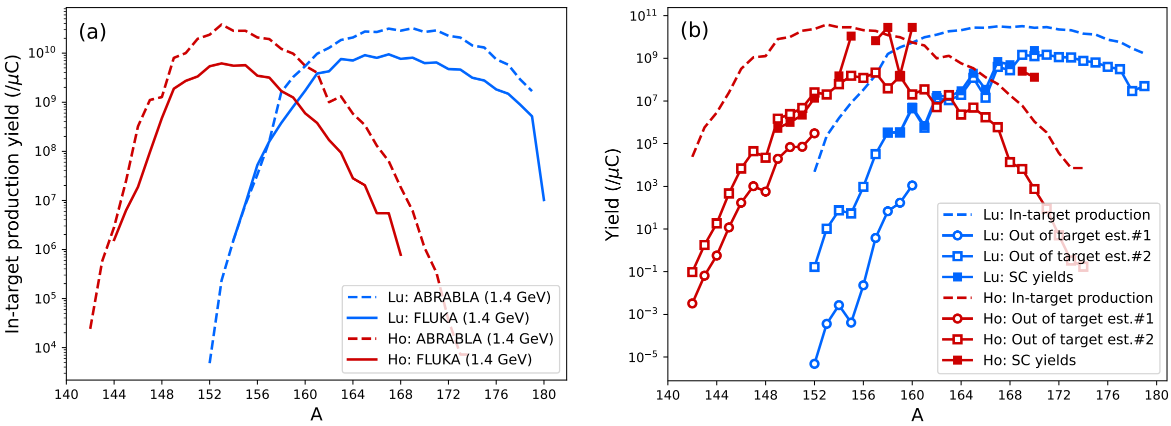

Figure 3: (a) In-target production yield simulations using ABRABLA (dashed lines) and FLUKA (solid line) with 1.4 GeV protons on a Ta-foil target. (b) In-target production yield simulations (lines) using ABRABLA with 1.4 GeV protons and from-target production yield estimates (empty markers) for Lu (blue) and Ho (red) isotopes, using a Ta-foil target. Production yield estimates are given for two approaches (circles and squares). Historic yields (full markers) from the SC with 0.6 GeV protons are also shown.

There are currently no known production yields for the Lu and Ho isotopes using 1.4 GeV protons from the PSB. Figure 3(a) shows in-target production yield simulations using ABRABLA (dashed lines) [27, 28] and FLUKA (solid line) [29] with 1.4 GeV protons on a Ta-foil target. Displaying different relative behaviours as the isotopes become more neutron-deficient, this could result in an order of magnitude difference for the isotopes of interest. Figure 3(b) presents historic production yields (full markers) from the SC with 0.6 GeV protons, alongside simulations (dashed lines) for in-target production rates (ABRABLA simulations for Ta foil and 1.4 GeV beam energy) and out-of-target production estimates (empty markers) using two different approaches. Estimate #1[1] and #2[2] both use the in-target production ABRABLA simulations with 1.4 GeV protons on a Ta-foil target. Estimate #1 interpolates the release fraction parameters between nearby elements and applies this to the in-target production to estimate the out-of-target production yields. The resulting estimates for Lu (blue circles) assume a release behaviour similar to promethium. Similarly, the resulting estimates for Ho (red circles) assume a behaviour between dysprosium and erbium. Estimate #2 employs a different approach, extrapolating the release fraction parameters from the SC yields with 0.6 GeV protons to the in-target production simulations with 1.4 GeV protons, in order to calculate the out-of-target production estimates for Lu (blue squares) and Ho (red squares). Given the large variation in estimated yields of the two different approaches, in addition to the dependence on the simulation code used, yields measurements of the Lu and Ho isotopes are necessary to benchmark the models and provide more accurate

[1]Kindly provided by J. Wessolek (CERN/Uni. of Manchester) for the ISOLDE yields team
[2]Kindly provided by T. E. Cocolios (KU Leuven)

estimates for the very neutron-deficient species.

We request a total of 8 shifts to perform resonance ionization scheme tests and yield measurements of the Lu and Ho isotopes. The shift request is as follows:

- 2 shifts to determine the best resonance ionization scheme for lutetium
- 3 shifts to perform yield measurements for 6 isotopes of lutetium (0.5 shift/isotope)
- 3 shifts to perform yield measurements for 6 isotopes of holmium (0.5 shift/isotope)

With this essential information, we aim to propose in-source laser spectroscopy of neutron-deficient Lu isotopes, followed by neutron-deficient Ho isotopes. Utilising the PI-LIST setup, we hope to perform the first measurements of the charge radii of the proton-emitting ^{151}Lu.

We note that this Letter perfectly complements the ongoing investigation into the yields of the lanthanide elements with a Ta-foil target and the LIST performed by ISOLDE's RILIS and target-ion source teams [30]. It provides a good opportunity to test these predictions (estimate #1) based on previous lanthanide yield measurements [31] and benchmark these to improve future predictions. We hope that such complementary measurements will also allow for ease of scheduling as the demand for the LIST increases.

Summary of requested shifts: 8 shifts of radioactive beam

References

[1] K.M. Lynch et al., Tech. rep., CERN-INTC-2023-016, INTC-P-657, CERN, Geneva (2023), `https://cds.cern.ch/record/2845948`

[2] B. Cheal, L. Rodriguez, S. Bai, K. Blaum, P. Campbell, R. Garcia Ruiz, P. Imgram, K. Koenig, T. Lellinger, P. Muller et al., Tech. rep., CERN-INTC-2022-041, INTC-I-245, CERN, Geneva (2022), `https://cds.cern.ch/record/2834596`

[3] L.G. Sarmiento, T. Roger, J. Giovinazzo, B.A. Brown, B. Blank, D. Rudolph, A. Kankainen, H. Alvarez-Pol, A.A. Raj, P. Ascher et al., Nature Communications **14**, 5961 (2023)

[4] J. Cerny, J.E. Esterl, R.A. Gough, R.G. Sextro, Physics Letters B **33**, 284 (1970)

[5] B. Blank, M.J.G. Borge, Progress in Particle and Nuclear Physics **60**, 403 (2008)

[6] P. Woods, Nature **381**, 25 (1996)

[7] C.N. Davids, P.J. Woods, D. Seweryniak, A.A. Sonzogni, J.C. Batchelder, C.R. Bingham, T. Davinson, D.J. Henderson, R.J. Irvine, G.L. Poli et al., Phys. Rev. Lett. **80**, 1849 (1998)

[8] L.S. Ferreira, E. Maglione, Phys. Rev. Lett. **86**, 1721 (2001)

[9] A.P. Robinson, C.N. Davids, G. Mukherjee, D. Seweryniak, S. Sinha, P. Wilt, P.J. Woods, Phys. Rev. C **68**, 054301 (2003)

[10] L.S. Ferreira, E. Maglione, Phys. Rev. C **61**, 021304 (2000)

[11] D. Seweryniak, P.J. Woods, J.J. Ressler, C.N. Davids, A. Heinz, A.A. Sonzogni, J. Uusitalo, W.B. Walters, J.A. Caggiano, M.P. Carpenter et al., Phys. Rev. Lett. **86**, 1458 (2001)

[12] U. Georg, W. Borchers, M. Keim, A. Klein, P. Lievens, R. Neugart, M. Neuroth, P.M. Rao, C. Schulz, et al., The European Physical Journal A - Hadrons and Nuclei **3**, 225 (1998)

[13] G. Alkhazov, A. Barzakh, I. Chubukov, V. Denisov, V. Ivanov, N. Buyanov, V. Fedoseyev, V. Letokhov, V. Mishin, S. Sekatsky, Nuclear Physics A **504**, 549 (1989)

[14] V. Fedosseev, K. Chrysalidis, T.D. Goodacre, B. Marsh, S. Rothe, C. Seiffert, K. Wendt, J. Phys. G: Nucl. Part. Phys **44**, 084006 (2017)

[15] B.A. Marsh, T. Day Goodacre, S. Sels, Y. Tsunoda, B. Andel, A.N. Andreyev, N.A. Althubiti, D. Atanasov, A.E. Barzakh, J. Billowes et al., Nature Physics **14**, 1163 (2018)

[16] J.G. Cubiss, A.N. Andreyev, A.E. Barzakh, P. Van Duppen, S. Hilaire, S. Péru, S. Goriely, M. Al Monthery, N.A. Althubiti, B. Andel et al., Physical Review Letters **131**, 202501 (2023)

[17] T.E. Cocolios, W. Dexters, M.D. Seliverstov, A.N. Andreyev, S. Antalic, A.E. Barzakh, B. Bastin, J. Büscher, I.G. Darby, D.V. Fedorov et al., Phys. Rev. Lett. **106**, 052503 (2011)

[18] M. Seliverstov, T. Cocolios, W. Dexters, A. Andreyev, S. Antalic, A. Barzakh, B. Bastin, J. Büscher, I. Darby, D. Fedorov et al., Physics Letters B **719**, 362 (2013)

[19] D.A. Fink, T.E. Cocolios, A.N. Andreyev, S. Antalic, A.E. Barzakh, B. Bastin, D.V. Fedorov, V.N. Fedosseev, K.T. Flanagan, L. Ghys et al., Phys. Rev. X **5**, 011018 (2015)

[20] R. Heinke, M. Au, C. Bernerd, K. Chrysalidis, T.E. Cocolios, V.N. Fedosseev, I. Hendriks, A.A.H. Jaradat, M. Kaja, T. Kieck et al., Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **541**, 8 (2023)

[21] T. Kron, R. Beerwerth, S. Raeder, S. Fritzsche, R. Heinke, P. Schönberg, M. Trümper, K. Wendt, Phys. Rev. C **102**, 034307 (2020)

[22] V.M. Gadelshin, R. Heinke, T. Kieck, T. Kron, P. Naubereit, F. Rösch, T. Stora, D. Studer, K. Wendt, Radiochimica Acta **107**, 653 (2019)

[23] T. Kieck, H. Dorrer, C.E. Düllmann, V. Gadelshin, F. Schneider, K. Wendt, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **945**, 162602 (2019)

[24] T. Kieck, S. Biebricher, C.E. Düllmann, K. Wendt, Review of Scientific Instruments **90**, 053304 (2019)

[25] K. Chrysalidis, S.G. Wilkins, R. Heinke, A. Koszorus, R. De Groote, V.N. Fedosseev, B. Marsh, S. Rothe, R. Garcia Ruiz, D. Studer et al., Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **463**, 476 (2020)

[26] R. Heinke et al., Tech. rep., CERN-INTC-2020-029, INTC-P-556, CERN, Geneva (2020), `https://cds.cern.ch/record/2717945`

[27] *The ISOLDE Yield Database, Version 0.2*, https://cern.ch/isolde-yields (2021), [Online; accessed 09.04.2024]

[28] J. Ballof, J. Ramos, A. Molander, K. Johnston, S. Rothe, T. Stora, C. Düllman, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **463**, 211 (2020)

[29] C. Duchemin, *Private communication* (2024)

[30] K. Chrysalidis, R. Heinke, M. Au, C. Bernerd, A.A.H. Jaradat, U. Köster, R. Mancheva, B. Marsh, E. Reis, M. Schütt et al., Tech. rep., CERN-INTC-2022-042, INTC-I-246, CERN, Geneva (2022), `https://cds.cern.ch/record/2834598`

[31] K. Chrysalidis, R. Heinke, M. Au, C. Bernerd, A.A. Jaradat, U. Köster, R. Mancheva, B. Marsh, E. Reis, M. Schütt et al., Tech. rep., CERN-INTC-2023-065, INTC-I-263, CERN, Geneva (2023), https://cds.cern.ch/record/2872420

4 Details for the Technical Advisory Committee

4.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: *RILIS, CRIS high-resolution laser*

  ☒ To be used without any modification

4.2 Beam production

- Requested beams:
  - Neutron-deficient Lu isotopes, between ^{160}Lu and ^{151}Lu
  - Neutron-deficient Ho isotopes, between ^{151}Ho and ^{141}Ho
- Full reference of yield information: *ISOLDE Yield Database [27, 28], J. Wessolek (CERN/Uni. of Manchester) for the ISOLDE yields team and T. E. Cocolios (KU Leuven)*
- Target - ion source combination: *Ta-foil target with LIST*
- RILIS? *Yes + CRIS high-resolution laser light, as required*

  ☒ Special requirements: *LIST, laser scanning, laser shutter access, CRIS high-resolution laser light*)
- Additional features? *No*
- Expected contaminants: *TBD*
- Acceptable level of contaminants: *TBD*
- Can the experiment accept molecular beams? *No*
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? *Very good synergy with lanthanide yield measurements [30, 31] and laser spectroscopy of neutron-deficient Tm isotopes [2], both using Ta-foil target with the LIST.*

4.3 Shift breakdown

Summary of requested shifts:

With protons	Requested shifts
Determination of resonance ionization scheme for Lu	2
Yield measurements of 6 Lu isotopes, from ^{160}Lu towards ^{151}Lu	3
Yield measurements of 6 Ho isotopes, from ^{151}Lu towards ^{141}Lu	3

4.4 Health, Safety and Environmental aspects

4.4.1 Radiation Protection

- Radioactive sources required? *No*
- Collections? *No*