EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

# Laser spectroscopy of neutron-deficient thulium isotopes

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**Abstract:** We wish to obtain updated yields in the neutron-deficient rare earth region and in particular neutron-deficient isotopes of thulium down to $^{147}$Tm. This is with a view to proposing laser spectroscopic studies at COLLAPS, ultimately leading to a measurement of the mean-square charge radius of a proton emitter for the first time. The beam time requested will allow the use of a Ta foil target with the PSB and newly established RILIS scheme to be explored, in addition to the potential use of a new target container design.

**Requested shifts:** 6 shifts of radioactive beam and 2 shifts of stable beam.

# 1 Physics Motivation

High-resolution collinear laser spectroscopy is an indispensable tool in the study of ground and isomeric state nuclear structure. Model independent access is provided to the nuclear magnetic dipole and electric quadrupole moments, the nuclear spin and the mean-square charge radius. It therefore constitutes a unique probe of single particle and collective phenomena. Of much recent theoretical attention have been attempts to reproduce trends and features of the mean-square charge radius across the nuclear chart simultaneously, through ongoing developments in Density Functional Theory (DFT) [1, 2, 3]. For example, around the calcium region [4, 5, 6], nickel region [7, 8], and tin region [9, 10]. The ability to reproduce phenomena such as the ubiquitous odd–even staggering along isotope chains, or upward kinks seen at shell closures have been used as a basis to assess and develop various functionals of a Skyrme and Fayans type. Still more recently, these have been applied to isotopes of palladium, marking the first detailed analysis of deformed open shell nuclei [11]. We now propose to extend these studies into the neutron-deficient rare earth region of the nuclear chart.

Nuclear existence is limited on the neutron-deficient side by the proton drip line, but how the structure of the nucleus changes as this is approached is one of the perennial questions of nuclear physics research. While the existence of proton emission as a decay mode is well established, the properties of the nuclear state as this happens is not so clear. Laser spectroscopy has yet to be performed on a proton emitter. Of primary interest would be the first measurement of the nuclear mean-square charge radius for such an isotope and for those in the neighbourhood. The spatial extent of the proton distribution of such a metastable state would be expected to increase. However, the amount of this increase will depend on the angular momentum content of the orbital occupied by the unstable proton and the proton separation energy. Theoretically, the description of the narrow proton resonance and its radius will require a coupling between DFT and an open-quantum system framework [12]. In the neutron-deficient rare earth region, the isotope $^{147}$Tm is a promising candidate for study at ISOLDE, which has a 15% proton emission branch, while an alternative possibility would be $^{151}$Lu. Elsewhere, the Liverpool group is also working towards a measurement of the proton emitter $^{53m}$Co at JYFL, although this will be challenging.

Previous laser spectroscopic measurements of the ground states down to $^{157}$Tm date from 1988 [13] with $^{153,154}$Tm added in 2000 [14]. These measurements are summarised in table 1. None of the fundamental properties listed above are known below $^{153}$Tm and nuclear spins are assigned only tentatively. Laser spectroscopy will enable these to be established unambiguously. The thulium chain additionally appears one rich in structural change, with the odd–$A$ (even–$N$) isotopes displaying multiple changes in ground state spin. Understanding the systematics of the isomeric states, which are largely unexplored, may also help to theorise the nuclear spins of the isomeric states in $^{146}$Tm [15, 16, 17], without which the proton spectra are hard to interpret. For lutetium, optical measurements only extend as far down as $^{161}$Lu [18] and no such measurements in the wider region extend below the $N = 82$ shell closure. We therefore believe that the thulium isotopes en route to $^{147}$Tm are of interest in themselves.

## 2 Laser Spectroscopic Method

Thulium isotopes can be produced from the HRS target station, with the yield selectively enhanced using RILIS. This choice of the HRS will allow use of ISCOOL to provide bunched beams to the COLLAPS collinear laser spectroscopy setup for high resolution study. Here, the ions are overlapped with a co-propagating laser beam from a continuous wave laser. Acceleration electrodes Doppler tune the effective frequency as seen by the ions over the atomic resonances. The fluorescence photons emitted are detected using four photomultiplier tubes. A gate is applied to the photon signal corresponding to each ion bunch traversing the detection region which suppresses the background by four orders of magnitude. In cases where the study is to be performed on neutral atoms rather than the singly charged ions, the beam is first passed through an alkali vapour cell, and the tuning potential is applied to this chamber. Further details can be found in the review by Neugart *et al.* [19] or some of our recent papers, eg. [20, 21, 22, 23].

As a prerequisite to a full experiment, an optical transition between the atomic fine structure levels must be selected for the study. This is chosen on the basis of spectroscopic efficiency and sensitivity to the nuclear properties to be measured. Ideally a transition within the singly charged ion is preferred so that the spectroscopy may be performed on the ISOLDE radioactive ion beam directly. Otherwise the neutralisation process incurs efficiency losses as the electronic population is spread over several atomic levels other than that which the excitation is taking place from. A distortion of the spectral line shape can also occur due to inelastic processes during neutralisation which can complicate the analysis. In the case of the ion, almost all of the population is expected to reside in the ground state, particularly after $\sim 100\,\mathrm{ms}$ accumulation cycles in ISCOOL. Fortunately, thulium posses several lines from the ionic ground state, in particular the 313.2 nm $J = 4 \rightarrow J = 5$ line to the $31926.820\,\mathrm{cm}^{-1}$ level. This is a strong transition with an Einstein coefficient of $A = 1.2 \times 10^8/\mathrm{s}$. 100% of the decays occur via the same line back to the ground state, allowing the possibility of multiple resonant excitations per atom.

While the spectroscopic efficiency can be determined using the only stable isotope, $^{169}$Tm, the sensitivity of a spectroscopic line to the nuclear mean-square charge radius requires three isotopes (two isotope shifts) to be measured in order to determine the mass and field shift constants [24]. This also applies to the quadrupole moment, since the stable isotope has spin $I = 1/2$. The 589.7 nm and 597.3 nm transitions (of the neutral atom) explored in earlier work [13] are much weaker ($A < 4 \times 10^5/\mathrm{s}$) than the 313.2 nm line above, which is easily accessible using modern frequency doubling cavities coupled to a dye laser. An alternative ionic line would be the 384.9 nm transition from the ground state, which has an $s \rightarrow p$ character. Should an atomic line be found necessary, the most promising candidates may be from the $8771\,\mathrm{cm}^{-1}$ atomic level. This energy corresponds

| $A$ | $I^\pi$ | $\tau_{1/2}$ | $\mu$ ($\mu_N$) | $Q_s$ (b) | $\delta\langle r^2\rangle$ |
|---|---|---|---|---|---|
| 169 | $1/2^+$ | stable | −0.2310(15) | — | 0 |
| 168 | $3^+$ | 93.1 d | +0.226(11) | +3.23(7) | −0.084(4) |
| 167 | $1/2^+$ | 9.25 d | −0.197(2) | — | −0.126(3) |
| 166 | $2^+$ | 7.7 h | +0.092(1) | +2.14(3) | −0.209(3) |
| 166m | $(6^-)$ | 340 ms | ? | ? | ? |
| 165 | $1/2^+$ | 30.06 h | −0.139(2) | — | −0.250(2) |
| 164 | $1^+$ | 2.0 m | +2.37(3) | +0.706(51) | −0.347(6) |
| 164m | $6^-$ | 5.1 m | ? | ? | ? |
| 163 | $1/2^+$ | 1.810 h | −0.082(1) | — | −0.404(2) |
| 162 | $1^-$ | 21.70 m | +0.068(8) | +0.69(3) | −0.537(5) |
| 162m | $5^+$ | 24.3 s | ? | ? | ? |
| 161 | $7/2^+$ | 30.2 m | +2.39(2) | +2.90(7) | −0.632(3) |
| 160 | $1^-$ | 9.4 m | +0.156(18) | +0.582(44) | −0.741(4) |
| 160m | $5^?$ | 74.5 s | ? | ? | ? |
| 159 | $5/2^+$ | 9.13 m | +3.408(34) | +1.93(7) | −0.850(4) |
| 158 | $2^-$ | 3.98 m | +0.042(17) | +0.74(11) | −1.002(7) |
| 158m | $(5^+)$ | ≈20 s | ? | ? | ? |
| 157 | $1/2^+$ | 3.63 m | +0.475(15) | — | −1.093(8) |
| 156 | $2^-$ | 83.8 s | ? | ? | ? |
| 155 | $11/2^-$ | 21.6 s | ? | ? | ? |
| 155m | $1/2^+$ | 45 s | ? | ? | ? |
| 154 | $(2^-)$ | 8.1 s | −1.14(2) | +0.4(9) | −1.486(19) |
| 154m | $9^+$ | 3.30 s | +5.91(5) | −0.2(4) | −1.522(15) |
| 153 | $(11/2^-)$ | 1.48 s | +6.93(11) | +0.5(10) | −1.615(31) |
| 153m | $(1/2^+)$ | 2.5 s | ? | ? | ? |
| 152 | $(2)^-$ | 8.0 s | ? | ? | ? |
| 152m | $(9)^+$ | 5.2 s | ? | ? | ? |
| 151 | $(11/2^-)$ | 4.17 s | ? | ? | ? |
| 151m | $(1/2^+)$ | 6.6 s | ? | ? | ? |
| 150 | $(6^-)$ | 2.20 s | ? | ? | ? |
| 149 | $(11/2^-)$ | 0.9 s | ? | ? | ? |
| 148 | $(10^+)$ | 0.7 s | ? | ? | ? |
| 147 | $11/2^-$ | 0.58 s | ? | ? | ? |

Table 1: Potentially accessible states ($\tau_{1/2} > 0.5$ s) and known properties.

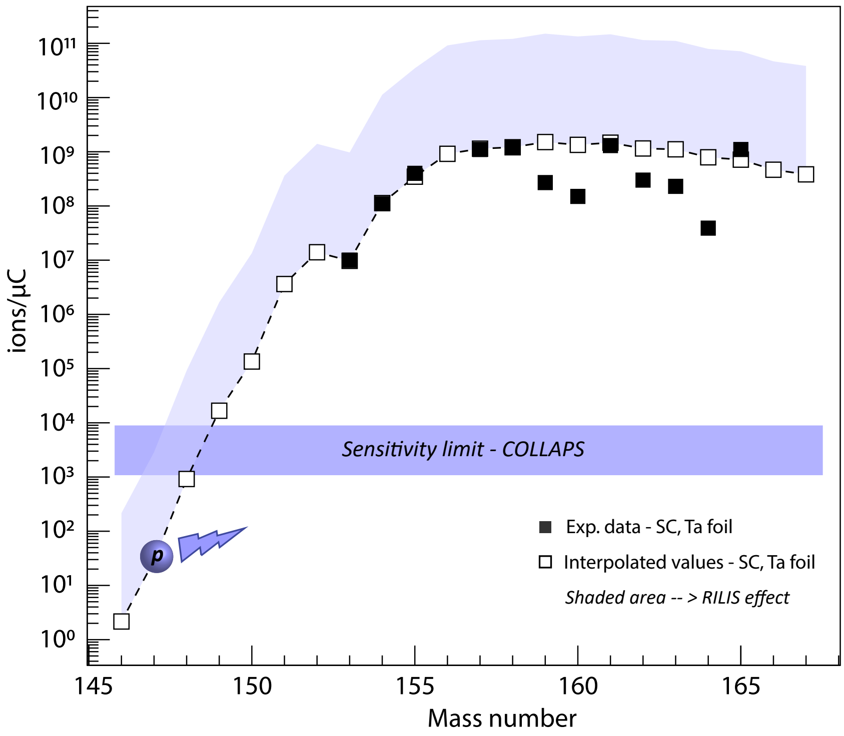


Figure 1: Measured and predicted yields.

approximately to the energy deficit between the ionisation potential of thulium and that of sodium which may be used for charge exchange. The 8771 cm$^{-1}$ level may therefore see a relatively high population among the atomic levels. Strong lines from this level lie in the 313 nm–325 nm range (conveniently close to the 313.2 nm line in the ion) and also in the 379 nm–395 nm range, accessible using a frequency doubled titanium sapphire laser which can be set up in parallel.

We therefore request two shifts of stable beam time and two shifts of radioactive beam time to determine the optimal transition, ahead of a full proposal. This will allow for the spectroscopic efficiency of the ionic transitions to be established, heating of the charge exchange cell to test the efficiency of the atomic transitions, then cooling the charge exchange cell to test sensitivity of the ionic line to the nuclear properties, and potentially reheating to repeat with the atomic line(s). Sufficient atomic physics information will also be gained to allow the hyperfine structures to be calculated for previously measured isotopes and predicted for those yet to be measured, to make the most efficient use of the subsequent beam time.

# 3 Predicted Yields and Beam Development

Yields of thulium isotopes in the ISOLDE database, and indeed those of the neutron-deficient rare earth region in general, pre-date the use of the PS Booster. Figure 1 shows the known yields (using a Ta foil target) together with extrapolated values to the more neutron-deficient isotopes, using in-target production rates and taking the half-lives into consideration. Very recently a highly efficient RILIS scheme has been developed for thulium [25, 26]. A prediction of a significant yield enhancement as a result is included in the figure.

However, as the interpolated yields shown in Fig. 1 rely on SC measurements, they can merely give a first impression. Therefore, we propose with this letter of intend to systematically measure production yields in this region of the nuclear chart with a Ta-foil target and RILIS. As low production yields are expected for the most deficient isotopes, other target-ion source developments such as improved target container designs for better target heating, potentially featuring higher diffusion rates, may be considered. We request 4 shifts for yield measurements (8 isotopes with 0.5 shifts each), which will provide sufficient data to interpolate Tm yields across the entire isotopic chain.

**Summary of requested shifts: We request 2 shifts of stable beam and 6 shifts of radioactive beam.**

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# Appendix

## DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

| Part of the | Availability | Design and manufacturing |
|---|---|---|
| COLLAPS installation | ☒ Existing | ☒ To be used without any modification |
| [Part 1 of experiment/ equipment] | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | ☐ New | ☐ Standard equipment supplied by a manufacturer<br>☐ CERN/collaboration responsible for the design and/or manufacturing |
| [Part 2 of experiment/ equipment] | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | ☐ New | ☐ Standard equipment supplied by a manufacturer<br>☐ CERN/collaboration responsible for the design and/or manufacturing |
| [insert lines if needed] | | |

HAZARDS GENERATED BY THE EXPERIMENT
Hazards named in the document relevant for the fixed COLLAPS installation.