Mapping the lanthanide region of the nuclear chart: Clean beams and high-resolution laser spectroscopy with ISOLDE's PI-LIST ion source

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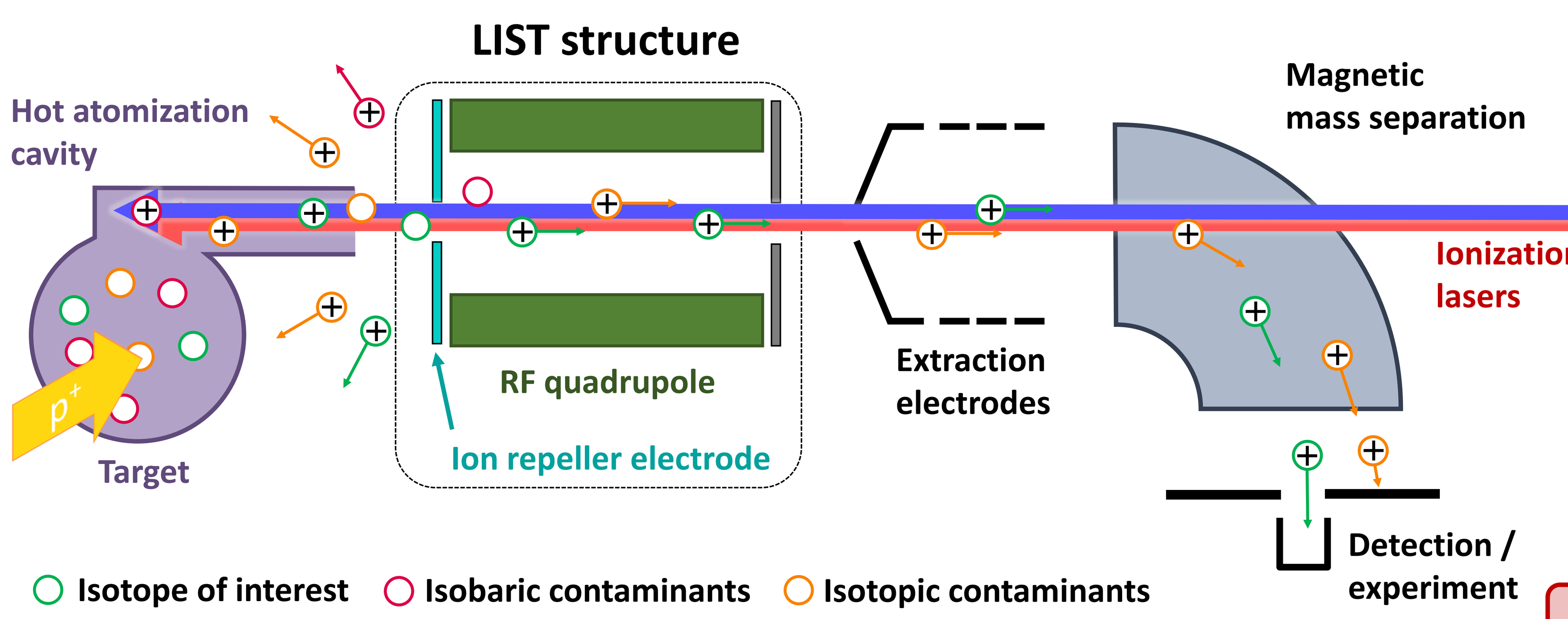
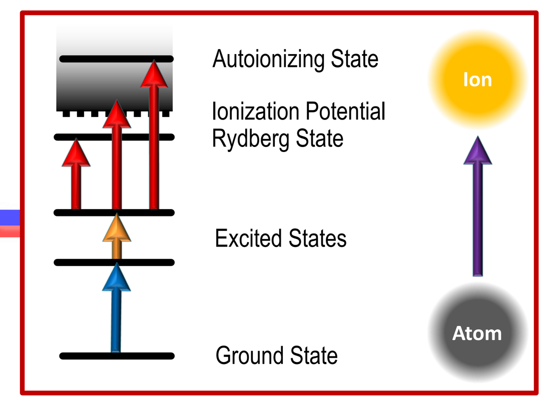
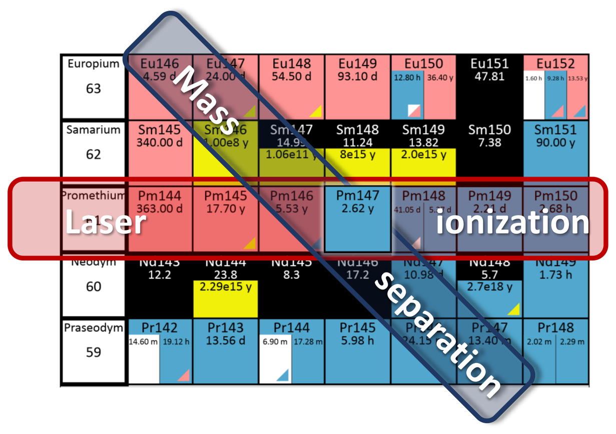
High-Purity Radioactive Ion Beam Production: The Laser Ion Source & Trap **LIST**

Resonance ionization laser ion sources (RILIS) [1] provide high selectivity and efficiency in the production of isotopically enriched **radioactive ion beams (RIBs)** at on-line facilities such as CERN – ISOLDE [2]. Wavelength-tunable lasers are used to address fingerprint-like electronic shell transitions to subsequently excite and detach an electron of the element of choice while leaving other species unaffected.

Additionally, precise measurements of **hyperfine structures and isotope shifts** in electronic transitions enable systematic studies of **nuclear ground state properties** such as spin, magnetic and electric moments, and changes in mean-squared charge radii.

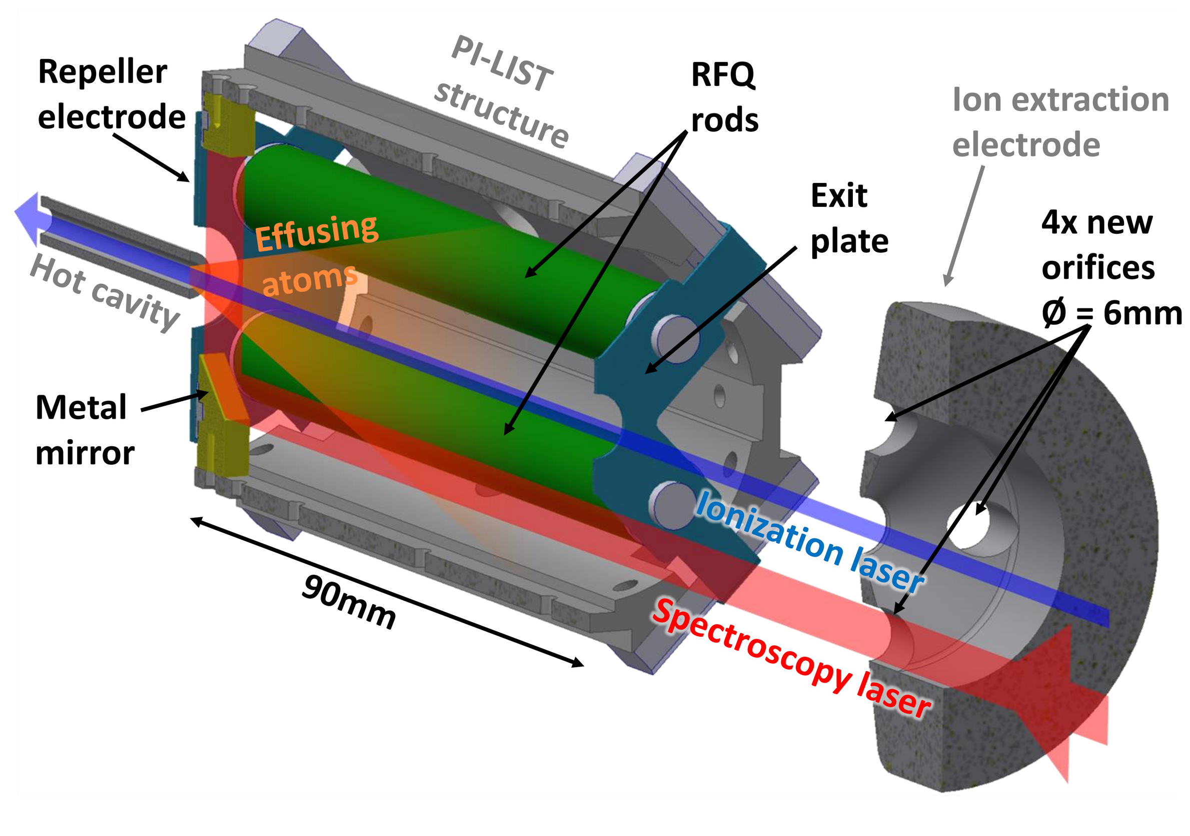






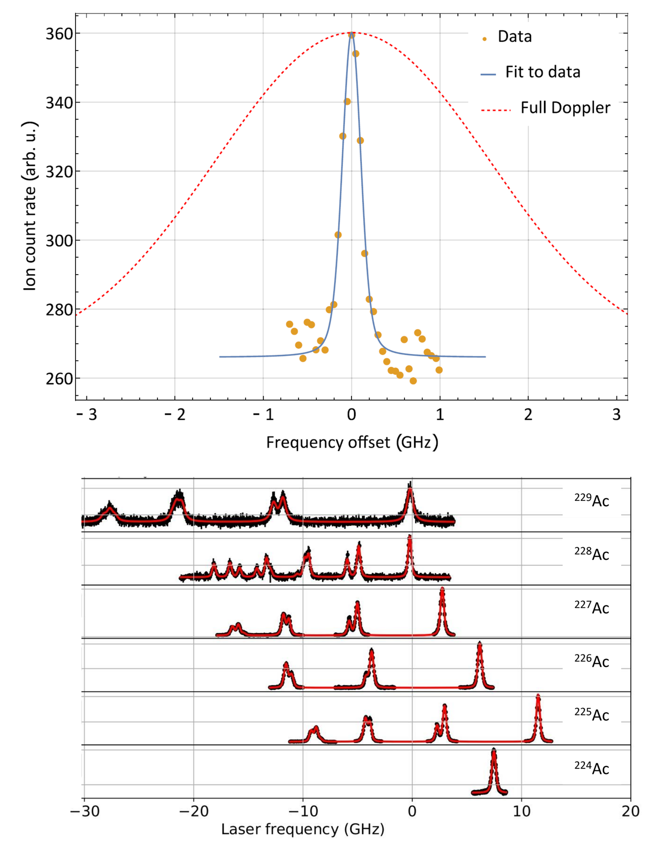
The Laser Ion Source & Trap, *LIST,* at ISOLDE achieves high beam purity by **spatial separation of the laser ionization region and the hot atomization cavity**, where surface ionization processes can cause isobaric contamination. LIST was developed in cooperation between ISOLDE and JGU, and successfully used for the first time for hyperfine structure studies in the neutron-rich polonium region [3, 4].

"Sub-Doppler" in-source laser spectroscopy: **PI-LIST**



CAD model of the PI-LIST as installed at ISOLDE [5]

- Experimental resolution in a hot cavity laser ion source is limited by **Doppler broadening in the order of several GHz**
- **PI-LIST** (Perpendicularly Illuminated Laser Ion Source and Trap) provides **crossed laser / atom beam environment** to address lateral velocity classes
- Successful ISOLDE integration in 2022 [5]
  - Resolution gain of one order of magnitude: **100 – 200MHz**
  - Efficiency in the order of **0.01 %** (Standard RILIS: 10%)
  - Nuclear structure investigation on neutron-rich actinium within **EU network LISA (Laser Ionization and Spectroscopy of Actinides)**
- Versatile ion source with in-situ mode change:
  - *Ion guide*: High efficiency, resembling RILIS
  - *LIST* [3]: Contamination suppression, reduced efficiency
  - *PI-LIST*: Laser spectroscopy and *isomer-pure* RIB production

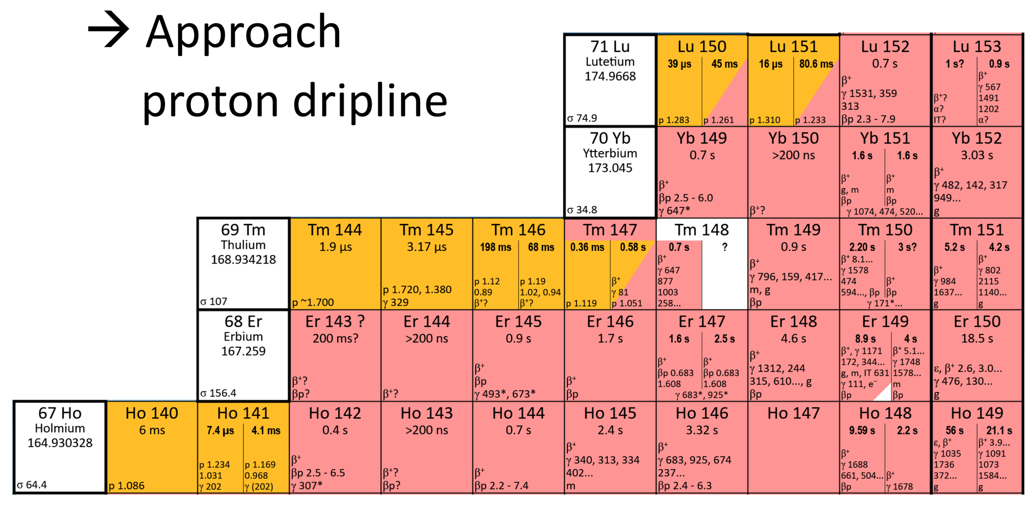


Resolution comparison [5] and actinium laser spectroscopy results

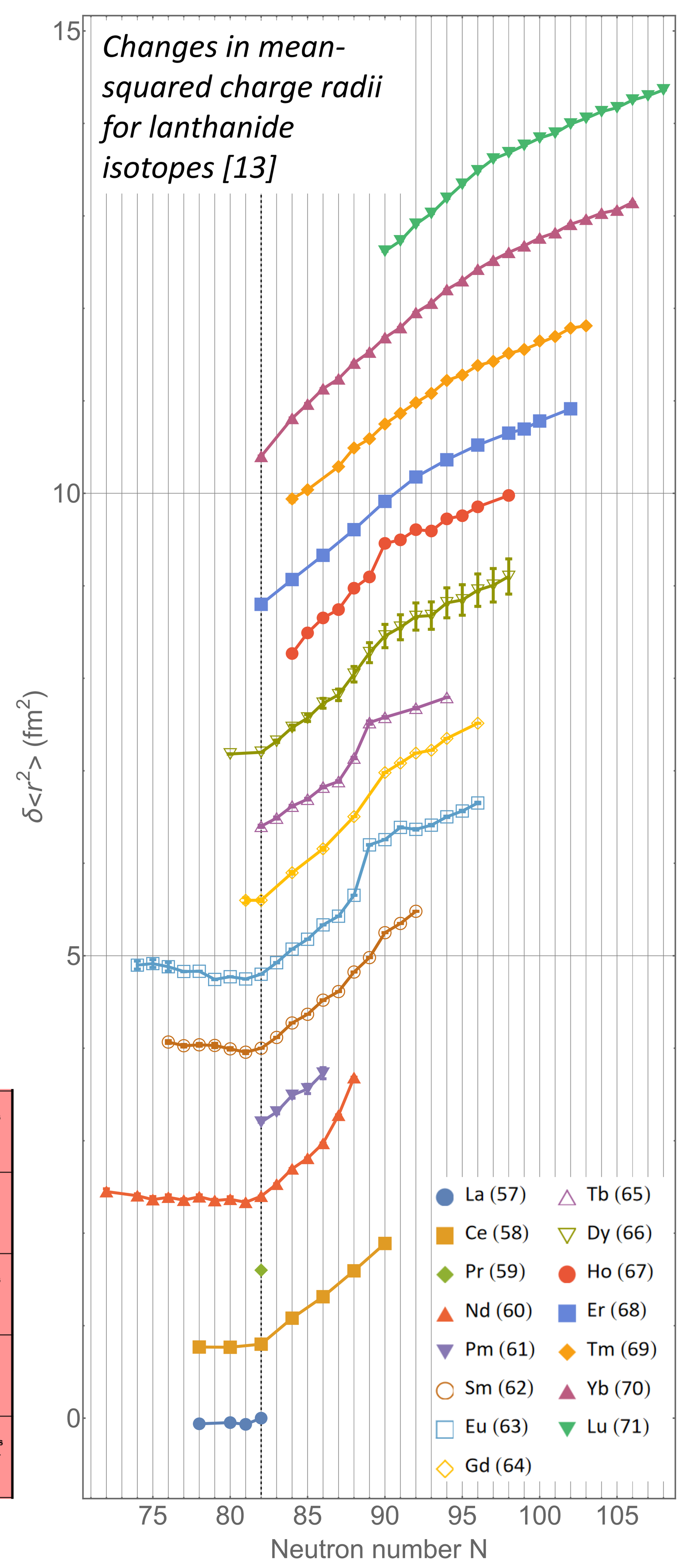
Lanthanides - Physics cases overview

Lanthanides are centered around the Z = 64 (gadolinium) „sub-magic" proton subshell closure, and all isotope chains cross the N = 82 neutron shell gap.

- Mapping of kink in charge radii around N = 88 [6]
  → Lower-Z boundary
- Pronounced odd-even-staggering (OES) for N < 82, vanishing in ^{141m}Sm [7]
  → Investigate Dy isomers
- Transition from spherical to strongly deformed nuclei at N < 75 predicted [8]
- Possible stable octupole deformation (inverted OES) around ^{154}Eu [9]
  → Map out neighbouring chains
- Sparse data on praseodymium [10]
- Proton emitters [11, 12]
  → Approach proton dripline



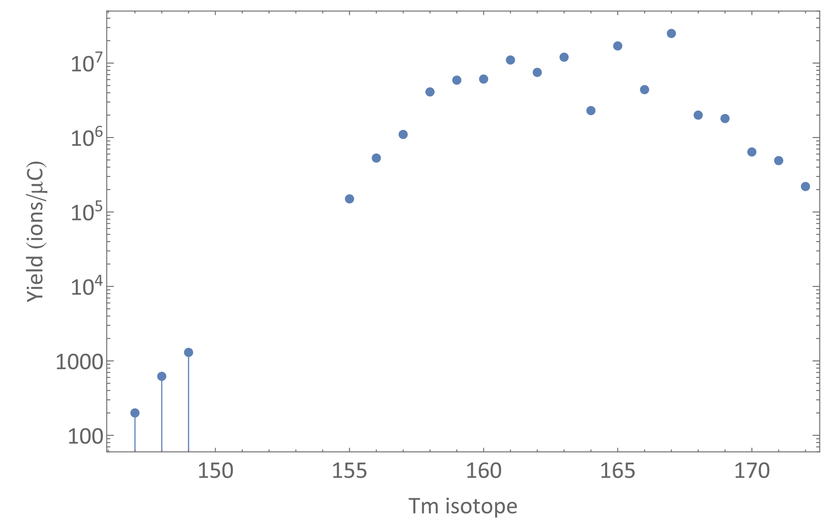
Nuclear chart excerpt showing proton-emitting isotopes



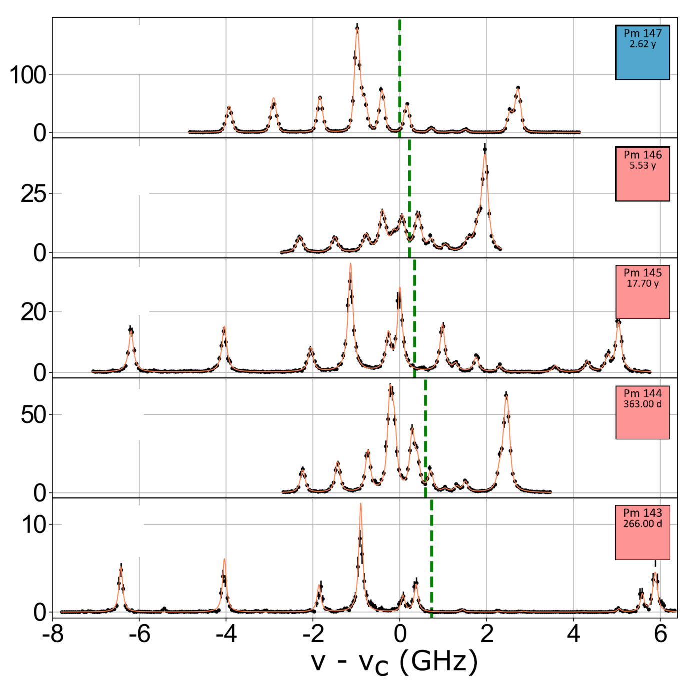
Developments

Campaign on lanthanide yield measurements from a Ta foil target with a (PI-)LIST unit launched this year (LoI 246 [14]).

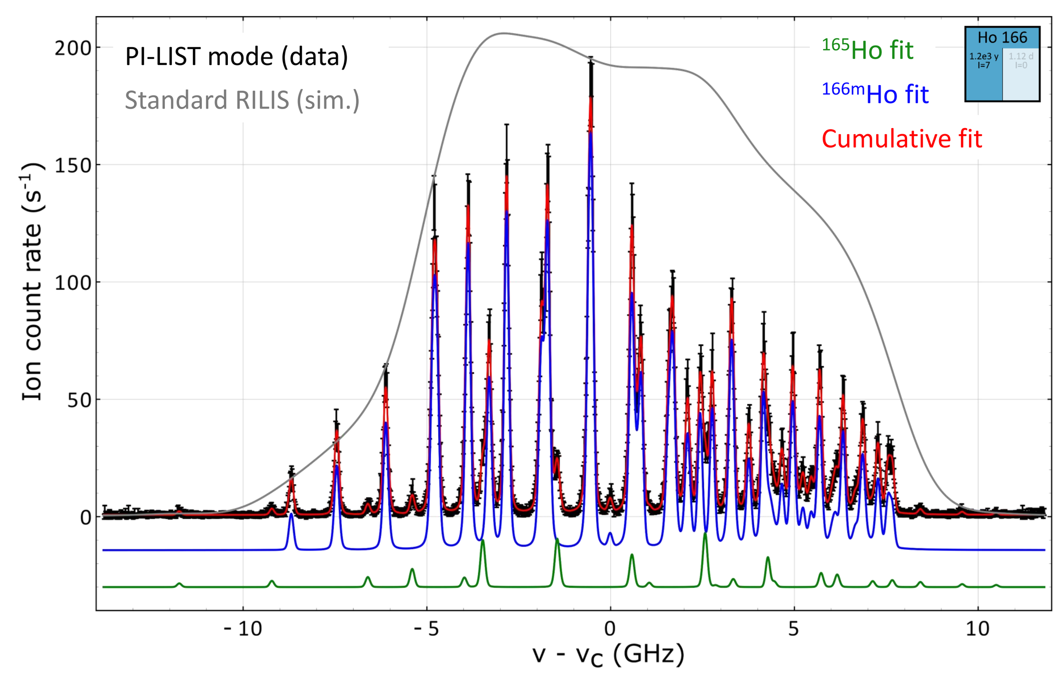
- Preparation for dedicated proposals
- Characterization of purity and sensitivity



Measured thulium yields with LIST (preliminary)



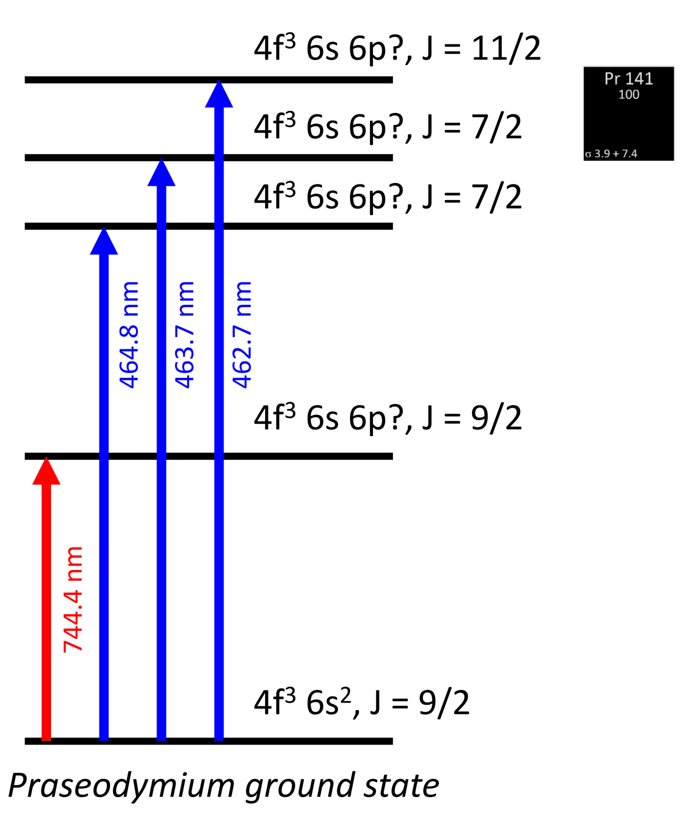
Promethium hyperfine structure [15]



Holmium hyperfine structure [16]

Off-line work on development of efficient ionization schemes, sensitivity to nuclear parameters, and benchmark reference data.

- High efficiency (multiple 10%) RILIS schemes for Tb [17], Dy [18], Ho [19], Tm [20], Yb [21], Lu [22]
- First-time hyperfine structure data on all-radioactive element promethium [15]
- Disentanglement of highly dense spectra (high *I* and *J*) of, e.g., ^{166m}Ho [16]
- Ongoing work on praseodymium in YETS



Praseodymium ground state transitions [23] being investigated

Contact & Refs.

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[1] V. Fedosseev *et al.,* J. Phys. G 44 084006 (2017)
[2] R. Catherall *et al.,* J. Phys. G 44 094002 (2017)
[3] D. Fink *et al.*, NIM B 344, 83-95 (2015)
[4] D. Fink *et al.*, PRX 5, 011018 (2015)
[5] R. Heinke *et al.*, NIM B 541, 8-12 (2023)
[6] R. Casten *et al.*, PRL 47.20 (1981)
[7] V. Letokhov *et al.,* J. Phys. G 18 1177 (1992)
[8] G. Leander *et al.,* Phys. Lett. B 110.1, 17-20 (1982)
[9] G. Alkhazov *et al.,* Z. Physik A 337, 257–259 (1990)
[10] N. Frömmgen *et al.,* Hyperfine Interact 240, 66 (2019)
[11] O. Klepper *et al.,* Z. Physik A 305.2, 125-130 (1982)
[12] S. Hofmann *et al.,* Z. Physik A 305.2, 111-123 (1982)
[13] I. Angeli *et al.,* Atomic and Nuclear Data 99.1 (2013)
[14] K. Chrysalidis *et al.,* INTC-I-246 (2022)
[15] D. Studer *et al.,* Eur. Phys. J. A 56, 69 (2020)
[16] R. Heinke, PhD thesis, JGU Mainz (2019)
[17] V. Gadelshin *et al.,* Front Med. 8:727557 (2021)
[18] D. Studer *et al.*, Hyperfine Interact. 238:1–11 (2017)
[19] T. Kieck *et al.,* NIM A. 945:162602 (2019)
[20] R. Heinke *et al.,* Front Med. 8:712374 (2021)
[21] G. Alkhazov *et al.,* NIM *A*. 306:400–2 (1991)
[22] V. Gadelshin *et al.,* Radiochim Acta. 107:653–61 (2019)
[23] A. Kramida *et al., NIST Atomic Spectra Database* (ver. 5.10) (2023)