In-source Laser Spectroscopy Studies of Neutron-rich Mercury at ISOLDE

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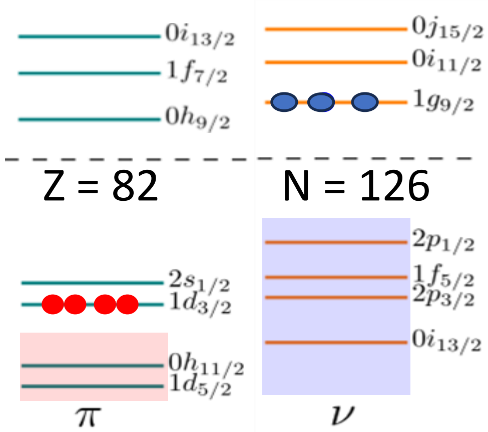
Why Mercury?

Shell closures Z = 82 N = 126

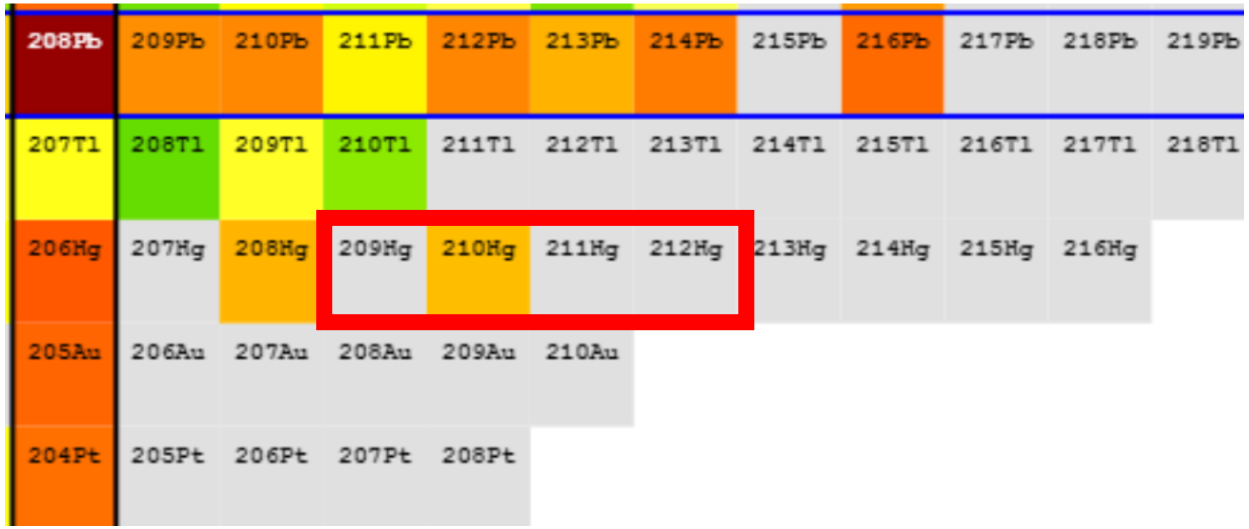


- Nuclear structure
  - Provides a benchmark test for the shell model
  - Lots of nuclear structure physics
- Nuclear astrophysics
  - Nuclear properties are vital for the input into rapid neutron-capture process network calculations

Known energies of first excited states

N = 126

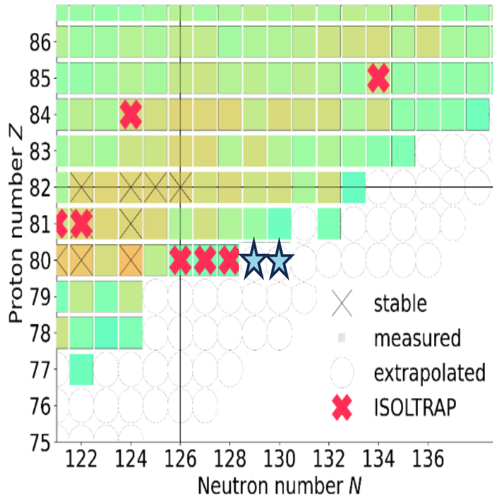
Z = 82

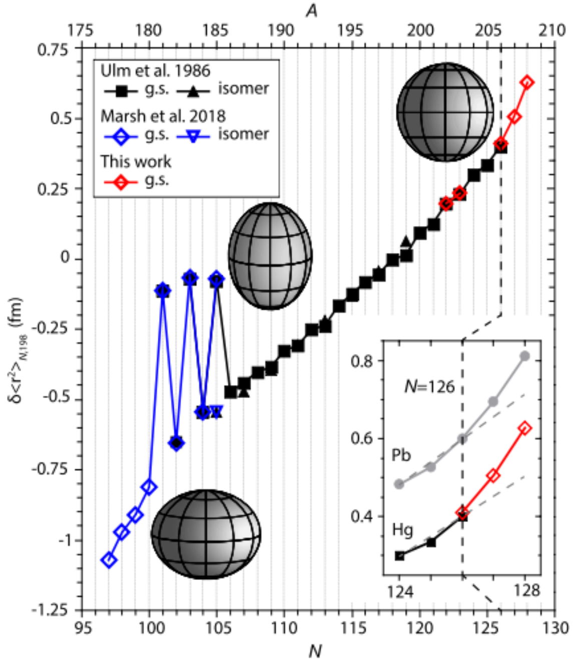


Due to how hard this area of the isotopic chart is to reach experimentally there are very few well-known nuclear properties southeast of ^{208}Pb

Previous measurements

- Charge radii measured up to ^{208}Hg and magnetic dipoles to ^{207}Hg
- Shell model calculations up to ^{211}Hg by S. Sharma et al., arXiv:2309.07903 (2023). Who have agreed to do dedicated calculations for this data set
- Masses have been measured up to ^{208}Hg – masses beyond this are extrapolated from systematic trends causing large uncertainties

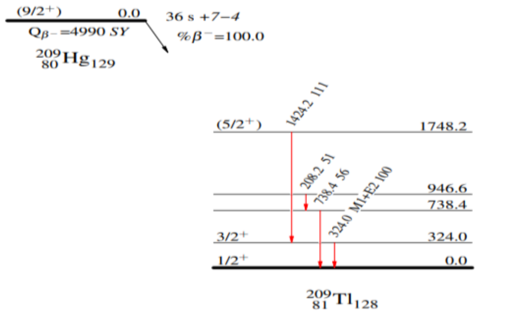




Half-life measurements $T_{\frac{1}{2}}$

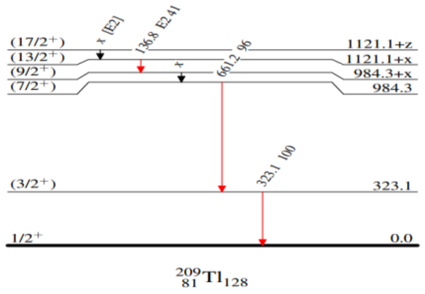
	Lanzhou	GSI	ISOLDE
^{208}Hg	41^{+5}_{-4} min [1]	132.2 ± 50.0 s [3]	135 ± 10 s [4]
^{209}Hg	35^{+9}_{-6} s [2]	6.3 ± 1.1 s [3]	
^{210}Hg			

[1] L. Zhang *et al.*, CPL **14,** 507 (1997); [2] Zhang Li *et al.*, PRC **58**, 156 (1998);
[3] R. Caballero-Folch *et al.*, PRC **95**, 064322 (2017); [4] R. J. Carroll *et al*. PRL **125**, 192501 (2020).



Lanzhou, decay

Zhang Li *et al.*, PRC **58**, 156 (1998)



GSI, isomer

N. Al-Dahan *et al.*, PRC **80**, 061302(R) (2009)


PHYSICAL REVIEW LETTERS **125,** 192501 (2020)

Competition between Allowed and First-Forbidden β Decay: The Case of ^{208}Hg → ^{208}Tl

R. J. Carroll, Zs. Podolyák, T. Berry, H. Grawe, T. Alexander, A. N. Andreyev, S. Ansari, M. J. G. Borge, M. Brunet, J. R. Creswell, L. M. Fraile, C. Fahlander, H. O. U. Fynbo, E. R. Gamba, W. Gelletly, R.-B. Gerst, …

Motivation for further measurements

Continuation of the campaign to map ground and isomeric state properties across the Pb region

Charge radii measurements help probe nucleon-nucleon interactions

Further charge radii points after the N = 126 kink

Magnetic moments provide direct information on single particle configurations of valence nucleons

Shell model predictions across the region need testing

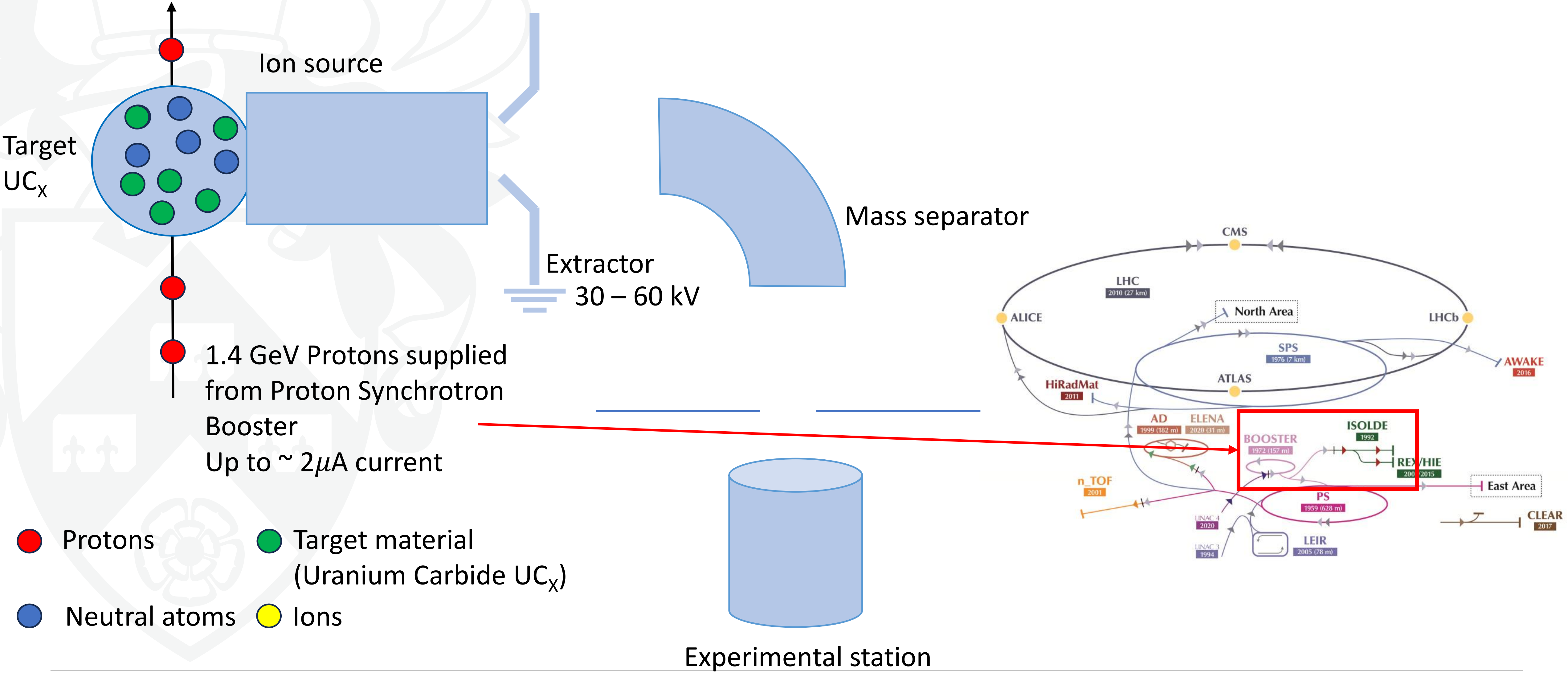
- Magnetic moments provide a powerful testing tool
- Effective interactions used need data to be modified

Shell-model study on spectroscopic properties in the region "south" of ^{208}Pb

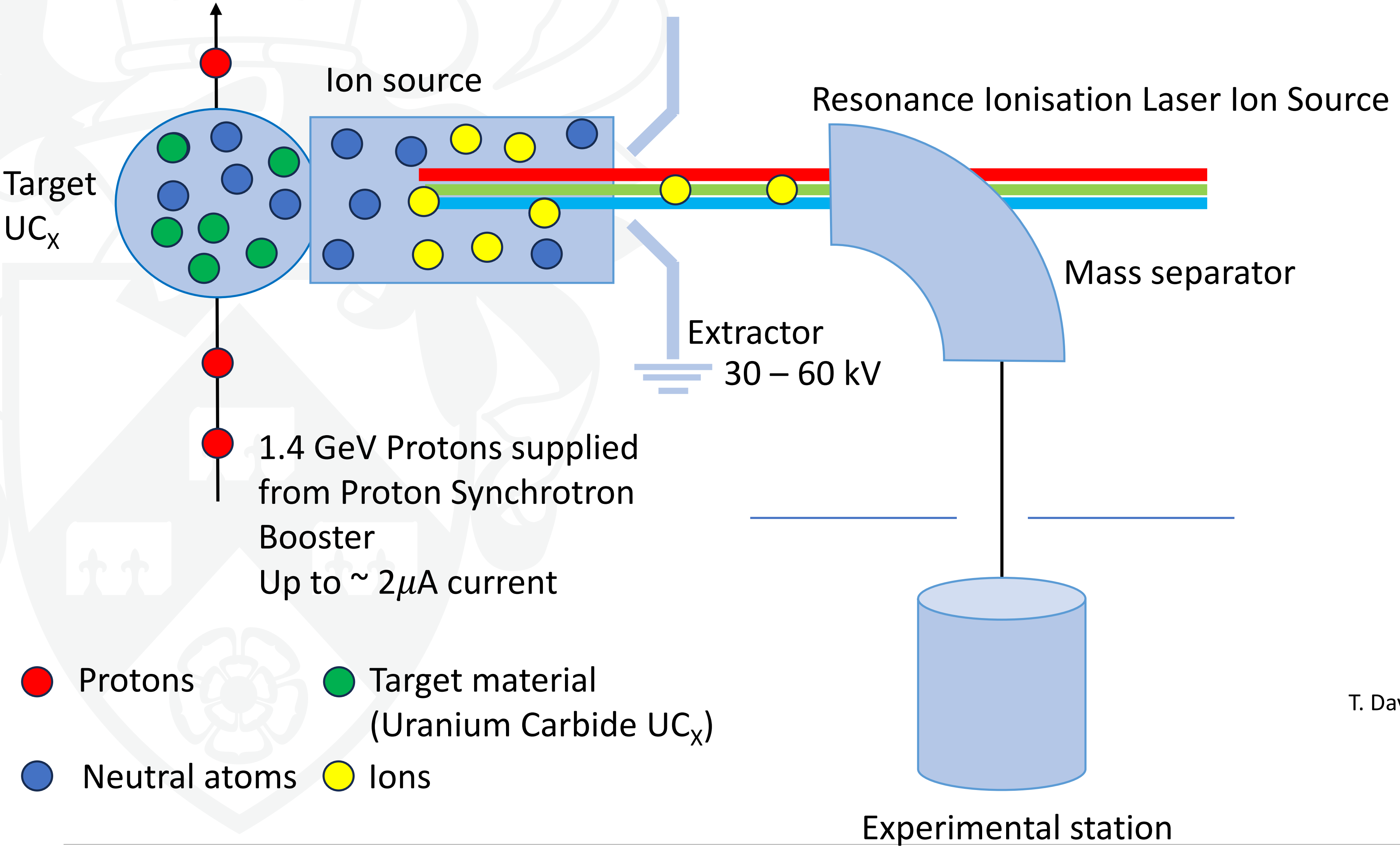
Cenxi Yuan,[1,*] Menglan Liu,[1] Noritaka Shimizu,[2] Zs. Podolyák,[3] Toshio Suzuki,[4,5] Takaharu Otsuka,[6,7,8,9] and Zhong Liu[10,11]

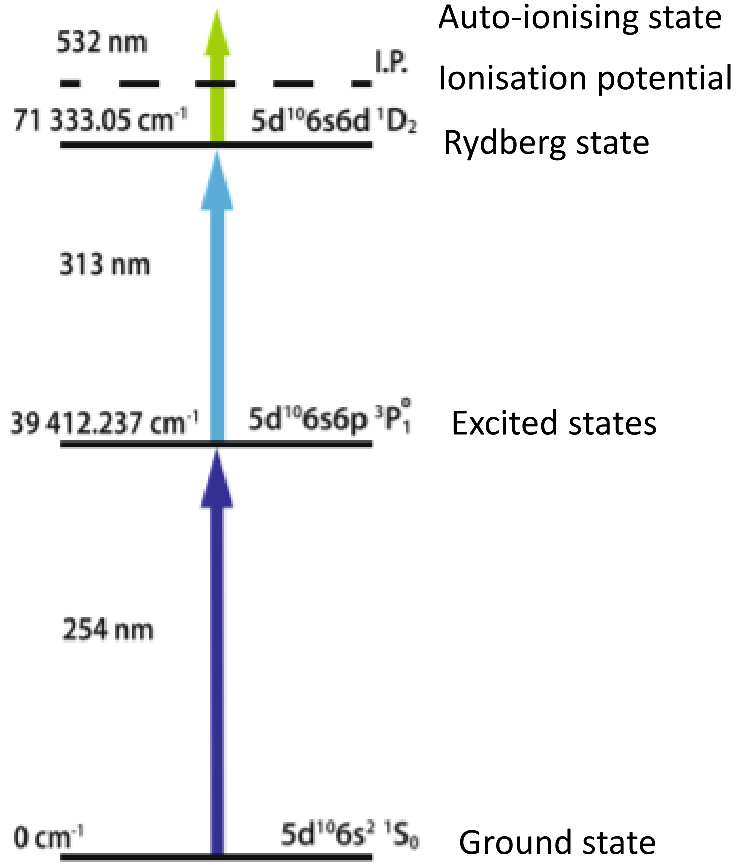
Nothing is known!

ISOLDE & Radioactive Ion Beam Production



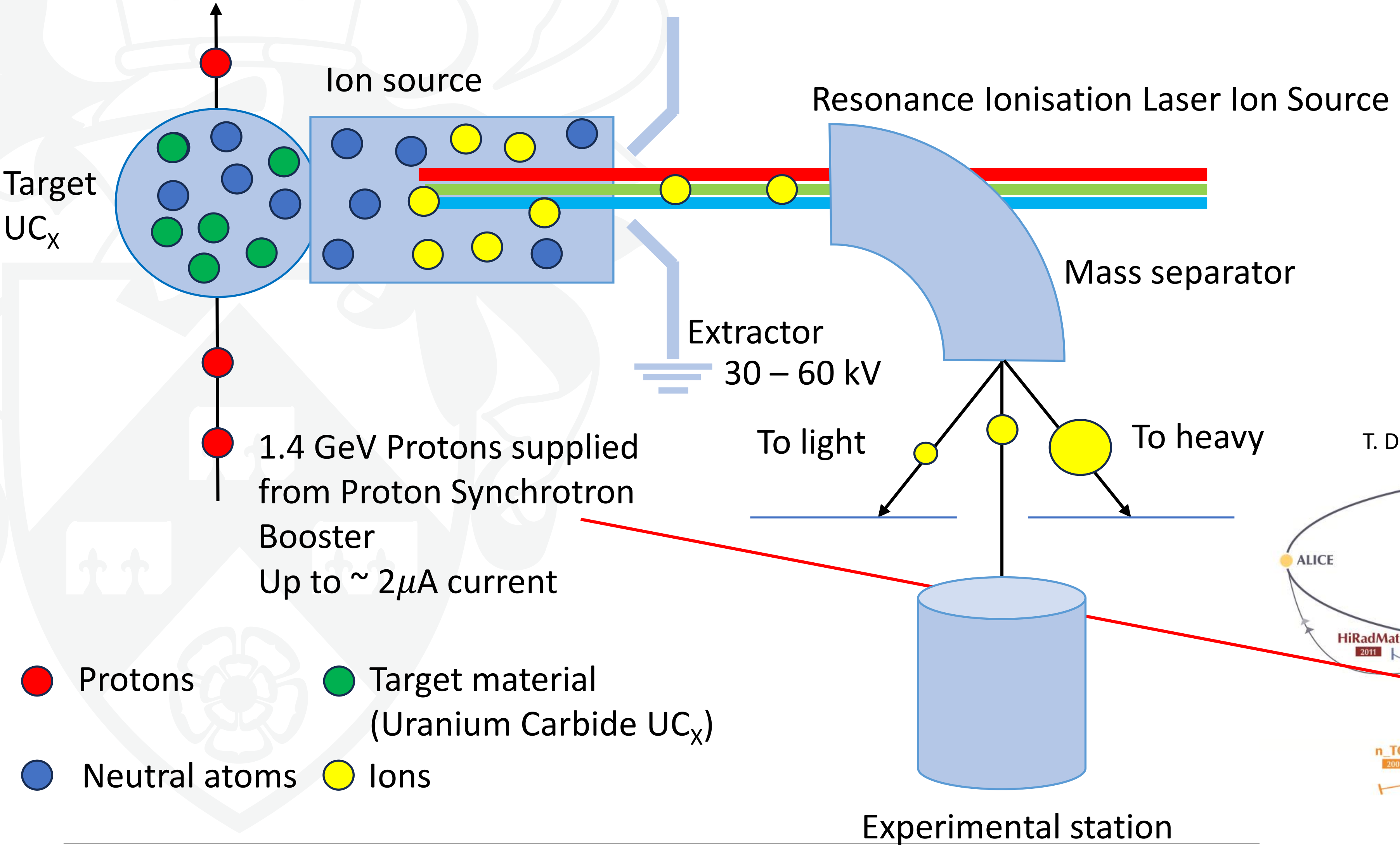
ISOLDE & Radioactive Ion Beam Production

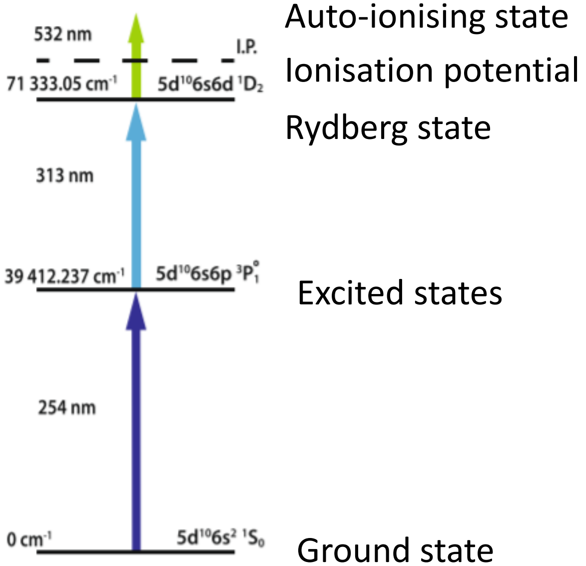




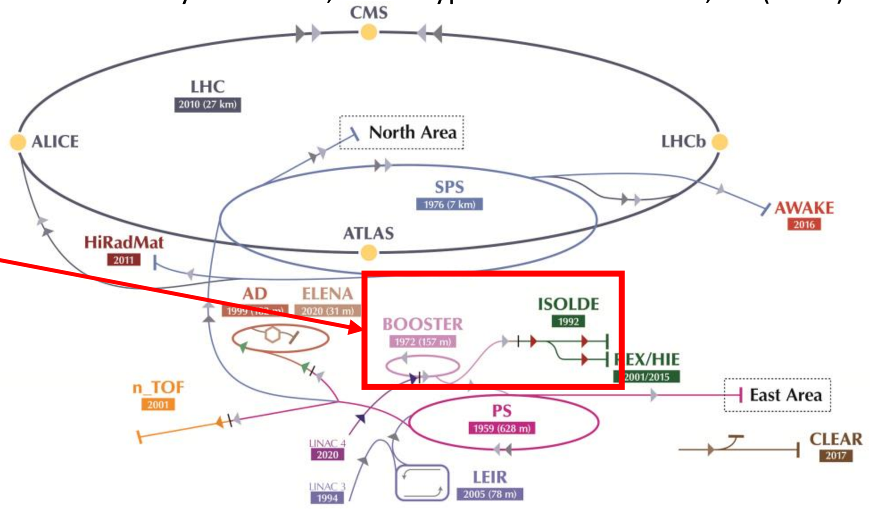
T. Day Goodacre, et al. Hyperfine Interact 238, 41 (2017).

ISOLDE & Radioactive Ion Beam Production

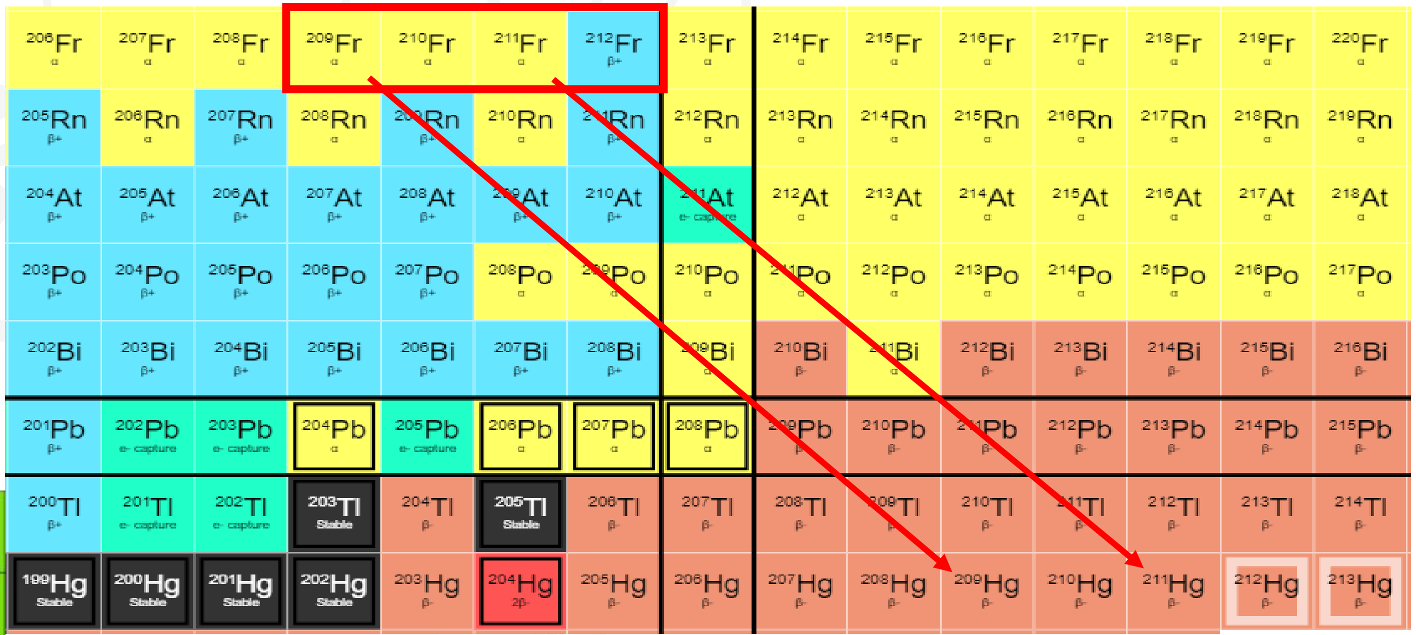


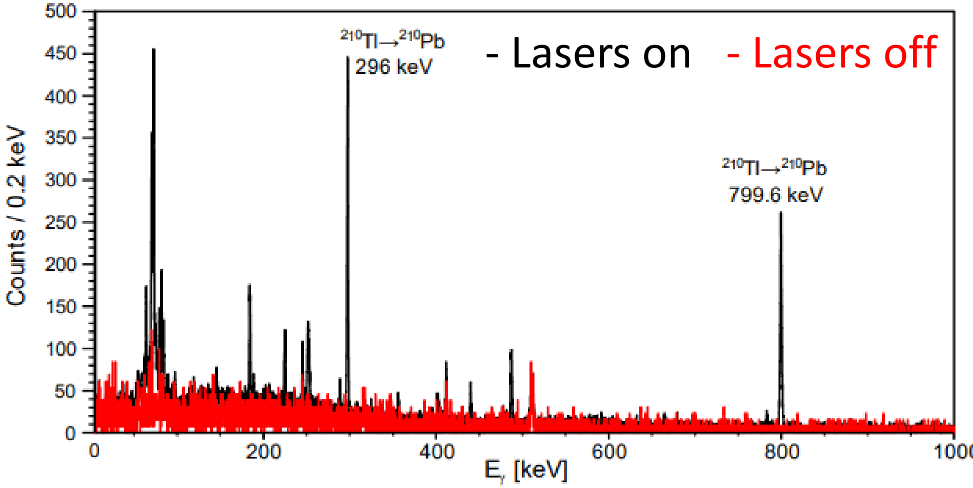


T. Day Goodacre, et al. Hyperfine Interact 238, 41 (2017).



Why have there been no previous measurements at ISOLDE?



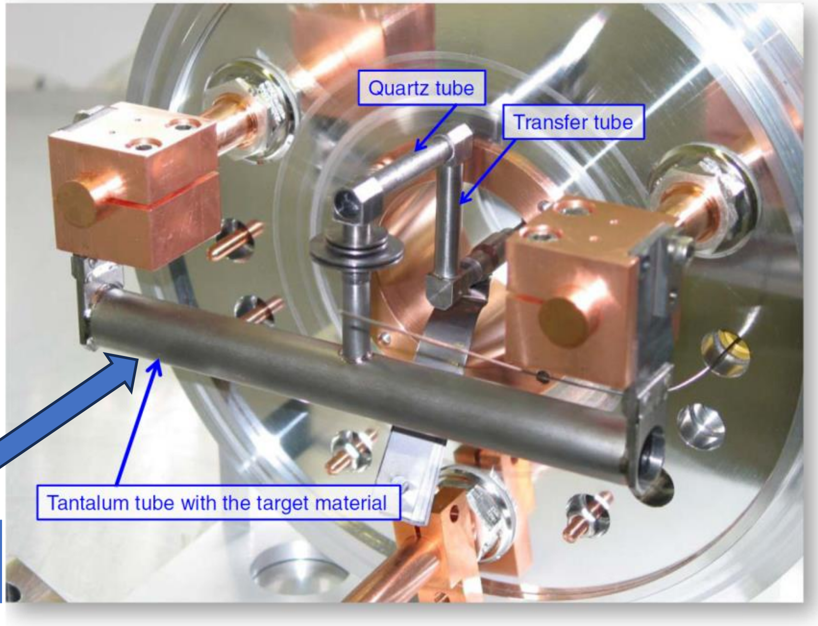


Large isobaric contamination

Group 1 elements are easily surface ionized

Surface-ionised Francium has in-target production yields for A = 209 – 213 of 10^8 – 10^9 atoms/μC).

Whereas Mercury is orders of magnitude lower therefore the data is dominated by the Francium



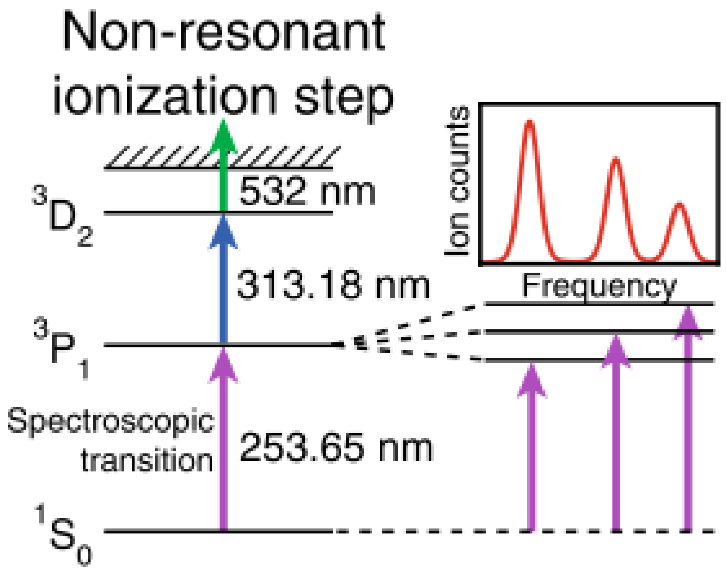
Heated to ~2000 K

Laser spectroscopy

Hyperfine structure

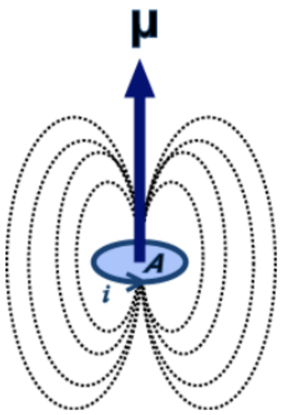
$$\Delta\frac{E}{h} = \frac{K}{2}\underbrace{A} + \frac{3K(K+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}\underbrace{B},$$

$$K = F(F+1) - I(I+1) - J(J+1)$$



B.A. Marsh, *et al. Nature Phys* **14**, 1163–1167 (2018).

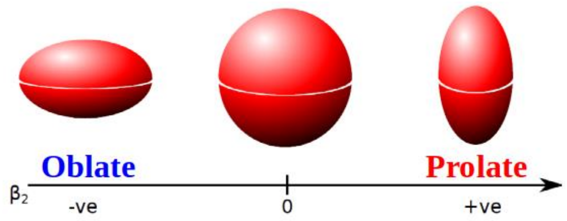
$$A = \frac{\mu B_e}{I \cdot J}$$



μ – Magnetic dipole moment

Provides information on the unpaired nucleons configuration

$$B = eQ_s\left\langle\frac{\delta V_e}{\delta z^2}\right\rangle$$



Q_s - Spectroscopic electric quadrupole moment

Allows the shape of the nucleus to be probed

Laser spectroscopy

Isotope/Isomer shift

$$\delta\nu_{IS}^{A,A'} = \delta\nu_{MS}^{A,A'} + \delta\nu_{FS}^{A,A'}$$
$$= M\frac{A'-A}{AA'} + F\delta\langle r^2\rangle^{AA'}$$

Mass shift

Field shift

Result of the change in electron energy from a difference in spatial distribution of nuclear charge

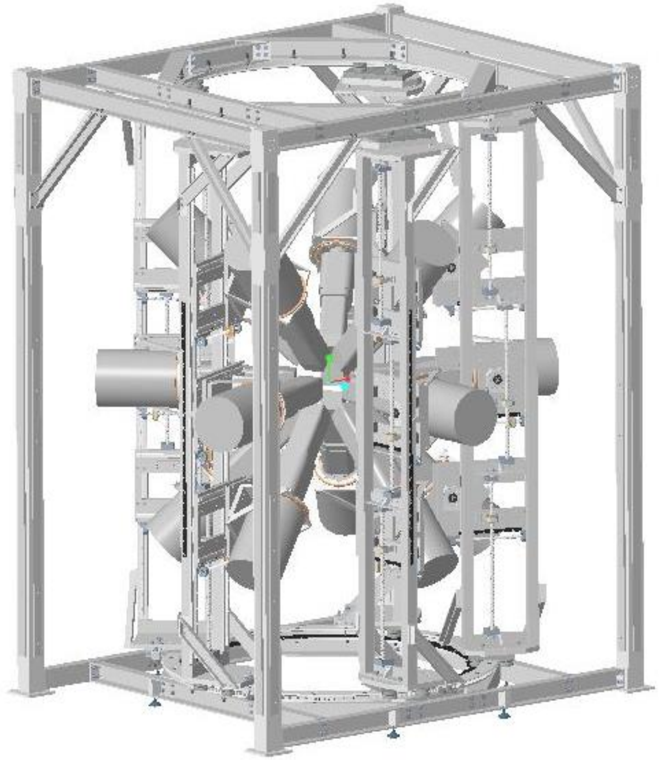
The field shift is proportional to the mean-square charge radii, an important nuclear property

Composed of the Normal mass shift (NMS) and the Specific mass shift (SMS)

NMS – Describes the reduced electron mass of the system

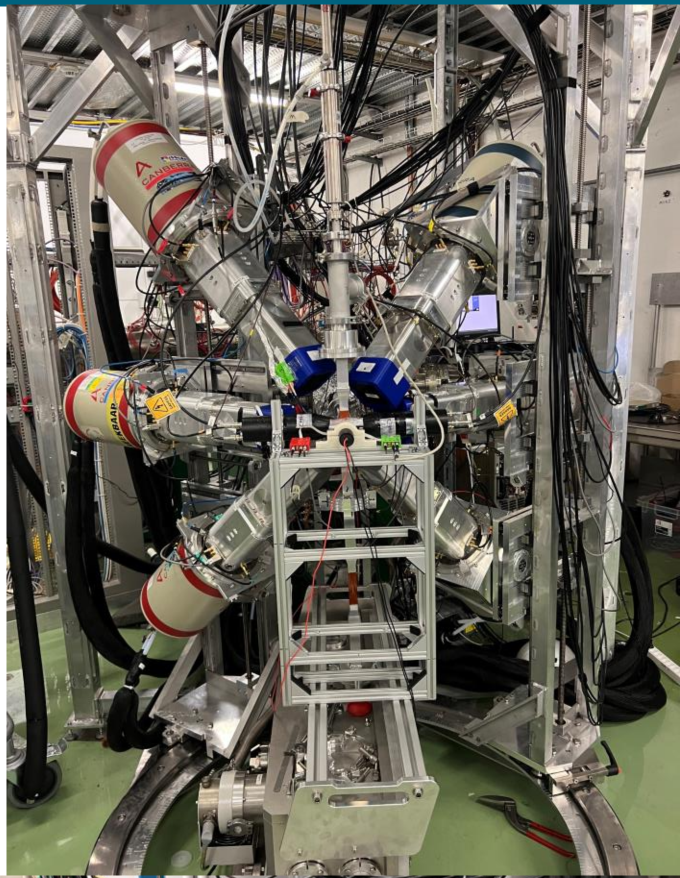
SMS – Originates from correlation effects between any two electrons in multi-electron systems

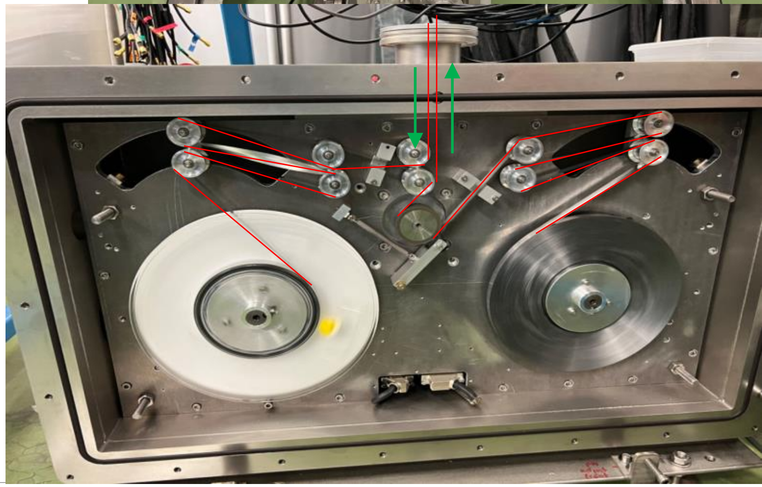
ISOLDE Decay Station



Made in York!

- A variety of chambers depending on the experiment
- Can utilize a variety of radiation detectors for gamma and particle spectroscopy
- York play a major role at IDS with Dr James Cubiss being the spokesperson and have made contributions to the setup such as chambers, gantries and the frame





Planned and proposed measurements

A York Led experiment!

● - Measurements that are almost certain to be made

○ - Difficult measurements that will be attempted

	Measurement		
Isotope	**β-γ decay**	**Mass**	**IS + hfs**
^{209}Hg	●	●	●
^{210}Hg	●	●	●
^{211}Hg	●	○	○
^{212}Hg	○		

- γ measurements made with 10 clovers at the implantation position and 2 at a secondary position

- β measurements will be conducted with an array of plastic scintillators

- Isotope shifts and hyperfine structure measurements made via RILIS for $^{209, 210}$Hg and hopefully ^{211}Hg

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Laser & decay spectroscopy and mass spectrometry of neutron-rich mercury isotopes south-east of ^{208}Pb

10th January 2024

A. Algora[1], B. Andel[2], A. N. Andreyev[3], S. Antalic[2], D. Balabanski[4] M. Benhatchi[5], J. Benito[6], C. Bernerd[7], K. Blaum[8], J. A. Briz[6], R. B. Cakirli[9], K. Chrysalidis[7], T. Cocolios[10], J. G. Cubiss[3], T. Day Goodacre[11], V. N. Fedosseev[7], L. M. Fraile[6], L. P. Gaffney[12], G. Georgiev[5], P. F. Giesel[13], K. Gladnishki[14], R. Heinke[7], Y. Hirayama[15], A. Illana[6], D. Kocheva[14], U. Köster[16], D. Lange[8], R. Lica[17], Yu. A. Litvinov[18], D. Lunney[5], B. A. Marsh[7], A. McFarlane[3], J. Mišt[2], A. Morales[1], M. Mukai[19], S. Naimi[5], L. Nies[7], T. Niwase[15], J. Ojala[12], B. Olaizola[20], C. Page[3], R. D. Page[12], J. Pakarinen[21], Z. Podolyak[22], G. Rainovski[14], M. Rosenbusch[15], S. Rothe[7], P. Schury[15], Ch. Schweiger[8], L. Schweikhard[13], S. Sharma[23], A. Sitarčík[2], P. Srivastava[23], K. Stoychev[7], M. Stryjczyk[21], P. Van Duppen[10], Y. Watanabe[15], J. Wilson[3], Z. Yue[3,7] + IDS collaboration

[1]IFC, CSIC, Valencia, Spain; [2]Comenius University in Bratislava, Slovakia; [3]University of York, UK; [4]ELI-NP, Bucharest, Romania; [5]CNRS/Université Paris-Saclay, France; [6]Universidad Complutense de Madrid, Spain; [7]CERN, Geneva, Switzerland; [8]Max-Planck-Institute for Nuclear Physics, Germany; [9]Department of Physics, Istanbul University, Turkey; [10]IKS, KU Leuven, Belgium; [11]University of Manchester, UK; [12]University of Liverpool, UK; [13]Universität Greifswald, Germany; [14]Sophia University, Bulgaria; [15]WNSC, IPNS, KEK, Japan; [16]ILL, Grenoble, France; [17]IFIN-HH, Romania; [18]GSI, Germany; [19]RIKEN, Japan; [20]IEM-CSIC, Madrid, Spain; [21]JYFL, Jyvaskyla, Finland; [22]University of Surrey, UK; [23]Department of Physics, IIT, Roorkee.

Spokesperson: J. G. Cubiss [james.cubiss@york.ac.uk], D. Lange [daniel.lange@cern.ch], A. N. Andreyev [andrei.andreyev@york.ac.uk], U. Köster [koester@ill.fr]
Contact person: Ch. Schweiger [christoph.schweiger@cern.ch], Z. Yue [zixuan.yue@york.ac.uk]

Thank you!

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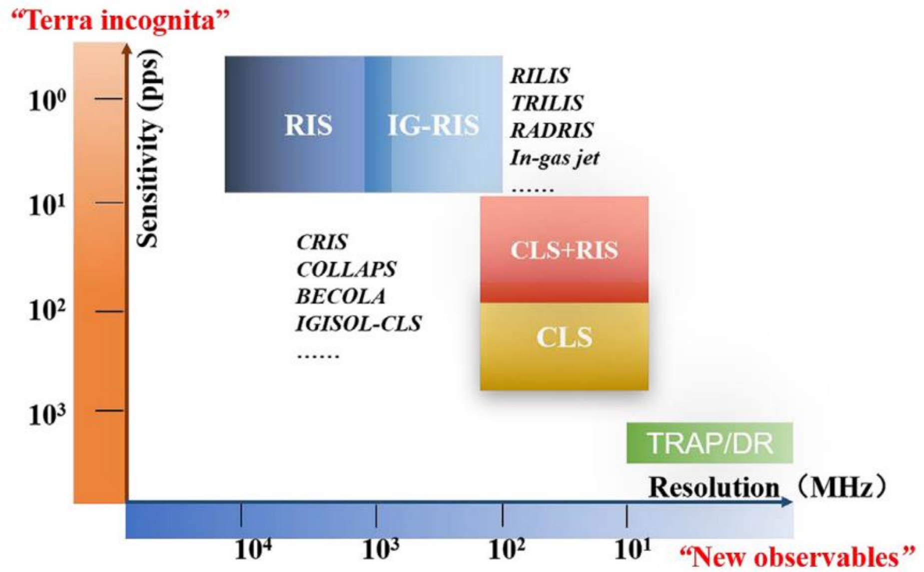
Laser Spectroscopy

- Model independent way to measure nuclear properties from the hyperfine structure and the isotope/isomer shift



X.F. Yang, S.J. Wang, S.G. Wilkins et al. Progress in Particle and Nuclear Physics 129 (2023) 104005

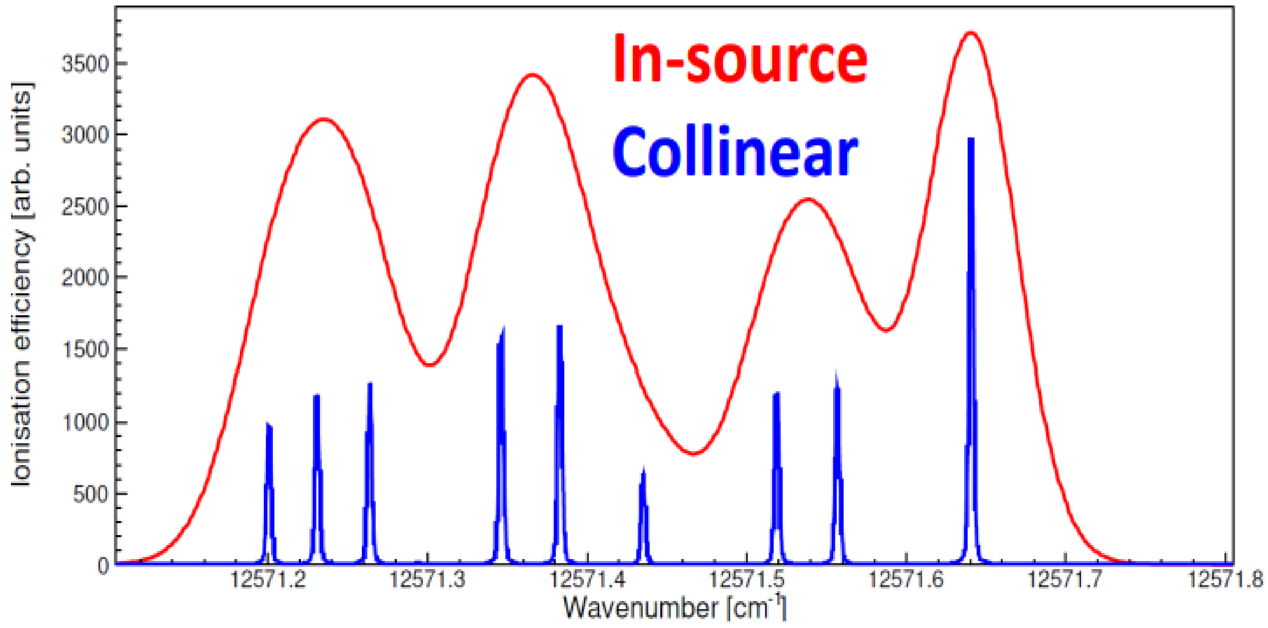
- Two common methods at ISOLDE:

In-source laser spectroscopy

- High beam intensities
- low resolution

Collinear spectroscopy

- High resolution
- Low beam intensities



R.P. de Groote et al., PLB 827, 136930 (2022)

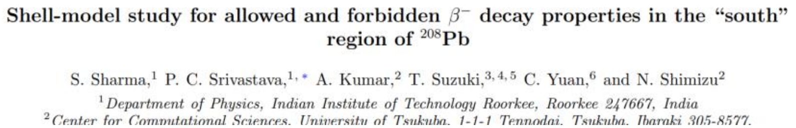
Motivation for further measurements

Nuclear Physics Motivations

- Competition between allowed and first forbidden β decays (may explain the ^{209}Hg $T_{\frac{1}{2}}$ discrepancy)
- Study trend in S_{2n} beyond N=126 in Z<82 region, use ΔS_{2n} to probe weakening of N=126 closure
- Explore interaction strength between last proton and neutron, δV_{pn}
- Further charge radii points after the N = 126 kink

Nuclear Astrophysics Motivations

- Derived mass excess important for restricting nuclear mass models - input for *r*-process network calculations.
- $T_{1/2}$, log *ft*, P_n place constraints on models used for *r*-process network calculations

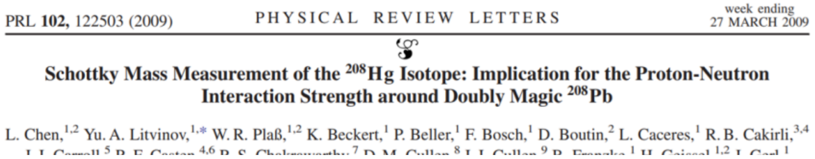

Shell-model study for allowed and forbidden β^- decay properties in the "south" region of ^{208}Pb

S. Sharma,[1] P. C. Srivastava,[1,*] A. Kumar,[2] T. Suzuki,[3,4,5] C. Yuan,[6] and N. Shimizu[2]
[1]Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247667, India
[2]Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577,


PRL 94, 092501 (2005) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2005

Proton-Neutron Interactions and the New Atomic Masses

R. B. Cakirli,[1,2] D. S. Brenner,[1,3] R. F. Casten,[1] and E. A. Millman[1]


PRL 102, 122503 (2009) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2009

Schottky Mass Measurement of the ^{208}Hg Isotope: Implication for the Proton-Neutron Interaction Strength around Doubly Magic ^{208}Pb

L. Chen,[1,2] Yu. A. Litvinov,[1,*] W. R. Plaß,[1,2] K. Beckert,[1] P. Beller,[1] F. Bosch,[1] D. Boutin,[2] L. Caceres,[1] R. B. Cakirli,[3,4]