The laser ionisation toolkit for ion beam production at thick-target ISOL facilities
Outline

★ Laser ion source types

★ Operating principle and goals

★ The ISOLDE RILIS (Laser technologies, setup and capabilities)

★ Thick target RILIS options (selectivity, efficiency, spectral resolution)

★ Future possibilities
Laser Ion Source Types

1a. Thick target + hot cavity: High yield; chemical dependence of release; > ms half-lives

1b. Thin target + gas catcher: Chemically independent release; > μs half-lives

2a. Projectile fragment separator + gas catcher: Chemically independent release; > μs half-lives

2b. Thin target + gas catcher: Chemically independent release; > μs half-lives

3a. Thick target + hot cavity: High yield; chemical dependence of release; > ms half-lives

3b. Thin target + gas catcher: Chemically independent release; > μs half-lives
Purpose

Radioactive ion beam production for most ISOLDE experiments

- Broad linewidth lasers
- Efficiency
- Most metallic elements

Isomer-selective ionization for nuclear physics experiments

- Narrow linewidth lasers
- Selectivity
- Heavy nuclei

- Highly-sensitive laser spectroscopy for atomic and nuclear structure physics
Producing isotope-pure beams

$^{132}\text{Sn}$
Producing isotope-pure beams

$^{132}\text{Sn}$

Element selection

$Z=50$
Producing isotope-pure beams

$A = N + Z = 132$

$^{132}\text{Sn}$

Element selection $Z = 50$

Mass selection $A = N + Z = 132$
Element selection by Laser Resonance Ionisation

atomic ‘Fingerprint’
Thick-target ISOL RILIS options

- **‘STANDARD’ RILIS**
  Hot Cavity Laser Ion Source

- **LIST (OR IG-LIS)**
  Laser Ion Source Trap Ion-Guide Laser Ion Source

- **VADLIS**
  Versatile Arc Discharge and Laser Ion Source
Accessible isotopes

>600 isotopes have been ionized with RILIS

**Inaccessible:**
Non-metals (high IP or 1st excited state)
< 210 nm is difficult to generate
<205 nm absorption in transmissive optics

B. A. Marsh, Resonance ionization laser ion sources for on-line isotope separators

http://dx.doi.org/10.1063/1.4858015
Every element requires dedicated atomic spectroscopy study to determine the optimal ionization pathway.

40 elements have so far been laser ionized at CERN/ISOLDE.

Ionization scheme development for **Ba, Ba$^{2+}$, Li, Cr, Ge and Hg**

**Cr scheme**
- Scan 560-581 nm
- Best AIS 579 nm
- 5s$^2$ 2.28 eV
- 698 nm 3.46 eV
- 358 nm

**Cr laser scans**
- New autoionizing states

**Hg scheme**
- 532 nm 10.4 eV
- 313 nm 8.84 eV
- 254 nm 4.89 eV
- 5d$^6$6s$^2$ 0 eV

**Hg laser scans**
- Second steps

**Ge scheme**
- 532 nm 7.90 eV
- 4s$^2$4p$^6$3$^2$D$_1$ 6.85 eV
- 569 nm 4.96 eV
- 275 nm 0, 0.07, 0.17 eV

**Ge laser scans**
- Second step

**LAiNET**

**PhD work:**
**Tom Day Goodacre**
Atomic physics results as a side-effect!

IP (At) = 9.31751(8) eV

ARTICLE

Measurement of the first ionization potential of astatine by laser ionization spectroscopy

S. Rothe\textsuperscript{1,2}, A.N. Andreyev\textsuperscript{3,4,5,6}, S. Antalic\textsuperscript{7}, A. Borschevsky\textsuperscript{8,9}, L. Capponi\textsuperscript{4,5}, T.E. Cocolios\textsuperscript{1}, H. De Witte\textsuperscript{10}, E. Eliav\textsuperscript{11}, D.V. Fedorov\textsuperscript{12}, V.N. Fedosseev\textsuperscript{1}, D.A. Fink\textsuperscript{1,13}, S. Fritzche\textsuperscript{14,15,1}, L. Ghys\textsuperscript{10,16}, M. Huyse\textsuperscript{10}, N. Imai\textsuperscript{1,17}, U. Kaldor\textsuperscript{11}, Yuri Kudryavtsev\textsuperscript{10}, U. Köster\textsuperscript{18}, J.F.W. Lane\textsuperscript{4,5}, J. Lassen\textsuperscript{19}, V. Liberati\textsuperscript{4,5}, K.M. Lynch\textsuperscript{1,20}, B.A. Marsh\textsuperscript{1}, K. Nishio\textsuperscript{6}, D. Pauwels\textsuperscript{16}, V. Perschina\textsuperscript{14}, L. Popescu\textsuperscript{16}, T.J. Procter\textsuperscript{20}, D. Radulov\textsuperscript{10}, S. Raeder\textsuperscript{2,19}, M.M. Rajabali\textsuperscript{10}, E. Rapisarda\textsuperscript{10}, R.E. Rossel\textsuperscript{2}, K. Sandhu\textsuperscript{4,5}, M.D. Seliverstov\textsuperscript{1,4,5,12,10}, A.M. Sjödin\textsuperscript{1}, P. Van den Bergh\textsuperscript{10}, P. Van Duppen\textsuperscript{10}, M. Venhart\textsuperscript{21}, Y. Wakabayashi\textsuperscript{6} & K.D.A. Wendt\textsuperscript{2}
Atomic physics results as a side-effect!

1. Polonium isotope production and separation

2. Resonance Laser Ionization Spectroscopy

3. Rydberg spectrum and multi-peak fit

4. Rydberg fit and ionization energy

\[ IE = 67896.310(14)(30) \text{ cm}^{-1} = 8.4180700(18)(37) \text{ eV} \]

Determination of the first ionization energy of polonium by resonance ionization spectroscopy – Part II: Measurement of odd-parity Rydberg states at CERN–ISOLDE.

D.A. Fink, K. Beaum, V.N. Fedoseev, B.A. Marsh, R.E. Rossel, S. Rothe

https://doi.org/10.1016/j.sab.2018.08.004
ISOLDE RILIS setup - detailed

HRS
- Hot cavity
- Target
- HRS target area
- HRS separator area
- Magnet window
- FS SUPRASIL
- 3° wedge
- Prism periscope
- FS quartz
- Reference plate
- HRS launch point
- Magnet window
- Reference point
- Mirror periscopes

ISCOOL
- Target
- HRS target area
- GPS separator area
- Magnet window
- Reference plate
- GPS launch point
- Reference area
- Reference cell

CRIS
- Ti:Sa
- Ti:Sa
- Ti:Sa
- Blaze
- Pickup
- Notch filter
- CCD
- Al mirror

FCU
- Beam shaping telescope
- 2-8 x beam expander

MSS NB dye
- CREDO dye
- CREDO dye

PHOTONICS R&D AG
- Rhenium nitrides

BLAZE
- Rhenium nitrides

GLM
- PISA
- CCD
- CCD
- CCD
- CCD
- PSD
- PSD
- PSD
- Bandpass filter

Dye pump laser

The first RILIS DPSS system is now almost 10 years old!

- Simple operation; better dye laser efficiency and beam quality
- Easier to transmit the beam to the ion source
- Objective assessment of degradation of beam quality
- Better compatibility with commercial dye lasers

IS400-2-G

10 kHz (9 ns), 100 W @ 532 nm

TEM 00

$M^2 = 1.1$

Circular, gaussian beam
Compact 60 W Ti:Sa pump lasers

2 lasers in use
1 spare

Smallest footprint on the market for 60 W @ 10 kHz

$M^2 > 10$ (Lower damage risk for Z-resonator TiSa pumping)

$\text{t}_{\text{pulse}} \sim 150 \text{ ns}$ (not suitable for dye laser pumping)

1 independent, low-jitter triggered pump laser per TiSa facilitates pulse timing synchronization
Independent laser for non resonant ionization

2/3 of RILIS schemes benefit

- 40W at 10 kHz
- 17ns Pulse
- Low Jitter
- Gaussian beam
- Much better transmission to source
- can be used for Dye and Ti:Sa pumping

B. Marsh et al., CERN-ATS-Note-2013-007 TECH
Multi-purpose pump laser

- New DPSS laser **Innolas Nanio** for Ti:Sa pumping and other applications
  - TEM00 – mode
  - 18W output @ 10kHz pulse rate, 30ns pulse length
- Simpler cooling mechanism → decreased risk for chiller failures
- Proposed laser for CERN-MEDICIS (Tender underway)

**Non-resonant ionization test:**

Demonstrated to be effective for non-resonant ionization

**Ti:Sapphire pumping test:**

Increased efficiency: lasing at <5W pump power
Prerequisite for ~3000 h operation / year:
Laser redundancy / reliability

Independent laser for non-resonant ionization

- 40W at 10 kHz
- 17ns Pulse
- Low Jitter
- Gaussian beam
- Much better transmission to source
- Can be used for Dye and Ti:Sa pumping

B. Marsh et al., CERN-ATS-Note 2013-007 TECH

Laser parameters

- TEM00 mode
- 18W output @ 10kHz pulse rate, 30ns pulse length
- Simpler cooling mechanism → decreased risk for chiller failures
- Proposed laser for CERN-MEDICIS (Tender underway)

Non-resonant ionization test:
Demonstrated to be effective for non-resonant ionization

Purchased in 2017/8
Just repaired
New Tisa cavities from Mainz / LARISSA

Improved alignment system
Smaller footprint
Easier change between fundamental, 2w, dual etalon etc modes

New addition:
Closed-loop piezo-actuated etalons
Grating-TiSa for broad-range atomic spectroscopy

Now capable of scanning in narrow-band mode and in the blue range (with intra-cavity frequency doubling)

Thanks to
Katerina Chrysalidis and
Felix Weber

P. Naubereit, master thesis, Nov. 2014, JGU Mainz

Development and applications of tunable solid-state laser techniques for the CERN-ISOLDE-RILIS
Katerina Chrysalidis - Poster Session 2
Towards ‘high-resolution’ spectroscopy

RILIS lasers with Fourier-limited Linewidth

Injection-seeded Ti:Sapphire laser cavity

Pulsed dye amplifier
First demonstration of Dowpper-free two-photon in-source laser spectroscopy at ISOLDE-RILIS

EMIS 2018

Katerina Chrysalidis

CERN, Johannes Gutenberg-Universität Mainz

On behalf of the RILIS team

97. An injection-locked Titanium:Sapphire laser system for a high-resolution resonance ionization spectroscopy.
Dr Mikael Reponen (University of Jyväskylä)

31. Development of new Ti:sapphire based laser sources for selective ionization and spectroscopy applications
Dr Volker Sonnenschein (University of Nagoya)
Standard ‘Hot-Cavity’ RILIS

**Laser requirements:**
High peak power, therefore short pulse length (<50 ns, 0.1-10 mJ)
High Rep rate: >10 kHz (100 μs laser/atom temporal overlap)
Laser line width > 5 GHz (> Doppler-broadened atomic line width)

**T ≈ 2100 °C**
High temperature target/transfer line/ion source assembly

- High efficiency
- Cavity plasma potential enhances ion survival

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Highly Efficient Ion Source for Surface and Laser Ionization
Dr Maxim Seliverstov (NRC “Kurchatov Institute” PNPI)

**Main issues:**
Surface ionized contaminants
Doppler broadened line-width

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G. D. Alkhazov et al.
NIM B69 (1992) 517
V.N. Fedoseev et al.
NIM B266 (2008) 4378
U. Koester et al.
Drawbacks of hot-cavity laser ion sources

- **Surface ionised contamination**
  - long standing issue but no universal solution has been found

- **Limited ion capacity (~ 1 uA)**
  - possible issue for EURISOL, ISOL@MYRRHA etc.

- Not currently suitable for all ISOL targets (liquid)

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**Highly Efficient Ion Source for Surface and Laser Ionization**

Dr Maxim Seliverstov (NRC “Kurchatov Institute” PNPI)

**POSTER SESSION 2**
Active surface-ion suppression (LIST)

First application of the Laser Ion Source and Trap (LIST) for on-line experiments at ISOLDE

D. A. Fink,1,4,5 A. Gottberg,6,7 A. Huyse,1,8 E. Imai,1,9 R. Catherall,1,10 J. P. Ramos,11,12 R. E. Rossel,11,12 S. Rothe,11,12 D. Pauwels,11,12 M. Sjödin,6,7 K. D. A. Wendt,7

SI Suppression

~$10^6$

Efficiency loss

~20-40
High Selectivity RILIS — ToF-LIS

LIST provides transverse confinement along ‘drift’ region
Hot-cavity (ion-guide) and standard LIST mode still available
VADLIS: an alternative to hot-cavity RILIS

So far demonstrated for: Ga, Cd, Hg (2015), Ba, Ba+, Sn, Mg (2016), Hg (2017), Mo, Hg (scheduled 2018).
VADLIS modes of operation

- New design with variable extraction voltage improves laser ion extraction
- Demonstrated off-line with Ga
- Demonstrated on-line with Mg: **factor 3 extraction efficiency improvement** when voltage was adjusted!
Mo(CO)$_6$ - Molecular breakup + ionisation

1) Creation and transport of volatile molecules of refractory metals

2) Dissociation by laser pulse

3) Resonance ionisation before atom/wall collision
Test planned for Winter 2018/19

~picosecond laser for molecular breakup

0-200 kHz (600 fs), 100W @ 515 nm

FX series INNOSLAB laser

75 x peak power increase w.r.t our 100 W IS-series laser

> 20 laser-molecule interactions per molecule (in hot cavity)

Test for Winter 2018/19

References
[1] https://isoyields2.web.cern.ch/
Revisiting to the 40-year old mercury story

Nuclear Shape Staggering in Very Neutron-Deficient Hg Isotopes Detected by Laser Spectroscopy

Institut für Physik, Universität Mainz, Mainz, Germany
(Received 1 April 1977)

unprecedented odd-even staggering

< $^{186}$Hg

The extension of these measurements down to $^{186}$Hg might be made feasible by improving experimental details. It could thus be determined whether the shape staggering extends further, and where the nuclear shape becomes stabilized finally.

Requirements to continue this measurement:

> 10 x RILIS efficiency improvement

RILIS compatibility with Liquid Pb target sensitive enough to measure < 1 ion / sec

Collection time limited by half-life

Low sensitivity of PMT
In-Source RIS of Mercury

First laser spectroscopy in the FEBIAD ion source

60 x Efficiency improvement

Protons
VADLIS ion source
GPS Magnet
Non resonant ionization step
\( \text{Spectroscopic transition} \)
\( 532 \text{ nm} \)
\( 313.18 \text{ nm} \)
\( 253.65 \text{ nm} \)

Windmill
radioactive decay spectroscopy

Faraday Cup
ion current measurement

MR-TOF MS
time-of flight mass spectrometry

Contaminant species
\( \bullet \) atom
\( \bullet \) ion

Isotope of interest

Efficiency improvement

\( \alpha \) counts
\( \beta \) counts

\( A, 198 \) [fm]

Mass Number, \( A \)

This work, gs/is
Prev. work, gs/is

177 Hg
178 Hg
179 Hg
180 Hg
181 Hg

Efficiency improvement

First laser spectroscopy in the FEBIAD ion source
The In-Source RIS collaboration at ISOLDE

Comenius University, Bratislava, Slovakia
GANIL, Caen, France
Helmholtz Institut Jena, Germany
ILL, Grenoble, France
Institut für Physik, Universität Mainz, Germany
IPN Orsay, France
JAEA, Tokai, Japan
KU Leuven, IKS, Belgium
PNPI, Gatchina, Russian Federation
RILIS and ISOLDE, CERN, Switzerland
SCK-CEN, Mol, Belgium
The University of Manchester, United Kingdom
The University of York, United Kingdom
University of Liverpool, United Kingdom
University of the West of Scotland, United Kingdom

>50 participants
14 institutes
RILIS
WINDMILL
ISOLTRAP
The application of RILIS for nuclear structure studies is limited by the achievable resolution of these very small scale observables.
Hg Windmill + MRTToF-MS spectra

177\(^{\text{Hg}}\)

178\(^{\text{Hg}}\)

179\(^{\text{Hg}}\)

180\(^{\text{Hg}}\)

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300\(^{\text{Hg}}\)
Characterization of the shape-staggering effect in mercury nuclei

Using resonance ionization spectroscopy, mass spectrometry, and computational methods, we have studied neutron-deficient mercury isotopes. The mass chart, including lead isotopes, allows us to observe the shape staggering between odd and even isotopes. This phenomenon is a striking example of the interplay between monopole and quadrupole interactions.

For the heavier mercury isotopes, the change in mean-square charge radius, $\delta(r^2)/A$, shows a redistribution of nucleons. This is particularly evident in the isotopic chain, where odd and even isotopes exhibit different shapes, corresponding to alternative populations of single-particle orbitals.

In this work, we have observed a significant increase in the mean-square charge radius, $\langle \beta_2^2 \rangle^{1/2}$, for odd isotopes. For example, $\langle \beta_2^2 \rangle^{1/2} = 0.313$ for $^{181}$Hg and $\langle \beta_2^2 \rangle^{1/2} = 0.174$ for $^{190}$Hg. These results are consistent with previous measurements and further support the idea of shape coexistence in the nuclear chart.
RILIS cavity development directions

- HC-RILIS
- HC-LIST
- VADLIS

High resistance cavity
Pulsed line heating

‘DC-offset’
Inverted-LINE

Short LIST
LWF-VADLIS

2-photon
HC-RILIS

PI-LIST

New materials

High resolution

ToF-LIS

High efficiency

Adjustable EXTRACTOR VOLTAGE

RILIS for M(CO)x breakup +

Ion load issues for next-gen facilities
Lets pool our resources for RILIS development!
Acknowledgements

The *(recent)* ISOLDE RILIS team


+ the group of K. Wendt