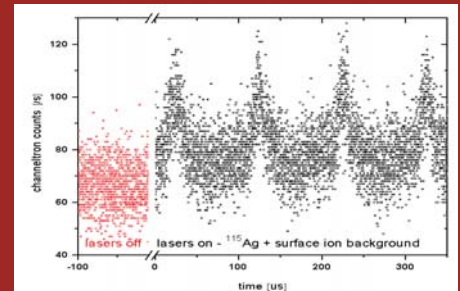
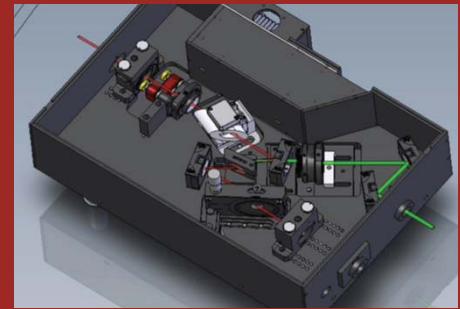
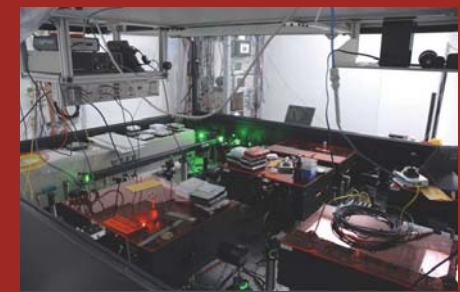
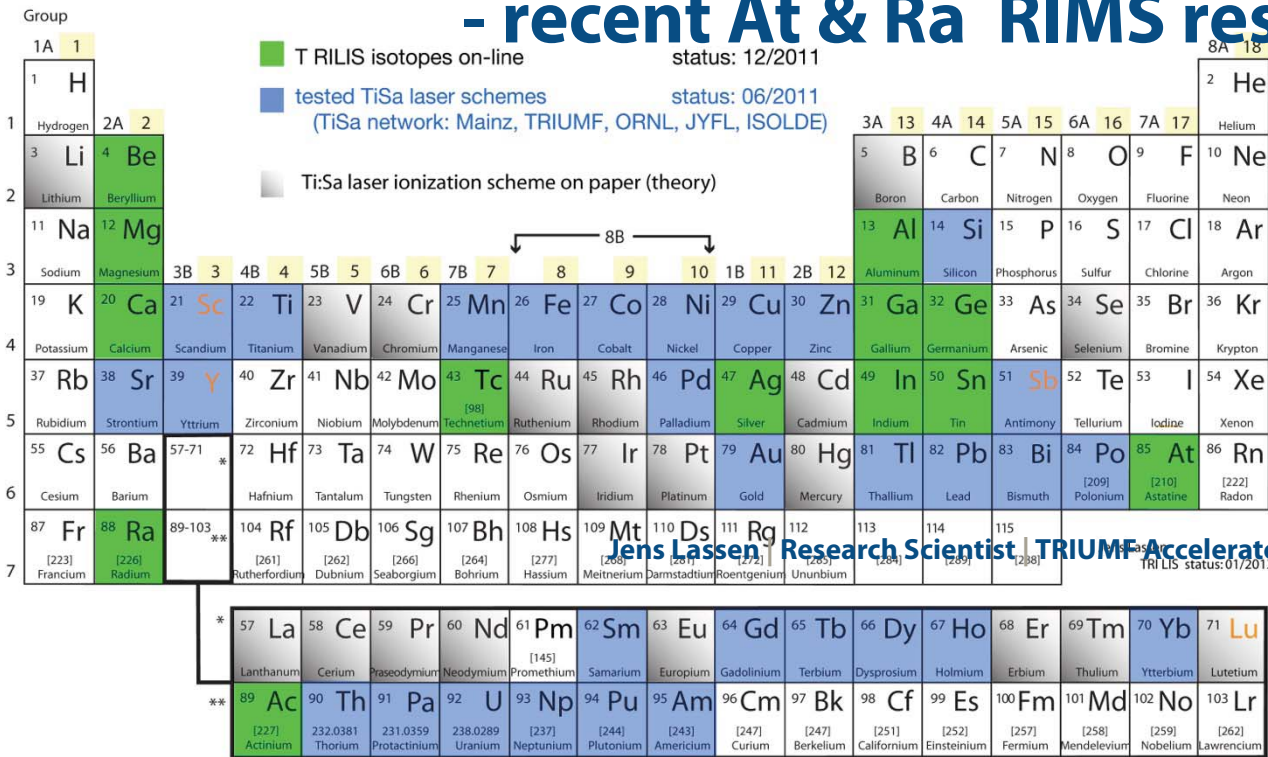


# T Resonant Ionization Laser Ion Source - recent At & Ra RIMS results



ISAC science forum 01Feb2012

Collaborations:

ORNL-HRIBF (Y. Liu), GANIL (N. Lemesne), CERN-ISOLDE (S. Rothe, V. Fedoseev)

Mainz U (Prof. K. Wendt), TU Darmstadt, U Applied Sciences Oldenburg

Current students:

U Guelph, FHO Emden, U Manitoba, TU Darmstadt

Funding: Government of Canada through NRC, NSCERC

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada



# TRIUMF

# the neighbourhood UC<sub>x</sub> based

91	<sup>1572</sup> Pa	Pa213	Pa214	Pa215	Pa216	Pa217	Pa218	Pa219	Pa220	Pa221	Pa222	Pa223	Pa224	Pa225	Pa226	Pa227	Pa228	Pa229	Pa230	Pa231	Pa232	Pa233
	9ms 0+	5.3 ms α	17 ms α	14 ms α	0.20 s EC,α	4.9 ms α	0.12 ms α	53 Ns 9/2- EC,α	0.78 Us EC,α	5.9 Us 9/2- α	2.9 ms α	6.5 ms EC,α	0.79 s α	1.7 s α	1.8 m EC,α	38.3 m (5/2-) EC,α	22 h 3+ EC,α	1.50 d (5/2+) EC,α	17.4 d (2-) EC,β,α,...	32760 y 3/2- α,sf	1.31 d (2-) EC,β	26.967 d 3/2- β
Th210	Th211	Th212	Th213	Th214	Th215	Th216	Th217	Th218	Th219	Th220	Th221	Th222	Th223	Th224	Th225	Th226	Th227	Th228	Th229	Th230	Th231	Th232
9ms 0+	37 ms EC,α	30 ms 0+ EC,α	140 ms α	100 ms 0+ α	1.2 s (1/2-) α	0.028 s 0+ EC,α	0.252 ms (9/2+) α	109 Ns 0+ α	1.05 Us EC,α	9.7 Us 0+ EC,α	1.68 ms (7/2+) α	2.8 ms 0+ α	0.60 s (5/2+) α	1.05 s 0+ α	8.72 m (3/2+) EC,α	30.57 m 0+ α	18.72 d (1/2+) α	1.9116 y 0+ α	7340 y 5/2+ α	7.538E+4 y 0+ α,sf	25.52 h 5/2+ β,α	1.405E10 y 0+ α,sf 100
Ac209	Ac210	Ac211	Ac212	Ac213	Ac214	Ac215	Ac216	Ac217	Ac218	Ac219	Ac220	Ac221	Ac222	Ac223	Ac224	Ac225	Ac226	Ac227	Ac228	Ac229	Ac230	Ac231
0.10 s (9/2-) EC,α	0.35 s EC,α	0.25 s α	0.93 s EC,α	0.80 s α	8.2 s EC,α	0.17 s 9/2- EC,α	0.33 ms (1-) α	69 Ns 9/2- EC,α	1.08 Us (1-) α	11.8 Us 9/2- EC,α	26.4 ms (3-) α	52 ms (3/2-) EC,α	5.0 s 1- EC,α	2.10 m (5/2-) EC,α	2.78 h 0- EC,β,α,...	10.0 d (3/2-) α, <sup>14</sup> C	29.37 h (1) EC,β,α,...	21.773 y 3/2- β,α	62.7 m 3+ β	62.7 m (3/2+) β	122 s (1+) β	7.5 m (1/2+) β
Ra208	Ra209	Ra210	Ra211	Ra212	Ra213	Ra214	Ra215	Ra216	Ra217	Ra218	Ra219	Ra220	Ra221	Ra222	Ra223	Ra224	Ra225	Ra226	Ra227	Ra228	Ra229	Ra230
1.3 s 0+ EC,α	4.6 s 5/2- EC,α	3.7 s 0+ EC,α	13 s 5/2(-) EC,α	13.0 s 0+ EC,α	2.74 m 1/2- EC,α	2.46 s 0+ EC,α	1.59 ms (9/2+) α	182 Ns 0+ EC,α	1.6 Us (9/2+) α	25.6 Us 0+ α	10 ms (7/2+) α	18 ms 0+ α	28 s 5/2+ α	38.0 s 0+ α, <sup>14</sup> C	11.435 d 3/2+ α, <sup>14</sup> C	3.66 d 0+ α, <sup>14</sup> C	14.9 d 1/2+ β	1600 y 0+ α, <sup>14</sup> C	42.2 m 3/2+ β	5.75 y 0+ β	4.0 m 5/2(+) β	93 m 0+ β
Fr207	Fr208	Fr209	Fr210	Fr211	Fr212	Fr213	Fr214	Fr215	Fr216	Fr217	Fr218	Fr219	Fr220	Fr221	Fr222	Fr223	Fr224	Fr225	Fr226	Fr227	Fr228	Fr229
14.8 s 9/2- EC,α	59.1 s 7+ EC,α	50.0 s 9/2- EC,α	3.18 m 6+ EC,α	3.10 m 9/2- EC,α	20.0 m 5+ EC,α	34.6 s 9/2- EC,α	5.0 ms (1-) α	86 Ns 9/2- α	0.70 Us (1-) EC,α	22 Us 9/2- α	1.0 ms 1- α	20 ms 9/2- α	27.4 s 1+ β,α	4.9 m 5/2- α	14.2 m 2- β	21.8 m 3/2(-) β,α	3.33 m 1- β	4.0 m 3/2- β	49 s 1- β	2.47 m 1/2+ β	38 s 2- β	50 s 0+ β
Rn206	Rn207	Rn208	Rn209	Rn210	Rn211	Rn212	Rn213	Rn214	Rn215	Rn216	Rn217	Rn218	Rn219	Rn220	Rn221	Rn222	Rn223	Rn224	Rn225	Rn226	Rn227	Rn228
5.67 m 0+ EC,α	9.25 m 5/2- EC,α	24.35 m 0+ EC,α	28.5 m 5/2- EC,α	2.4 h 0+ EC,α	14.6 h 1/2- EC,α	23.9 m 0+ α	25.0 ms (9/2+) α	0.27 Us 0+ α	2.30 Us 9/2+ α	45 Us 0+ α	0.54 ms 9/2+ α	35 ms 0+ α	3.96 s 5/2+ α	55.6 s 0+ α	25 m 7/2(+) β,α	23.2 m 0+ α	23.2 m 7/2 β,α	107 m 0+ β	4.5 m 7/2- β	7.4 m 0+ β	22.5 s 0+ β	65 s 0+ β
At205	At206	At207	At208	At209	At210	At211	At212	At213	At214	At215	At216	At217	At218	At219	At220	At221	At222	At223				
26.2 m 9/2- EC,α	30.0 m (5+) EC,α	1.80 h 9/2- EC,α	1.63 h 6+ EC,α	5.41 h 9/2- EC,α	8.1 h (5+) EC,α	7.214 h 9/2- EC,α	0.314 s (1-) EC,β,α,...	125 Ns 9/2- α	558 Ns 1- α	0.10 ms 9/2- α	0.30 ms 1- EC,β,α,...	32.3 ms 9/2- β,α	1.5 s β,α	56 s β,α	3.71 m 3 β,α	2.3 m β	54 s β	50 s β,α				
Po204	Po205	Po206	Po207	Po208	Po209	Po210	Po211	Po212	Po213	Po214	Po215	Po216	Po217	Po218								
3.53 h 0+ EC,α	1.66 h 5/2- EC,α	8.8 d 0+ EC,α	5.80 h 5/2- EC,α	2.898 y 0+ EC,α	102 y 1/2- EC,α	138.376 d 0+ α	0.516 s 9/2+ α	0.299 Us 0+ α	4.2 Us 9/2+ α	164.3 Us 0+ α	1.781 ms 9/2+ β,α	0.145 s 0+ α	10 s β,α	3.10 m 0+ β,α								
Bi203	Bi204	Bi205	Bi206	Bi207	Bi208	Bi209	Bi210	Bi211	Bi212	Bi213	Bi214	Bi215	Bi216									
11.76 h 9/2- EC,α	11.22 h 6+ EC	15.31 d 9/2- EC	6.243 d 6(+) EC	31.55 y 9/2- EC	3.68E+5 y (5+) EC	9/2- 100	5.013 d 1- β,α	2.14 m 9/2- β,α	60.55 m (1-) α,β,α,...	45.59 m 9/2- β,α	19.9 m 1- β,α	7.6 m β	3.6 m (1-) β									

140 142

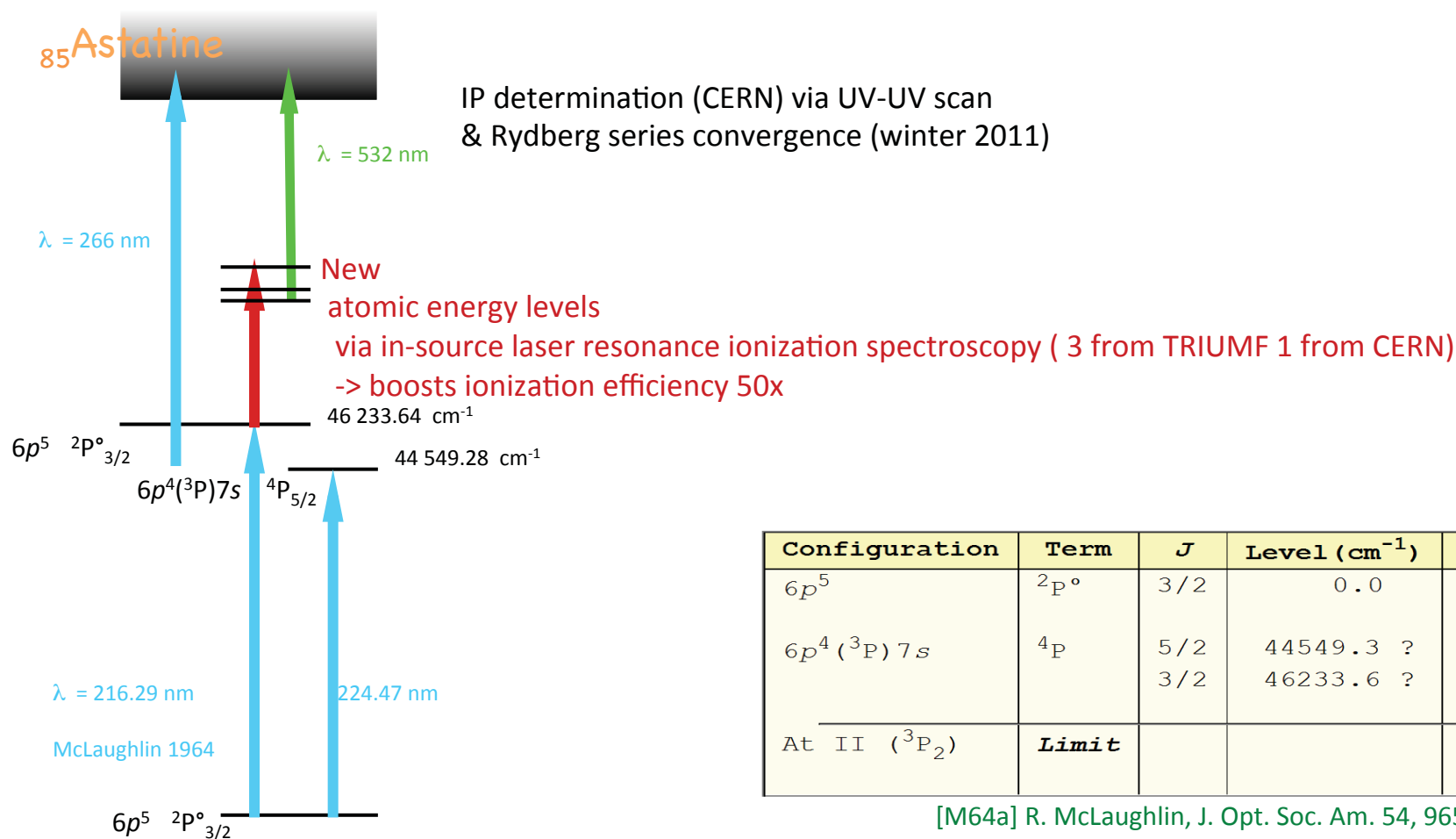
136 138

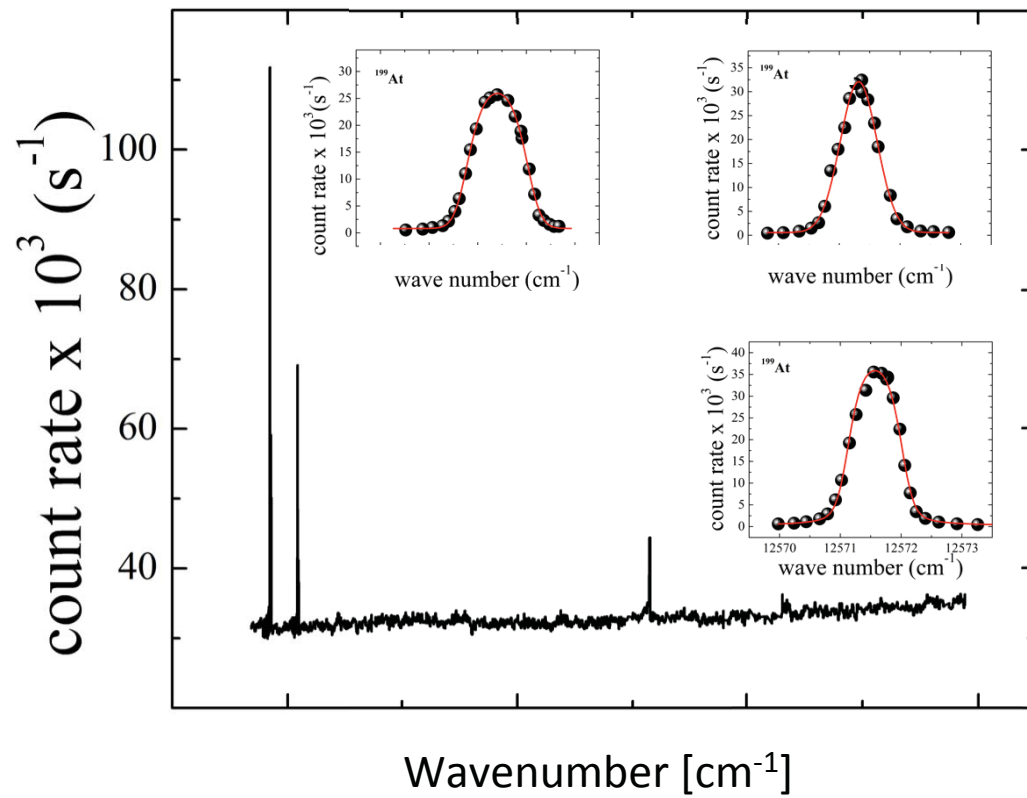
134

With p+ on target -> massive Fr background

without p+ -> only long lived isotopes -> clean Ra, Ac beams of select isotopes

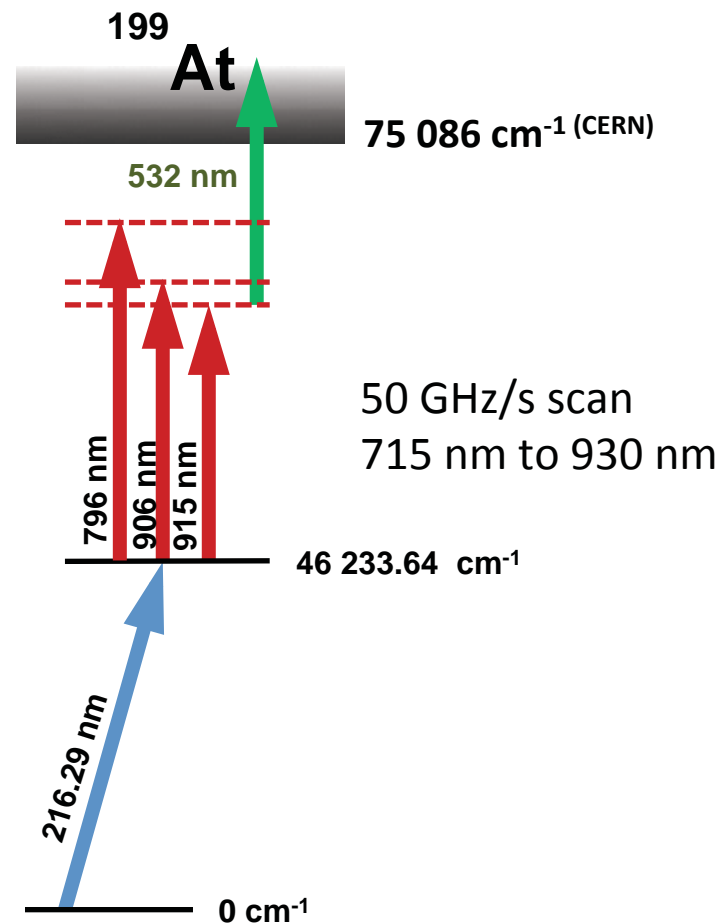
e.g. A=225





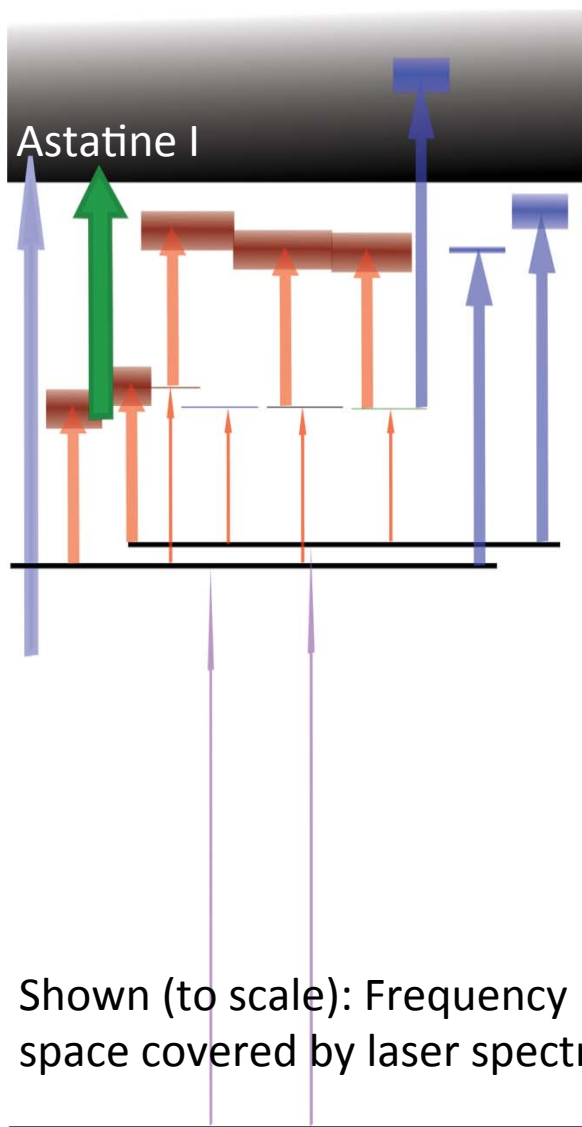
TRIUMF yield measurements:

At isotope	Yield (UV,UV)	Yield (UV, IR, 532nm)
199	$1 \times 10^3 \text{ s}^{-1}$	$5 \times 10^4 \text{ s}^{-1}$
218	$70 \text{ s}^{-1}$	$3 \times 10^3 \text{ s}^{-1}$



Three new energy levels found  
50 x increase in yield

J. Lassen et al., to be published



So far no autoionizing states

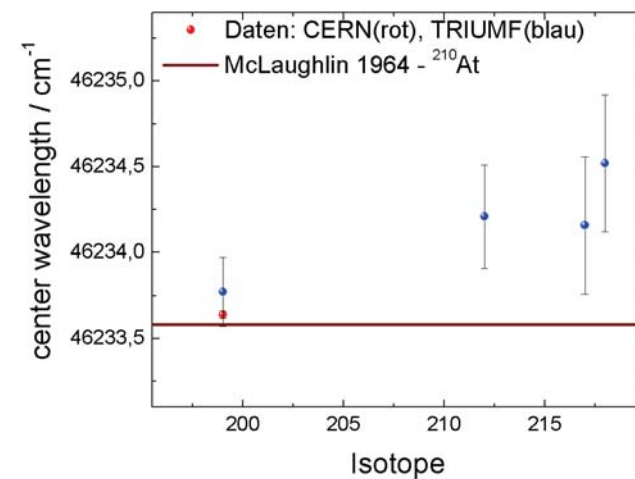
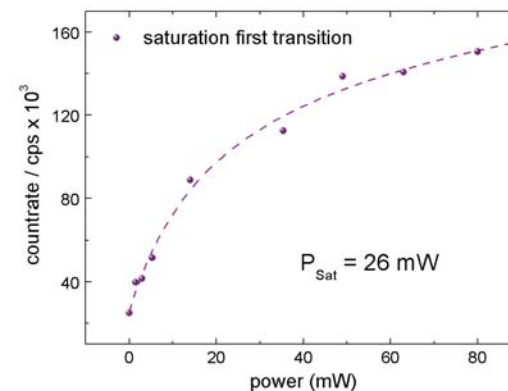
NEW: 24 measured 3<sup>rd</sup> excited states (even parity)

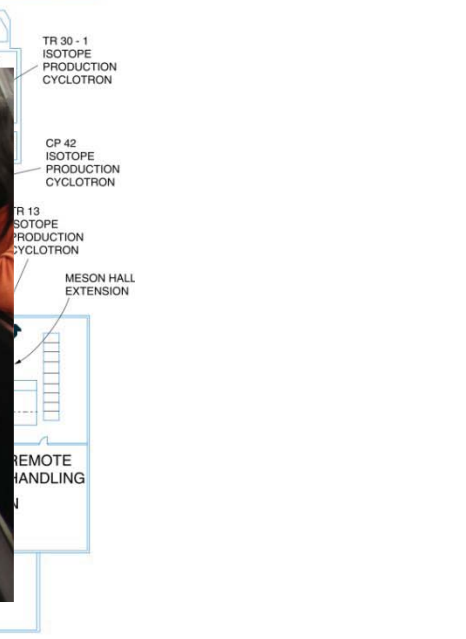
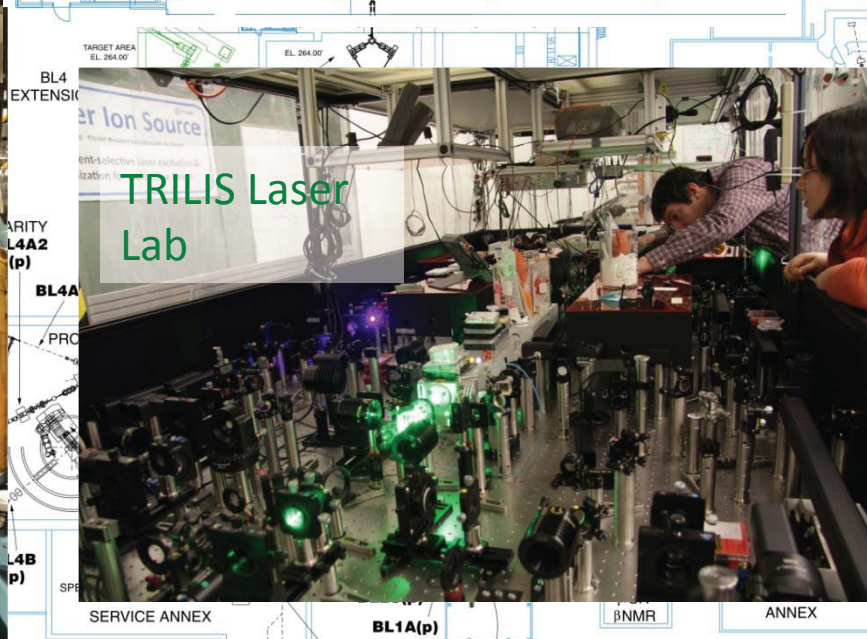
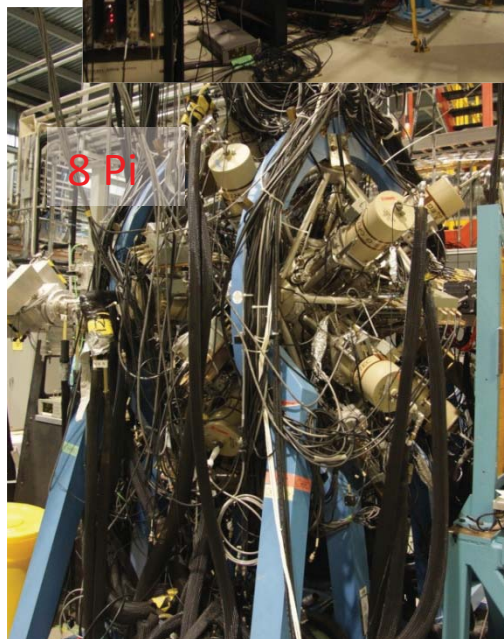
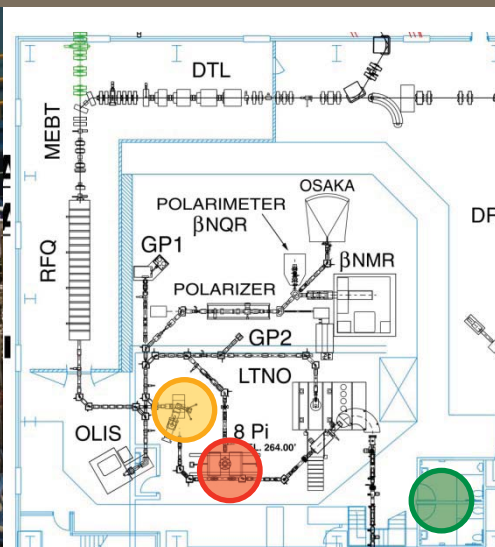
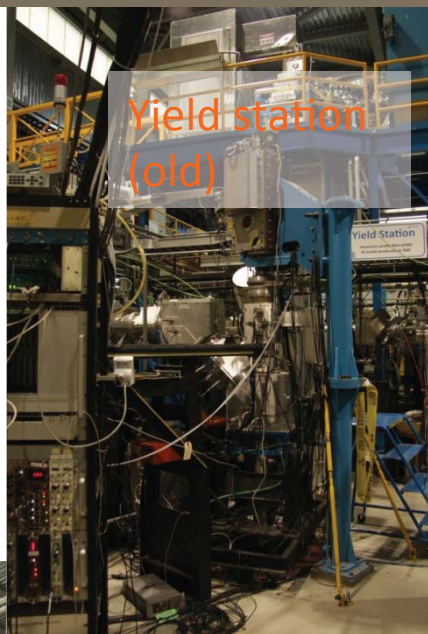
NEW: 8 measured 2<sup>nd</sup> excited states (odd parity)

Data evaluation in progress (in collaboration with atomic theory)  
Obtained wavenumber uncertainty about  $(0.5 - 1) \text{ cm}^{-1}$

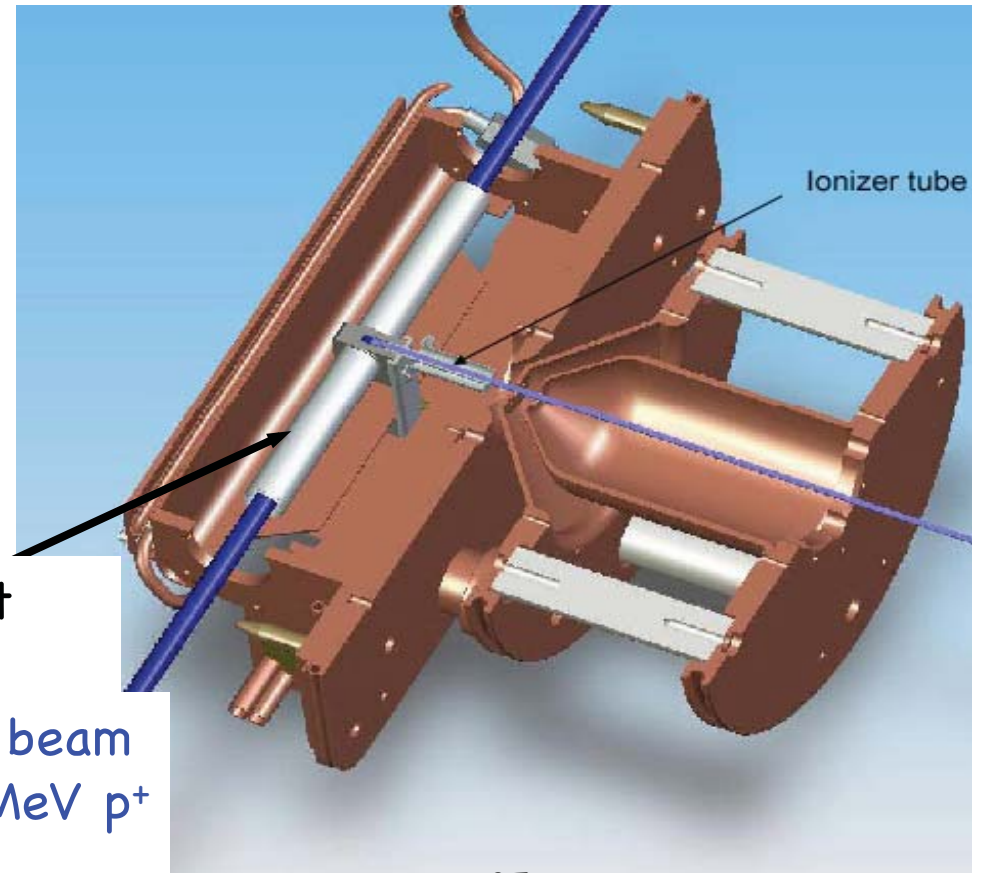
(to be published)

- Saturation measurement for first transition (approx. 26mW)
  - Saturation for second transitions
  - (approx. 100mW)
- 
- Optical isotope-shift of first transition (216 nm) isotopes 199, 212, 217 & 218 detected





thick target - hot cavity ISOL technique

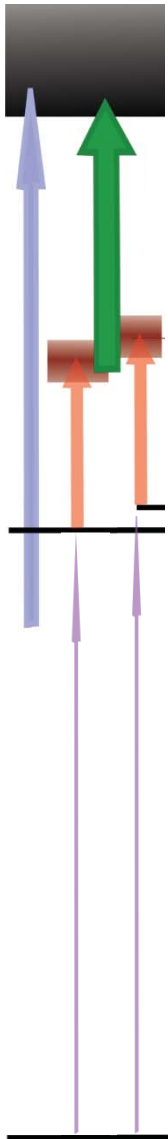


accelerator beam  
500 MeV  $p^+$

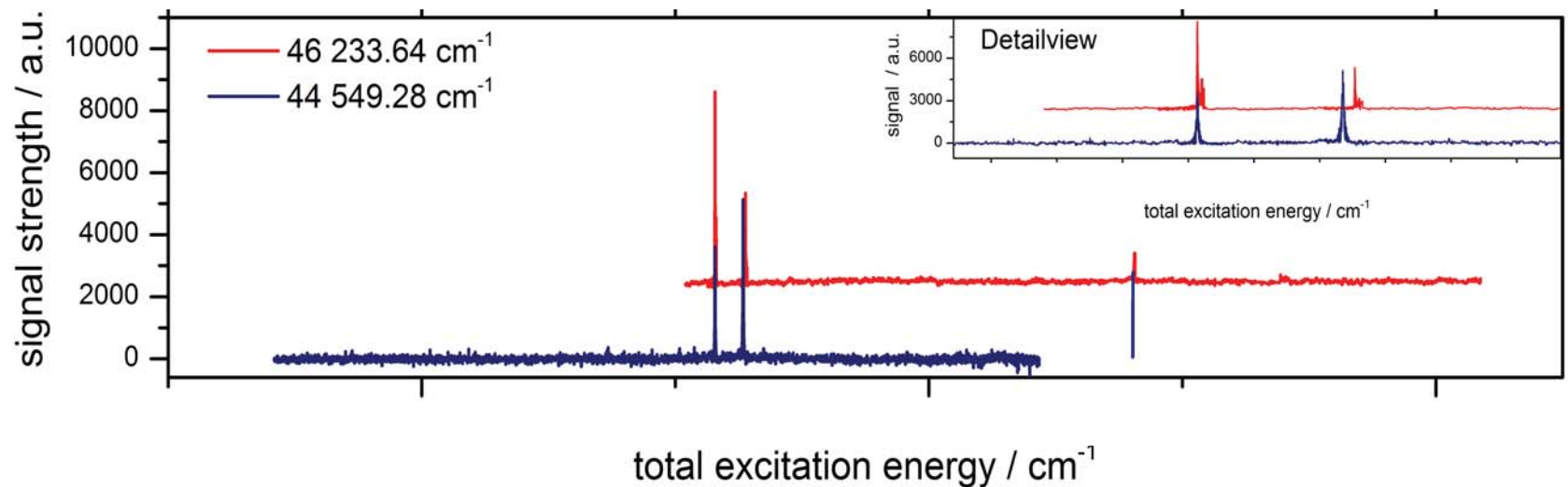
25 mm

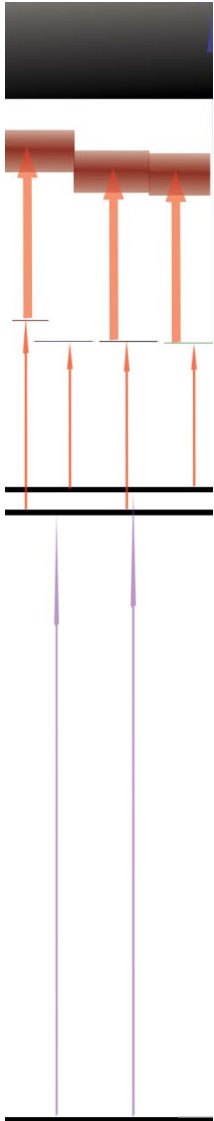
ISOL: isotope separator on-line



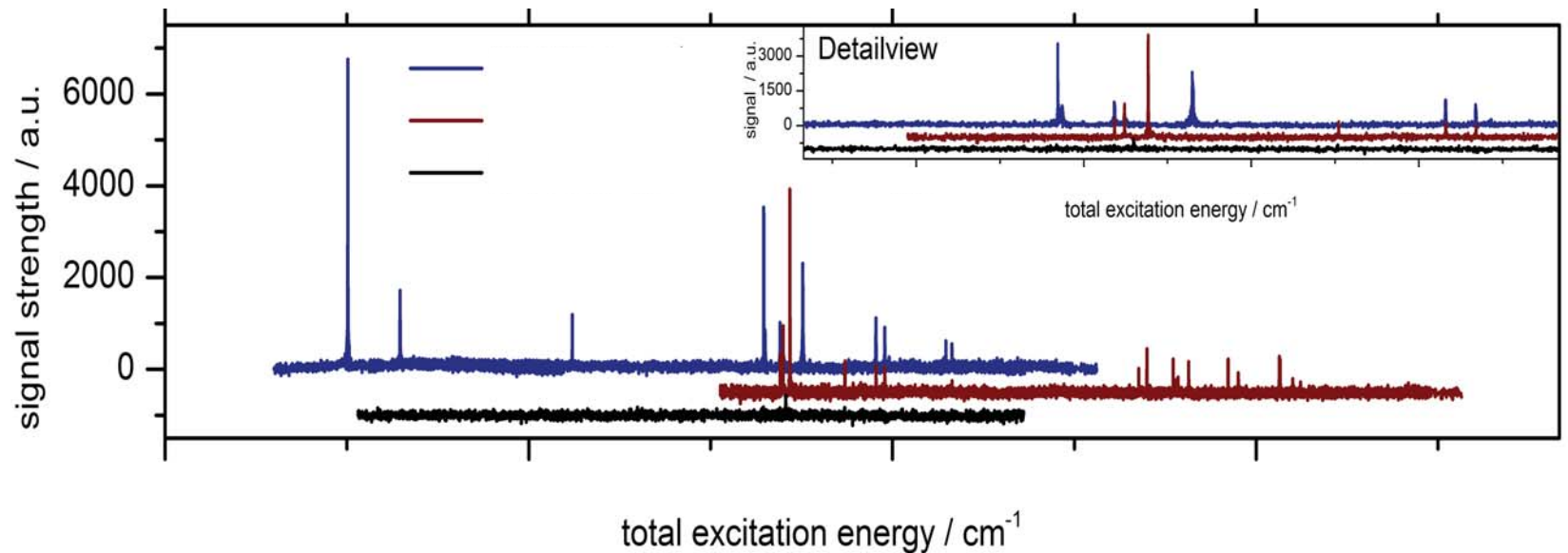


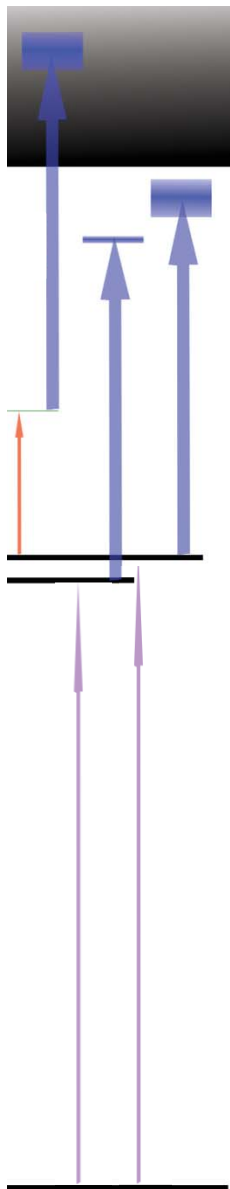
- Scan for SES from both first excited states
  - First scan last year, now repeated and second scan done,
  - 701nm transition was difficult to reach with the grating laser, therefore checked with conventional TiSa
- 6 transitions & 4 levels
  - SES @57277 cm<sup>-1</sup> (224+785nm) seen @ CERN in spring 2011 has to be corrected by ~10cm<sup>-1</sup>





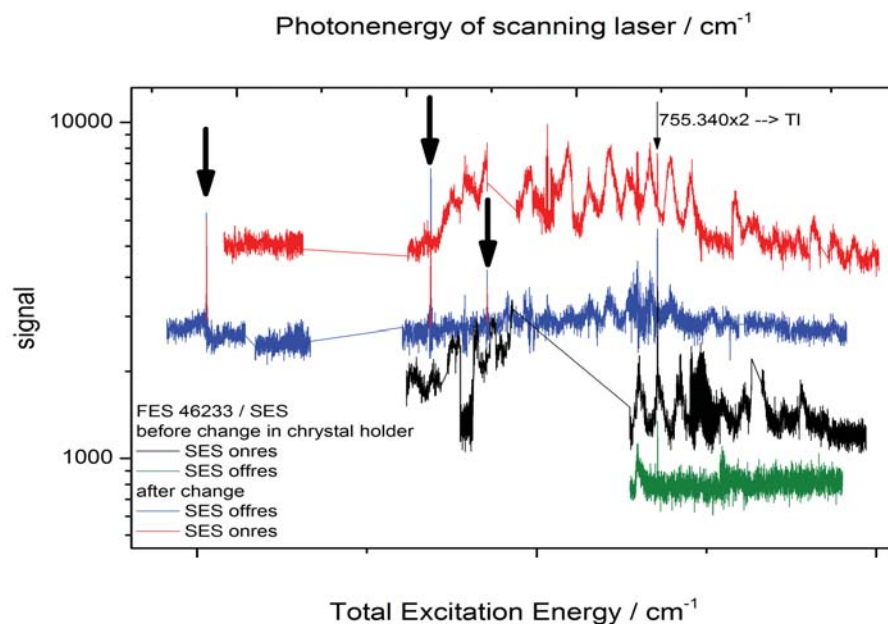
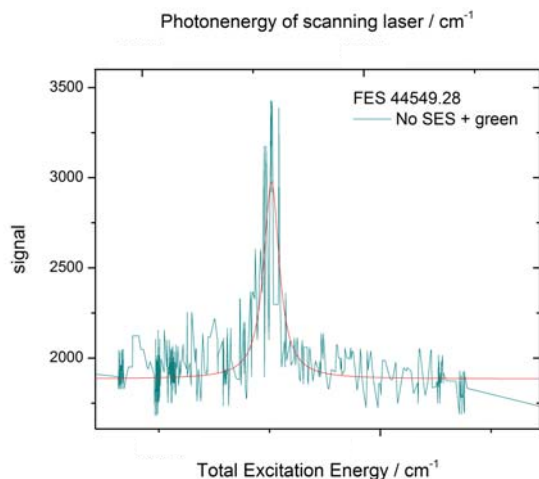
- Scan for TES from three of the four identified SES
  - Grating-Ti:Sa fundamental, temporal alignment from 720 – 900 nm possible
  - Ionization via one of the red steps
- 29 transitions and 24 levels

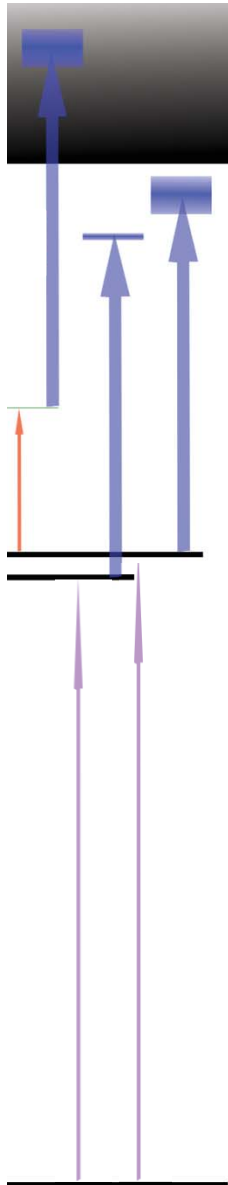




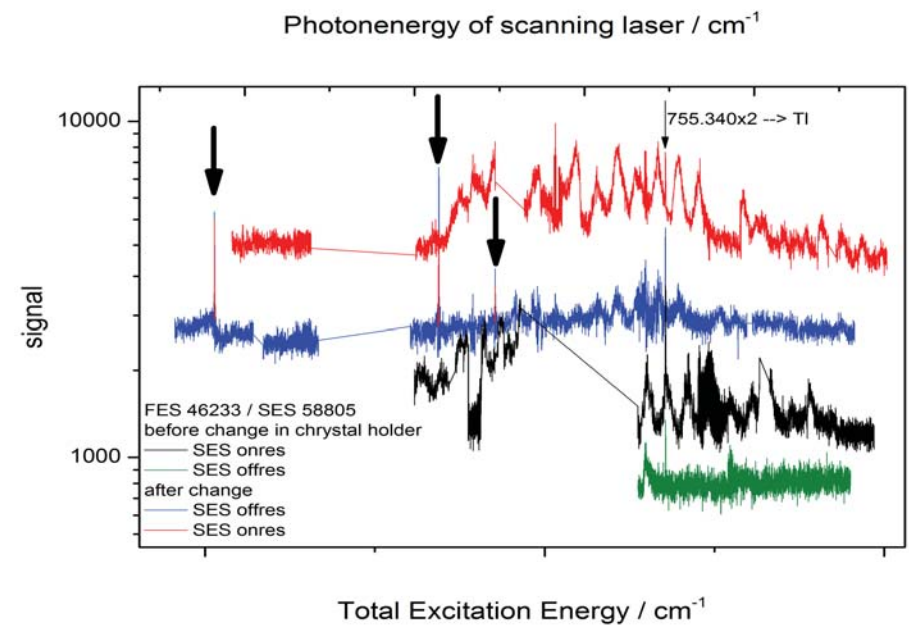
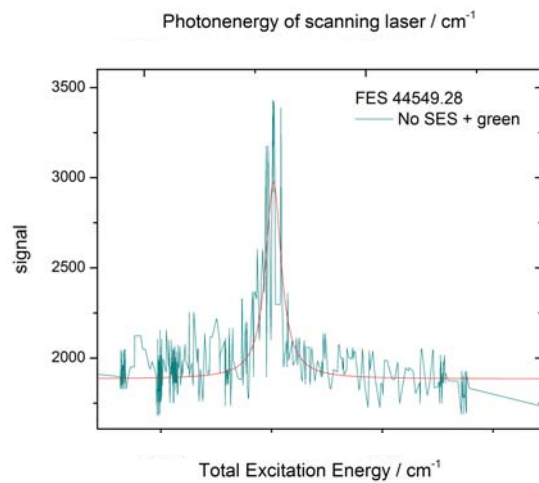
- Blue scan (frequency doubled) from FES & SES

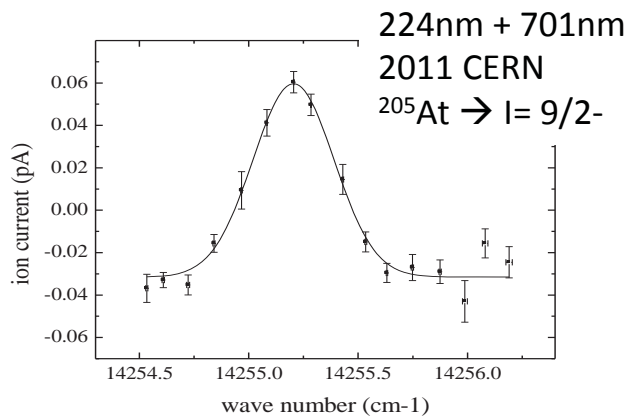
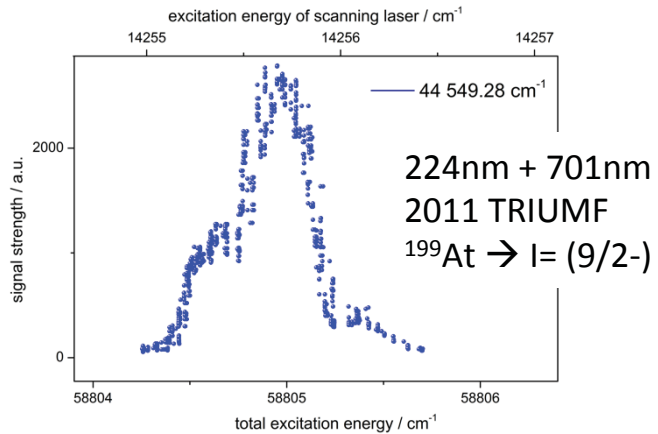
- Periodic structure due to non-resonant ionization and power fluctuation of the grating laser
- Blue also increased the background (not UV wavelength dependent), presumably TI
- Pointing stability without active stabilization of blue Ok for about 20-40 nm fundamental, then signal drops fast due to steering





- Scanning region limited to tuning range of doubling crystal
  - Scanning time slowed down significantly due to calibration requirements
  - > continued laser development required (theses: J. Grueneisen & T. Quenzel) work in progress
- Up to now: 4 transitions and 4 levels for SES, no AI state seen
- Additionally one TI transition at  $755.34\text{nm} \times 2$  was observed





## Outlook & work to do:

(i) Hyperfine structure & optical isotope shift measurements

(ii) 223, 225 At for EDM experiments

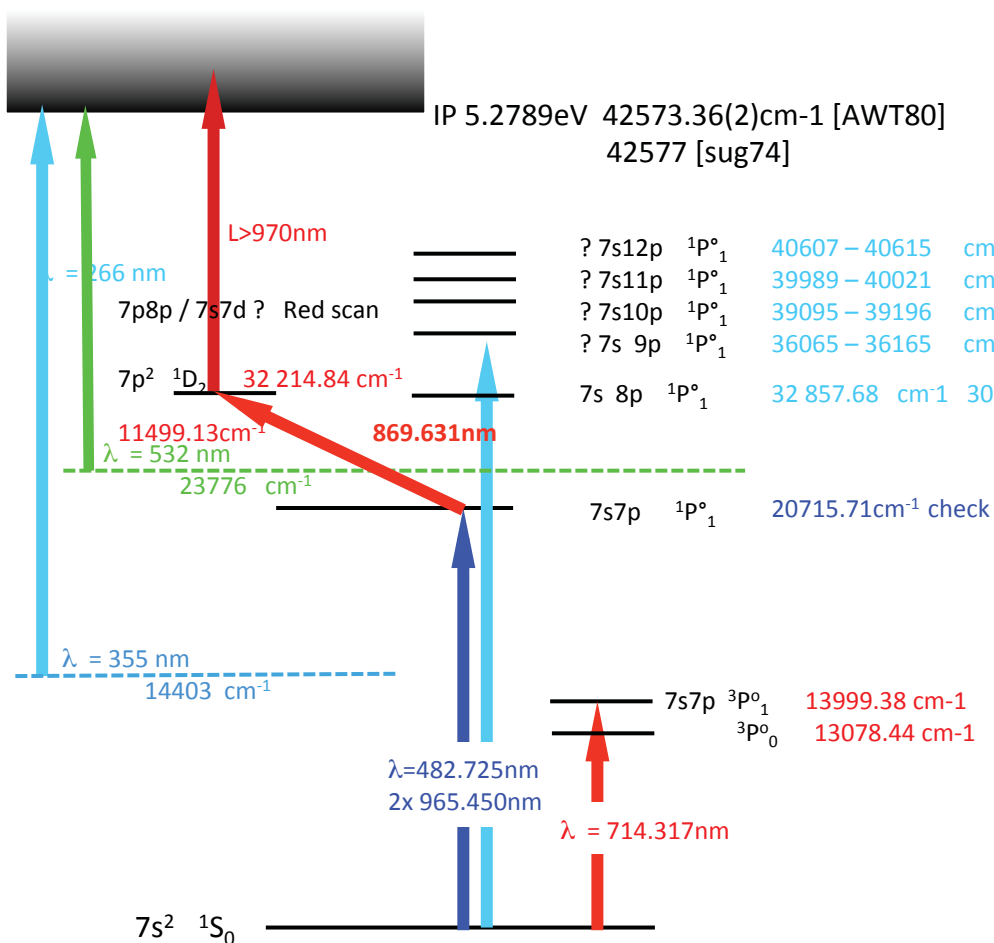
Indication of **HFS** for the 701nm transition starting from the 44549 cm-1 FES (224nm)

– Not visible in ISOLDE/CERN scan from spring 2011

To be investigated

## <sup>89</sup>225 Radium

- (i) IR scan for new states ... 482/IR/532, 304/IR (AI)
- (ii) Blue scan 482/blue (RYD-IP)
- (iii) 245–278 nm spectroscopy (3n)



IP\_Ra(i) eV 42573.36(2)cm<sup>-1</sup>

355nm limit (2x TiSa@710nm): cm<sup>-1</sup>  
266nm limit (2x YHP40): cm<sup>0</sup>

Sansonetti 17 energy levels, NIST (V4) 47 energy levels for Ra I.

J. Phys. B: Atom. Molec. Phys. **13** (1980) L133-L137.

### LETTER TO THE EDITOR

#### Bound, 7snp 1P<sub>0</sub> series in Ra I: measurements and predictions

J A Armstrong, J J Wynnet and F S TomkinsSS

t IBM T J Watson Research Center, Yorktown Heights, New York 10598, USA

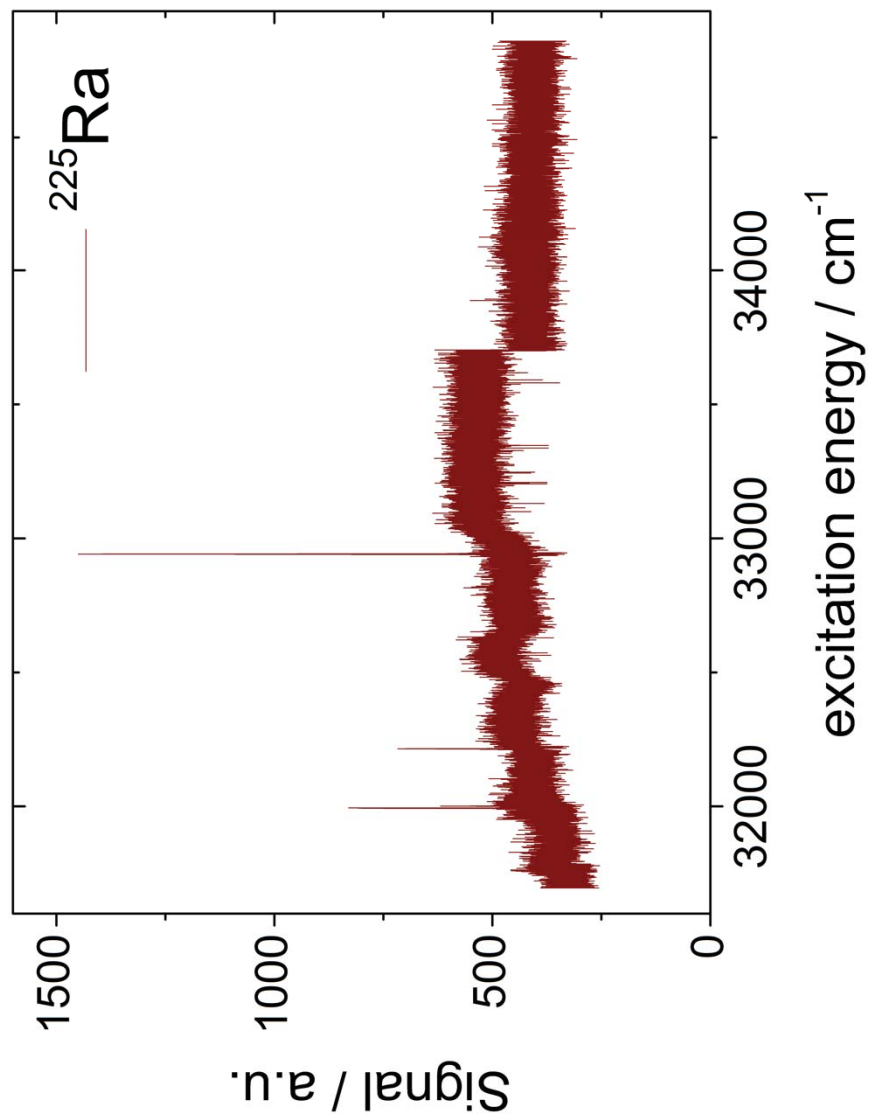
\$ Chem. Division, Argonne National Laboratory, Argonne, Illinois 60439, USA Received 27 November 1979

**Abstract.** Absorption measurements of the 7s13p-7s52p 'P: Rydberg series in Ra I are presented. A revised new value of the first ionisation limit (42573.36\*0.02cm<sup>-1</sup>) is derived.

From these measurements and from a systematic trend in Ca I, Sr I and Ba I, a multichannel quantum defect theory (MQDT) analysis is used to predict the location of the 7s9p-7s12p and 6d7p 'P: states.

Russell PR1934

Rasmussen Zphys 1934



First step  $7s7p \ ^1P^\circ \ J=1 \ 20\ 715.71 \text{ cm}^{-1}$   
 Second steps, green for ionization

measured [cm<sup>-1</sup>]    Literature [cm<sup>-1</sup>]

31 993.71	31 993.41	$7s7d \ ^3D \ 2$
32 000.84	32 000.82	$7s7d \ ^3D \ 1$
32 214.91	32 214.84	$7p^2 \ ^1D \ 2$
32 941.39	32 941.13	$7p^2 \ ^3P \ 2$

Best scheme

Signal enhancement **laser/surface= 3-4**  
 (without protons, low temperature target)

# TRIUMF Resonant Ionization Laser Ion Source - recent At & Ra RIMS

Recent on-line developments – At & Ra  
 status 2/2012

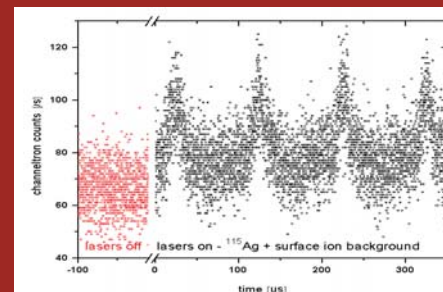
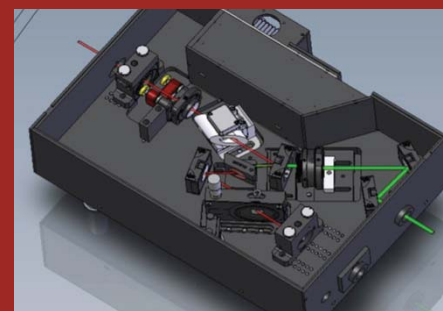
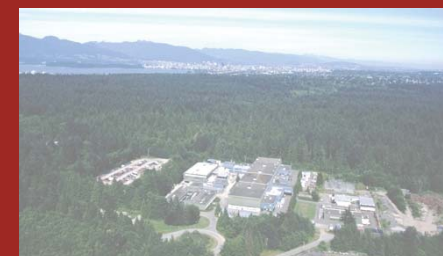
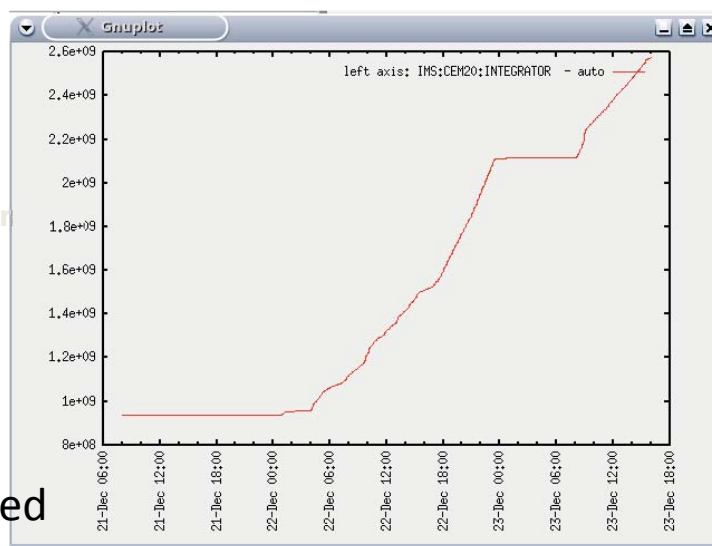
Jens Lassen | Research Scientist | TRIUMF Accelerator Division

ISAC science forum 01Feb2012

Collaborations:  
 ORNL-HRIBF, GANIL, CERN-ISOLDE  
 Mainz U, TU Darmstadt, U Applied Sciences Oldenburg

Current students:  
 U Guelph, FHO Emden, U Manitoba

CEM20 with A=225 mass  
 => approx. 3k Bq accumulated





Group

1A 1 2A 2 3A 13 4A 14 5A 15 6A 16 7A 17 8A 18

1 H 2 He  
Hydrogen Helium

2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne  
Lithium Beryllium Boron Carbon Nitrogen Oxygen Fluorine Neon

3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar  
Sodium Magnesium Aluminum Silicon Phosphorus Sulfur Chlorine Argon

4 19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr  
Potassium Calcium Scandium Titanium Vanadium Chromium Manganese Iron Cobalt Nickel Copper Zinc Gallium Germanium Arsenic Selenium Bromine Krypton

5 37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe  
Rubidium Strontium Yttrium Zirconium Niobium Molybdenum Technetium Ruthenium Rhodium Palladium Silver Cadmium Indium Tin Antimony Tellurium Iodine Xenon

6 55 Cs 56 Ba 57-71 \* 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn  
Cesium Barium Lanthanides Hafnium Tantalum Tungsten Rhenium Osmium Iridium Platinum Gold Mercury Thallium Lead Bismuth Polonium Astatine Radon

7 87 Fr 88 Ra 89-103 \*\* 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 113 114 115  
Francium Radium Actinides Rutherfordium Dubnium Seaborgium Bohrium Hassium Meitnerium Darmstadtium Roentgenium Ununbium [284] [289] [288]

8B 8 9 10

Legend:  
■ T RILIS isotopes on-line status: 12/2011  
■ tested TiSa laser schemes status: 06/2011 (TiSa network: Mainz, TRIUMF, ORNL, JYFL, ISOLDE)  
■ Ti:Sa laser ionization scheme on paper (theory)

Jens Lassen  
TRI LIS status: 01/2012

*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
	Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium

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