Исследование изотопов астата с помощью лазерного источника на установке ISOLDE (CERN): зарядовые радиусы и электромагнитные моменты

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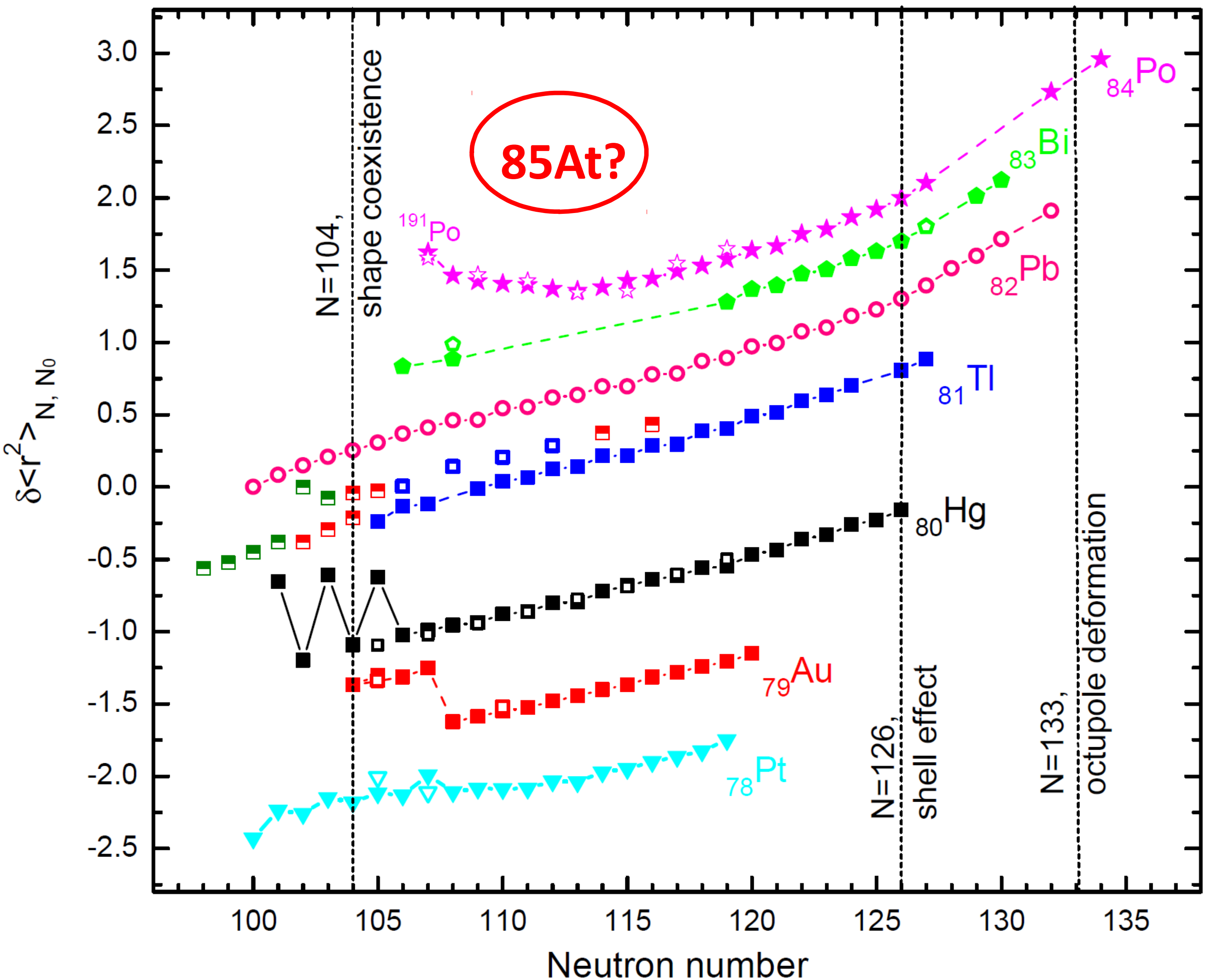
24.03.2015

Исследование изотопов астата с помощью лазерного источника на установке ISOLDE (CERN):

- Мотивация
- Экспериментальная техника (“Dual tunable laser system”, MR ToF, LIST)
- Оптическая спектроскопия атомов At
- Анализ данных
- Предварительные результаты: зарядовые радиусы и электромагнитные моменты

Charge radii in Pb-region

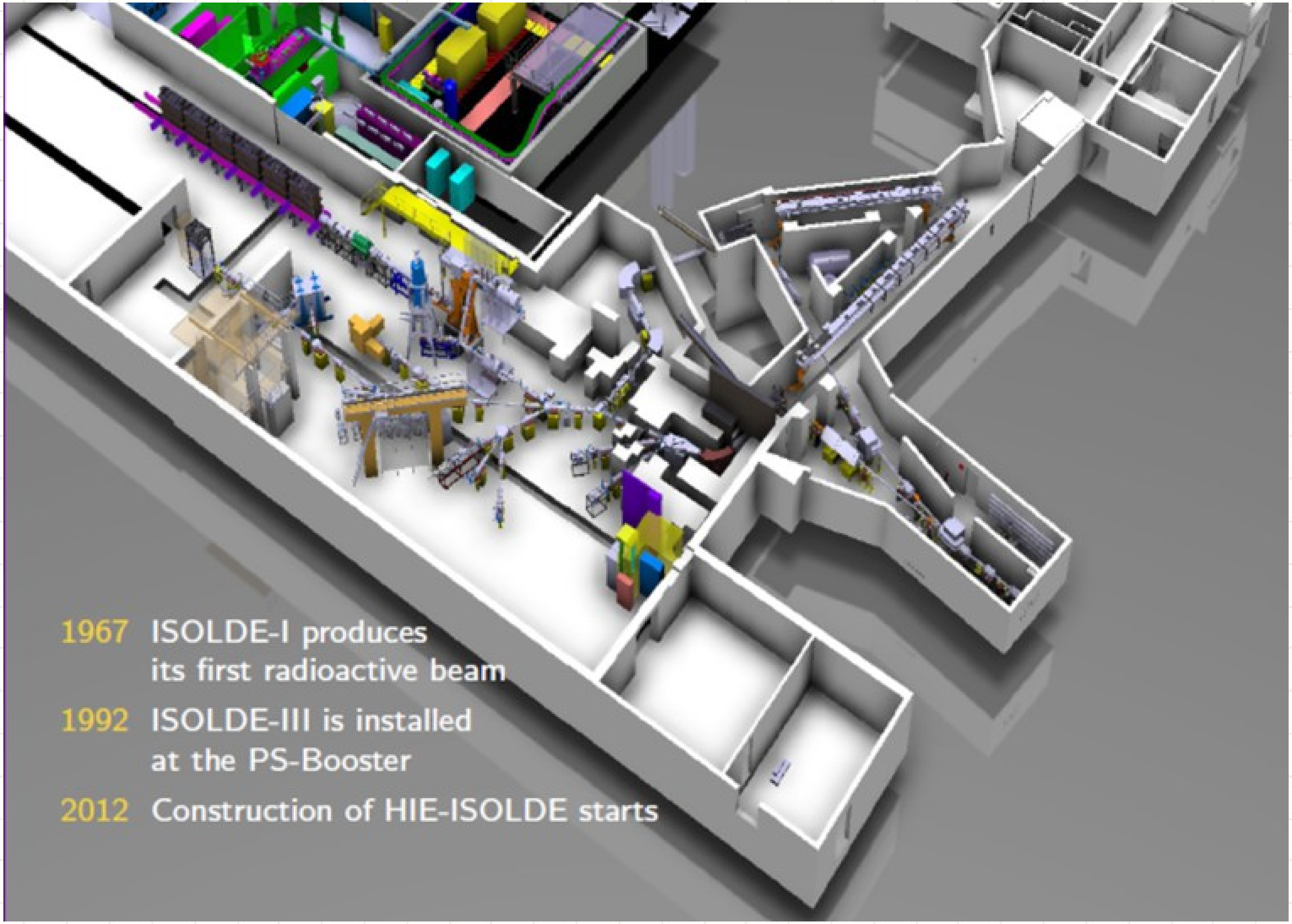


ISOLDE projects:

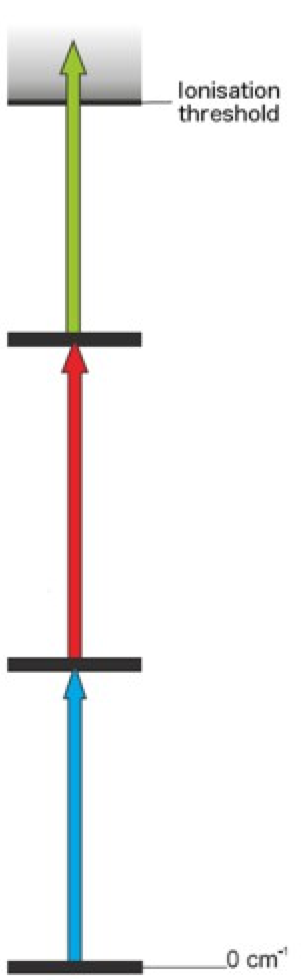
I-086:
"Development of astatine ion beams with RILIS"

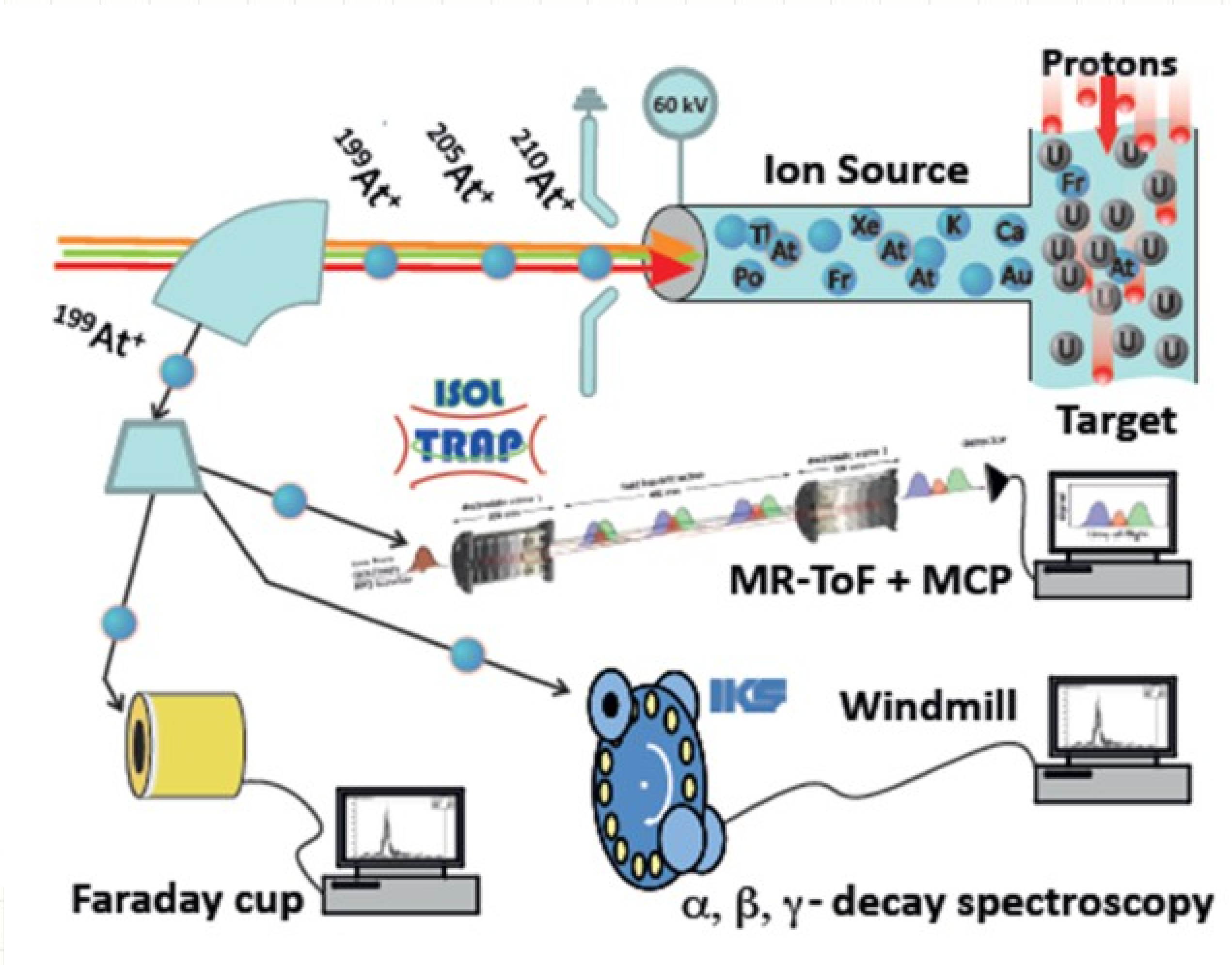
IS-534:
"Beta-delayed fission, laser spectroscopy and shape-coexistence studies with radioactive At beams"

ISOLDE (CERN)

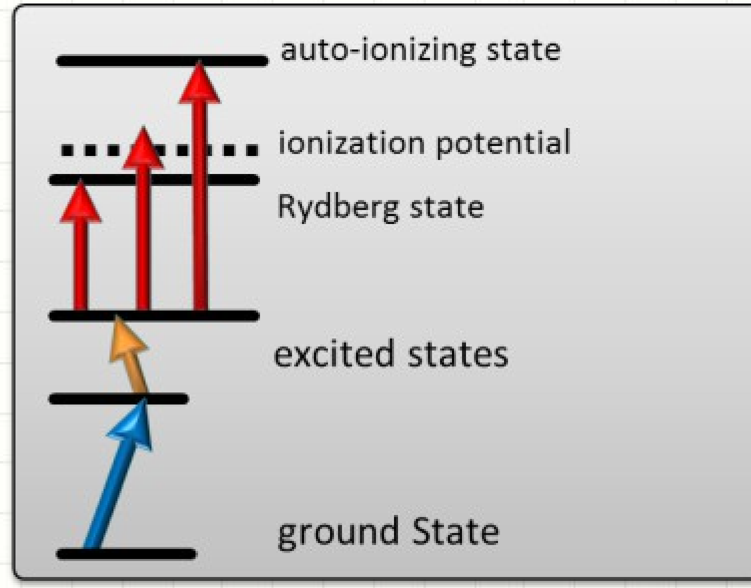

1967 ISOLDE-I produces its first radioactive beam
1992 ISOLDE-III is installed at the PS-Booster
2012 Construction of HIE-ISOLDE starts

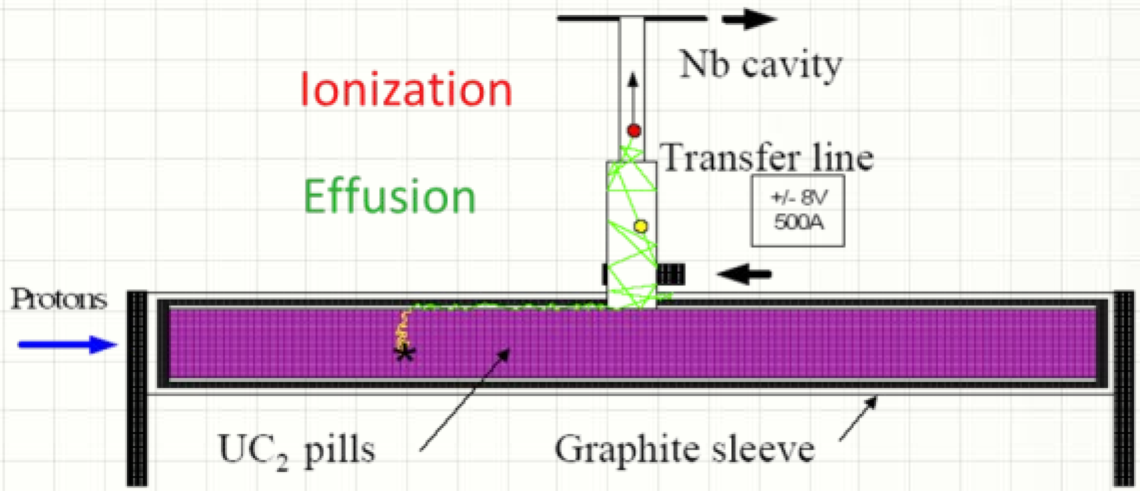
In-source laser spectroscopy





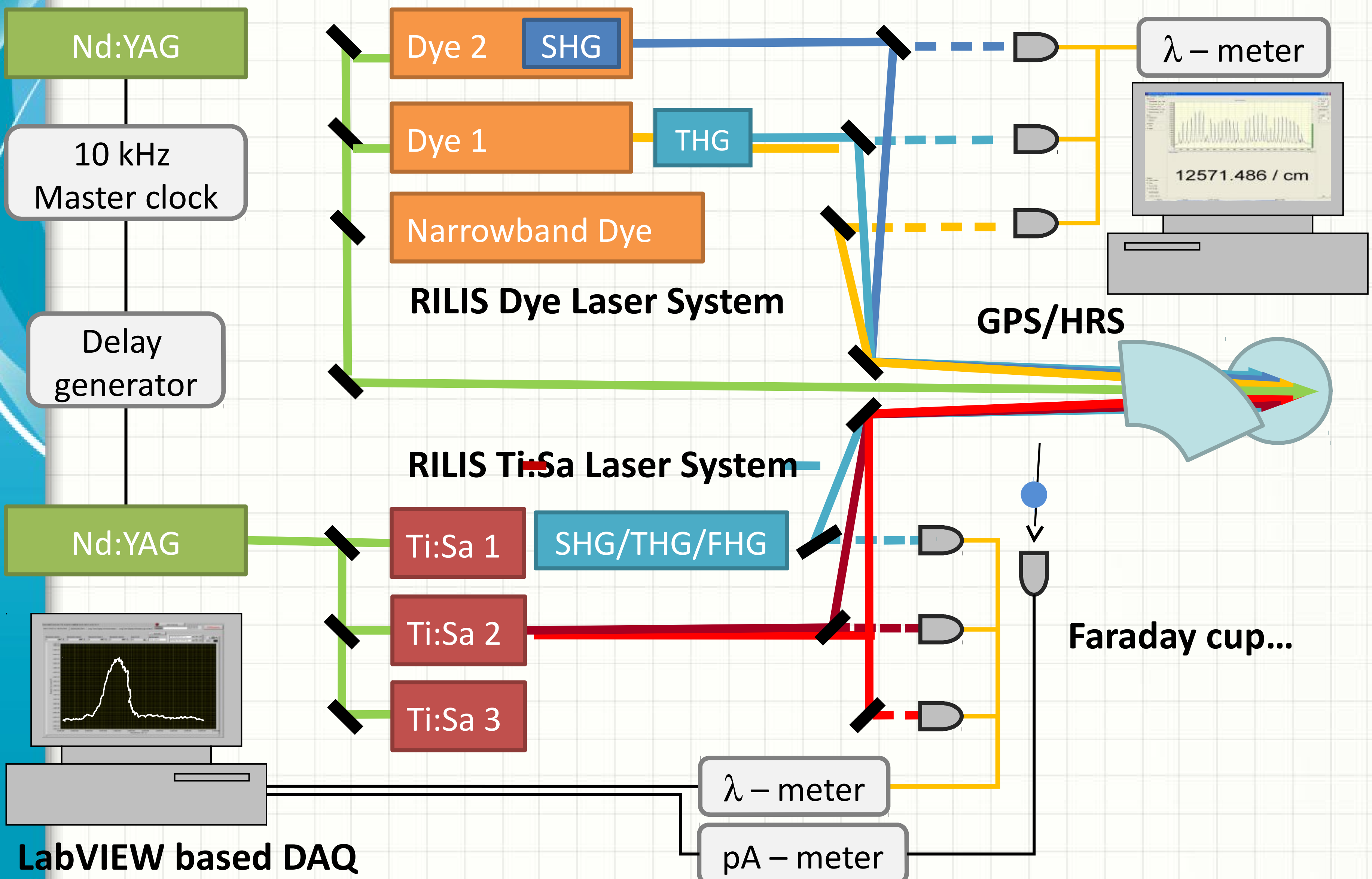
Target –Ion Source unit



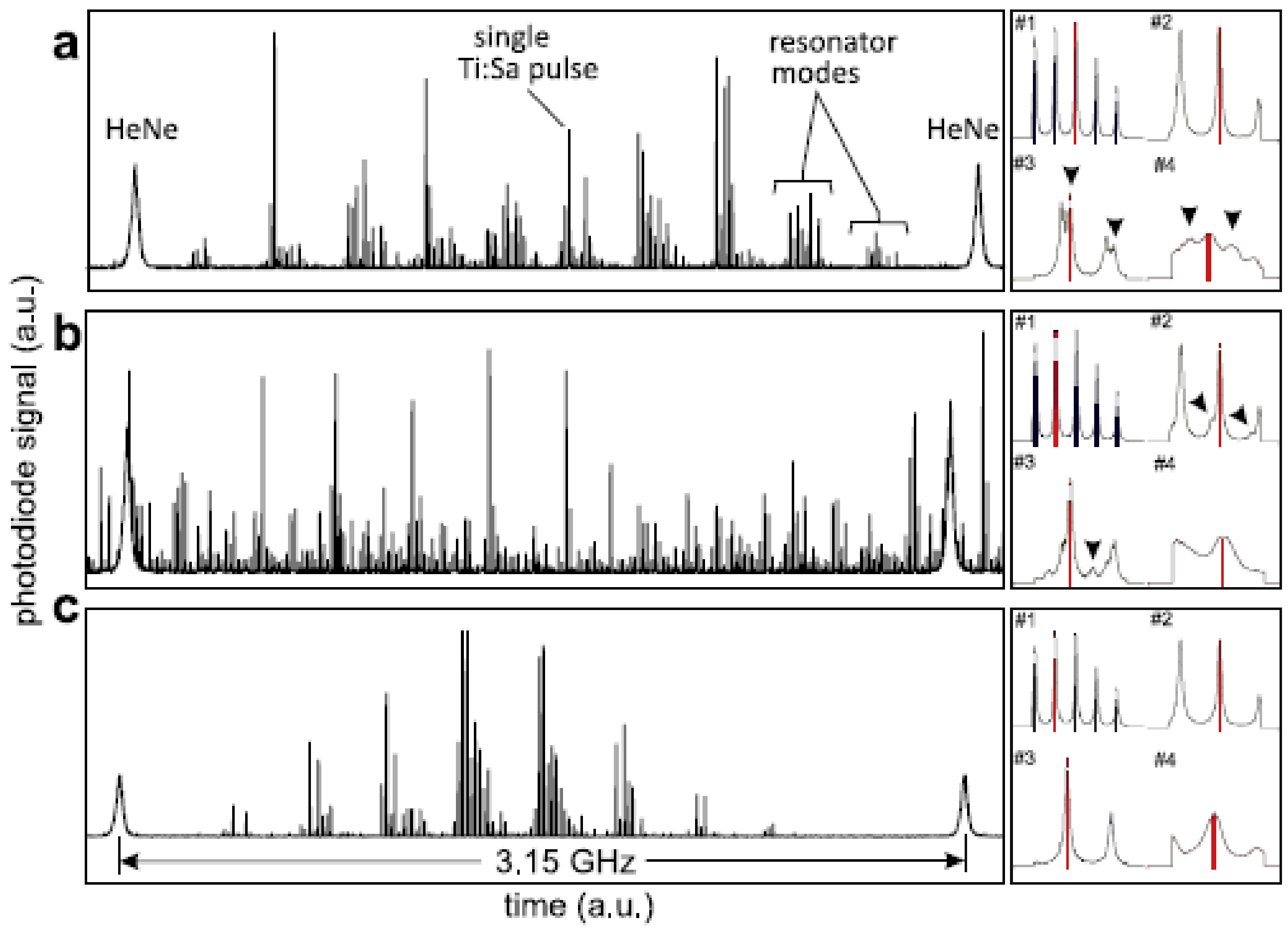


RILIS Lasers

RILIS laser system

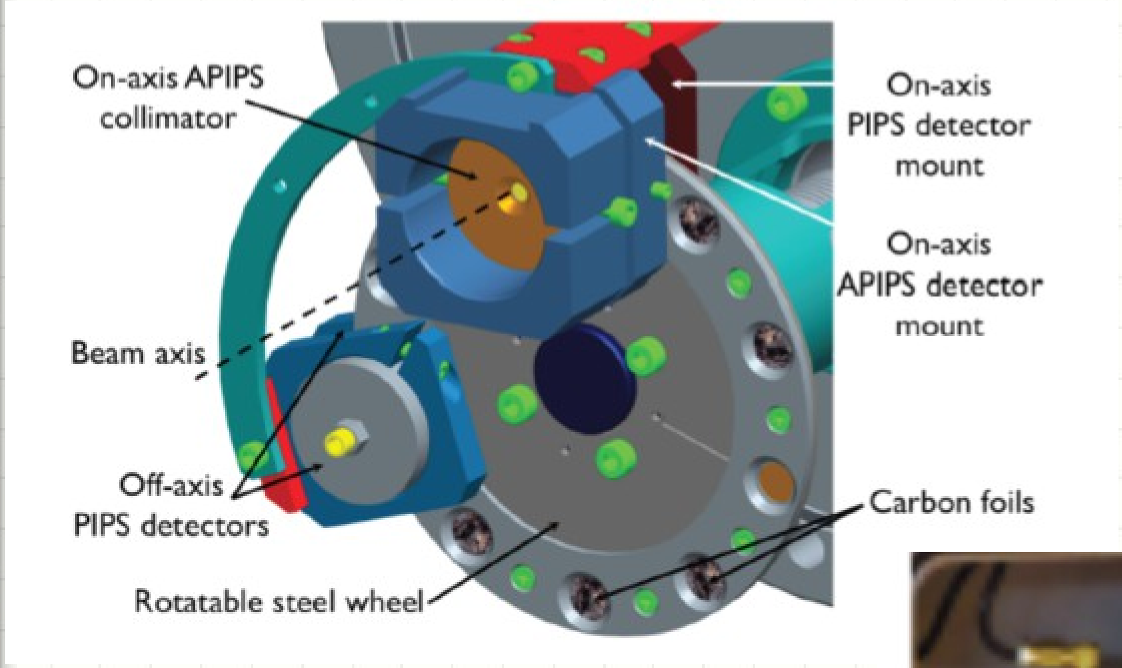


Narrow-band Ti:Sa laser

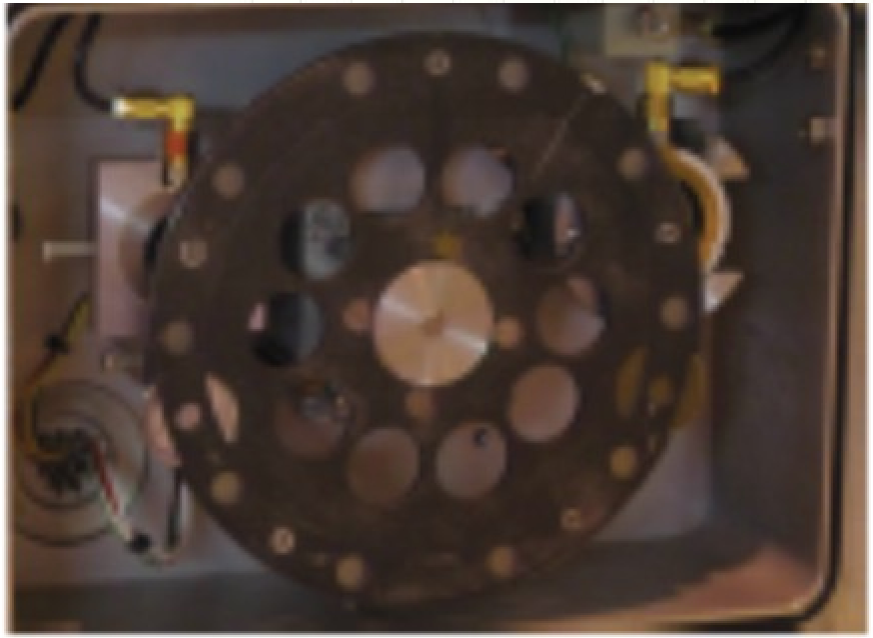


Spectra of the narrow-band Ti:Sa laser recorded with the scanning Fabry-Perot interferometer

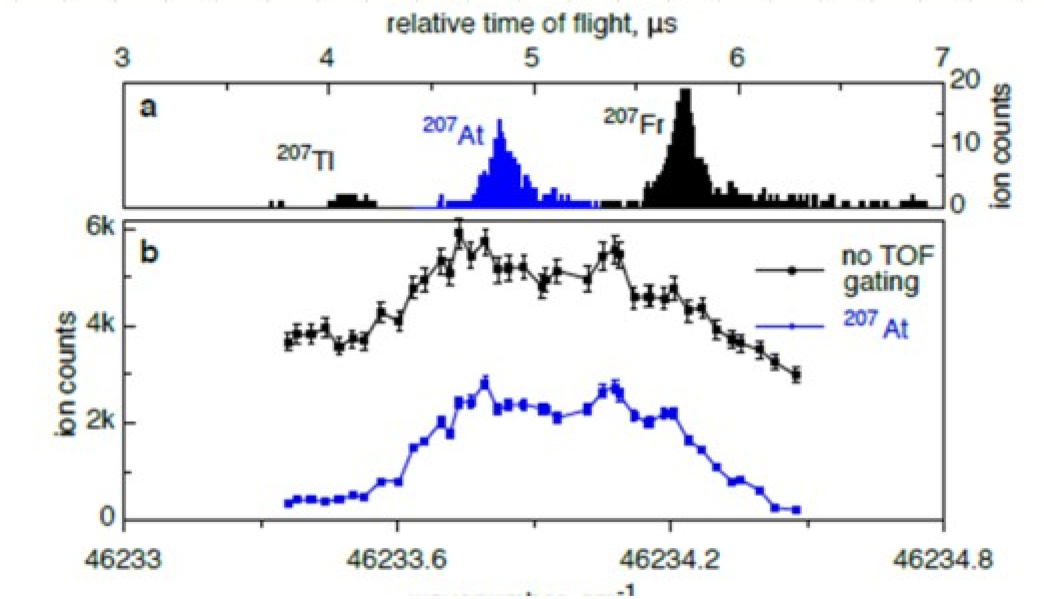
α-detection: "Windmill" station



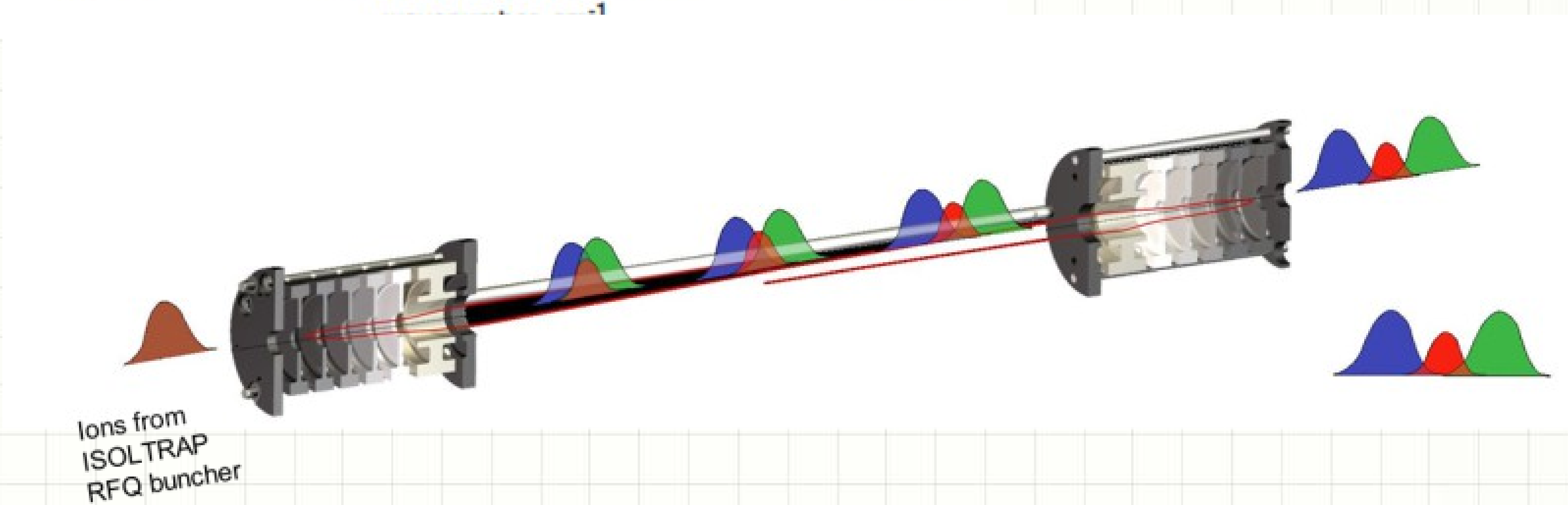
10 carbon foils:
10 mm diameter
20 µg/cm2



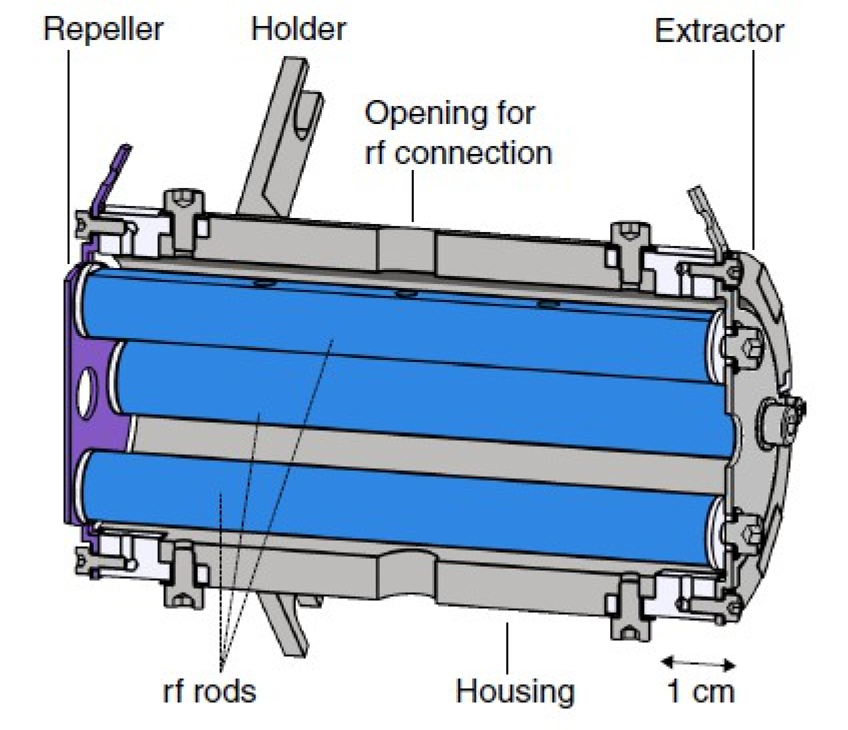
MR-ToF detection

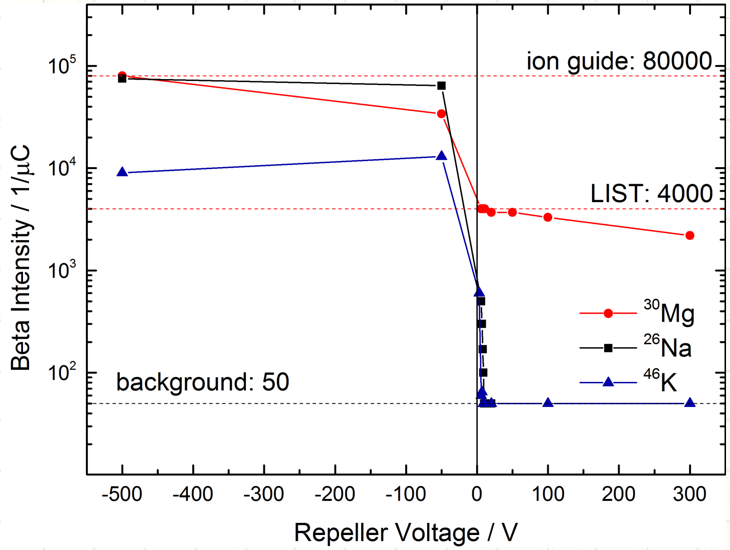


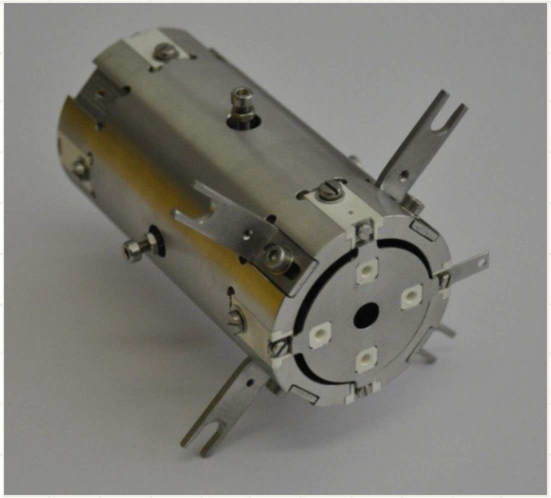
~1000 revolutions, ~35 ms, m/Δm ~ 105

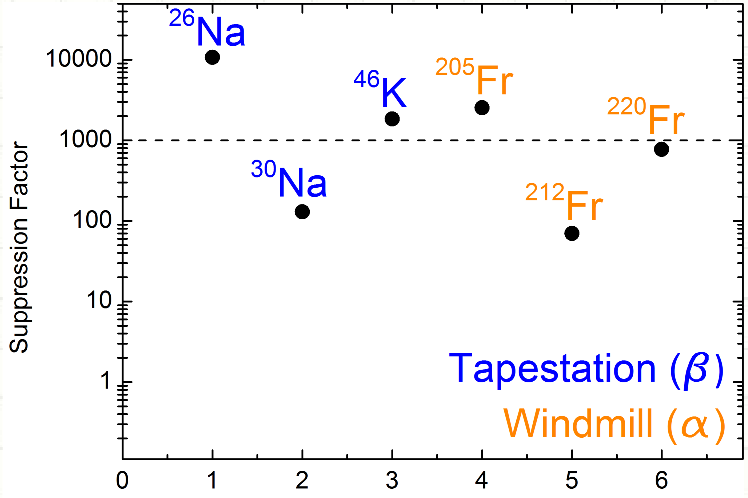


LIST: Laser Ion Source Trap

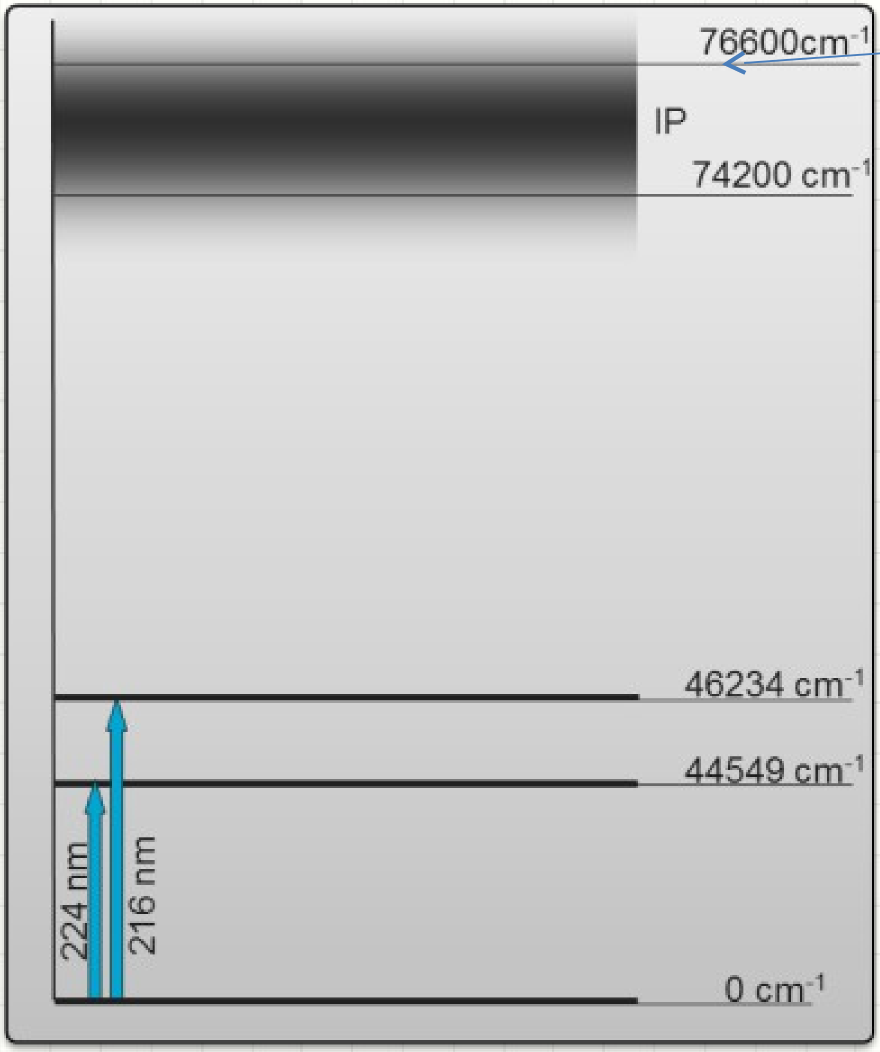








At: atomic spectroscopy

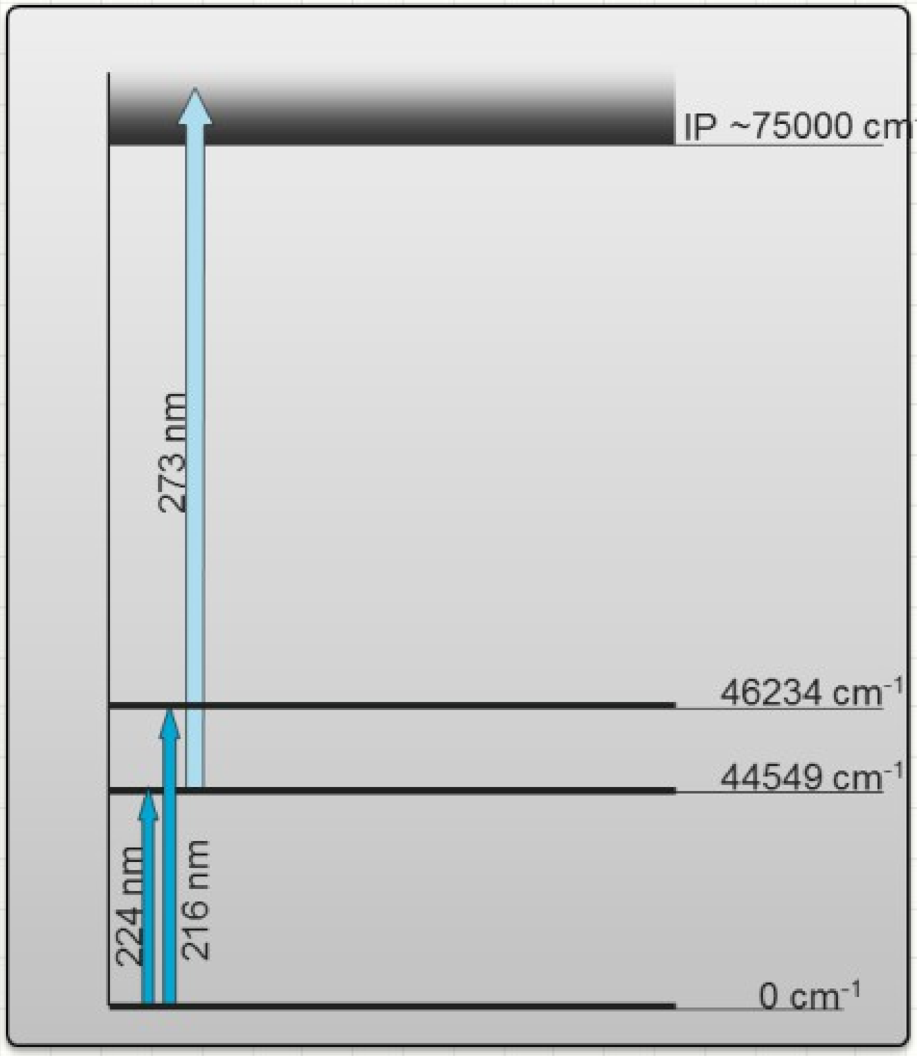


Theoretical estimation

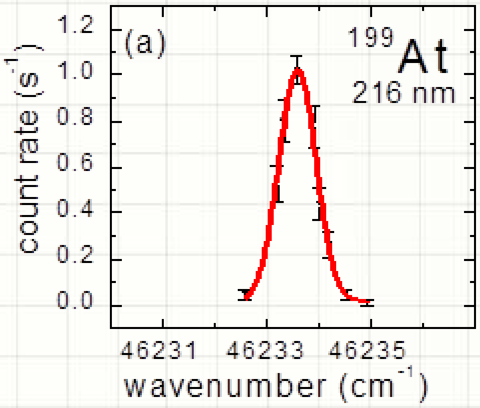
Reference	Year	IP (eV)	IP (cm^{-1})
[Fin55]	1955	9.2 ± 0.4	74 203 ± 6 500
[Kis60]	1960	9.5	76 623
[Kue91]	1991	9.4	75 816
[Mit06]	2006	9.24	74 526
[Cha10]	2010	9.35 ± 0.01	75 413 ± 160

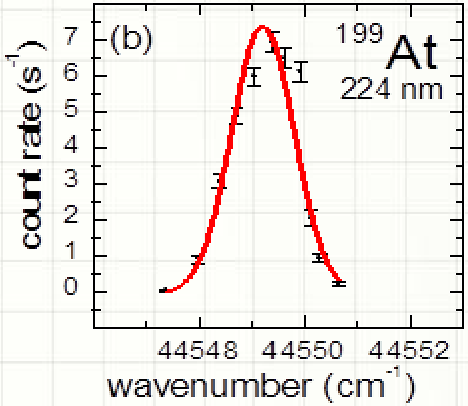
Only 2 lines were known!

At: atomic spectroscopy

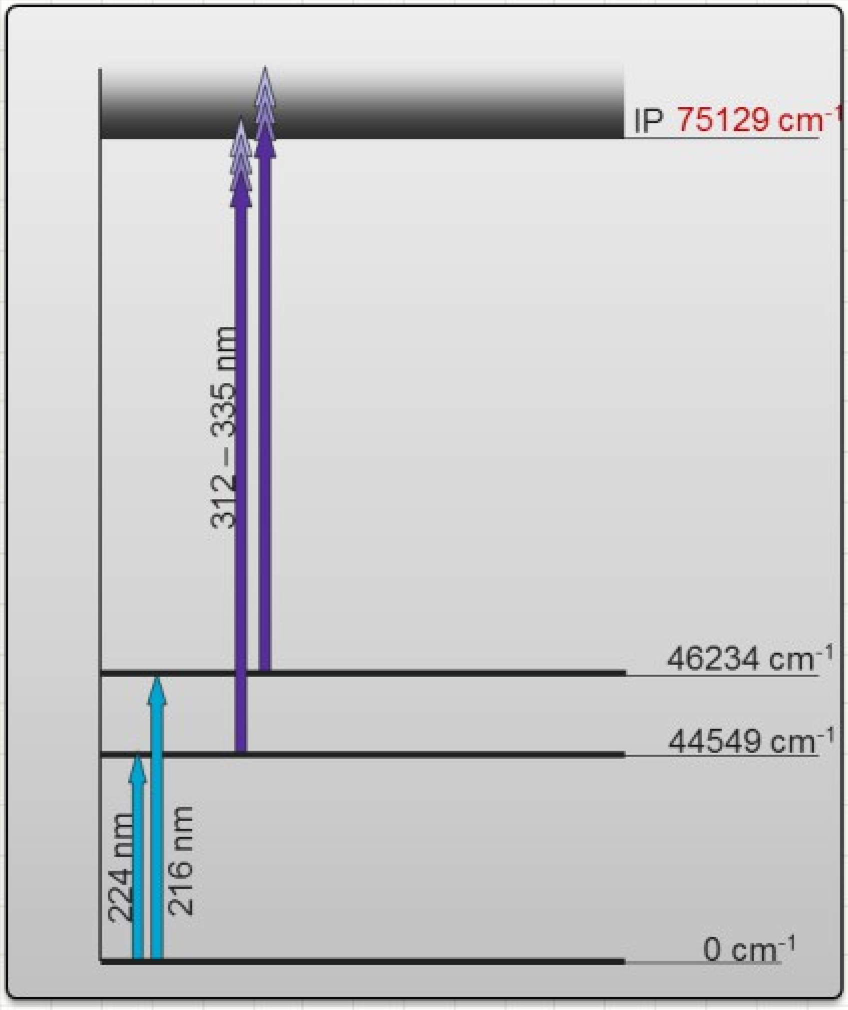


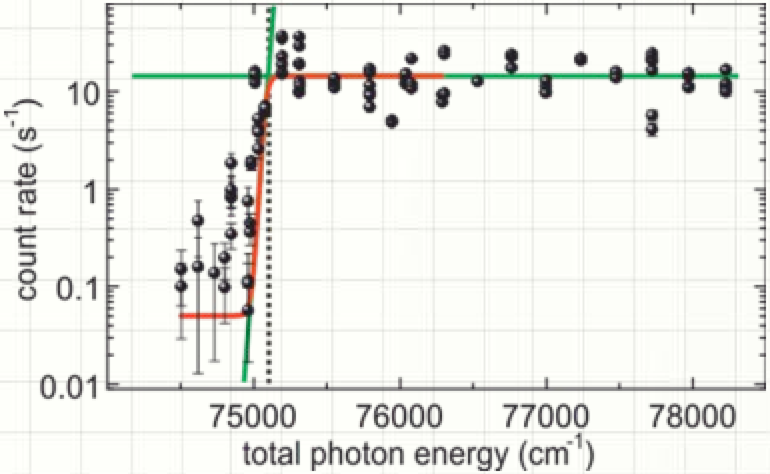
- ~2W @ 273 nm for non-resonant ionization
- Laser scans of 224 nm and 216 nm transitions
- Very low yields 1-10 s-1
- ~5 min per wavelength step





At: atomic spectroscopy



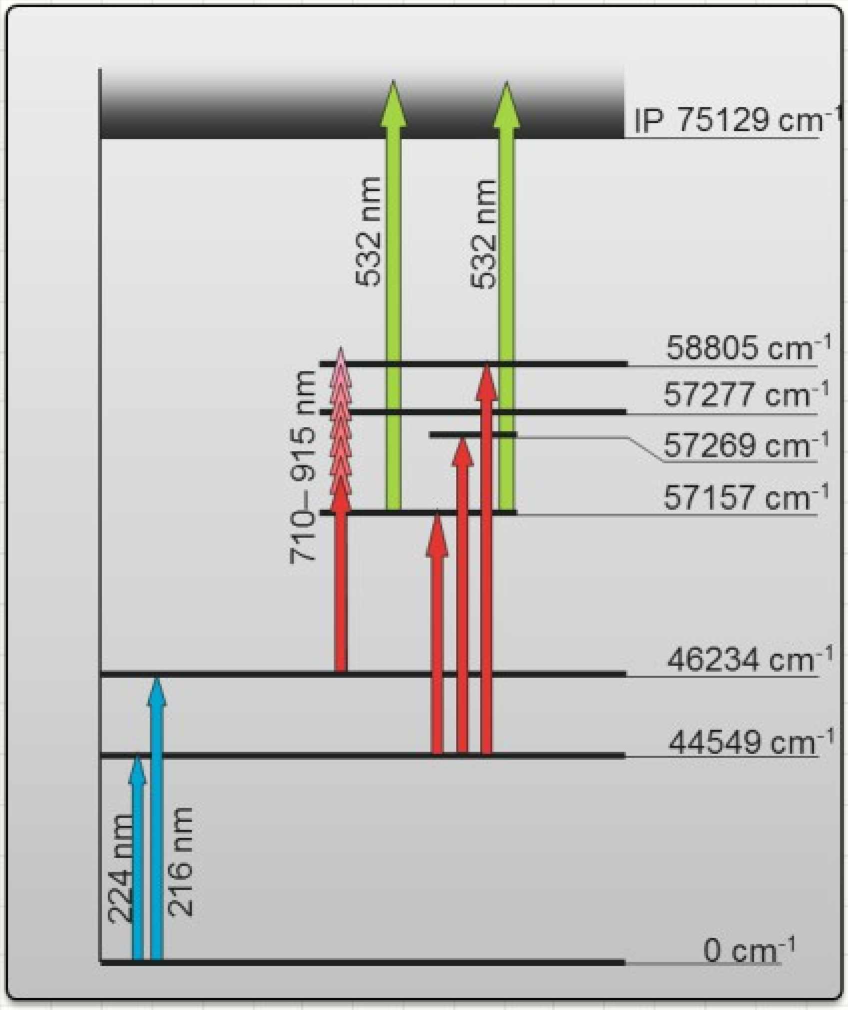


- Laser scan of second laser
- Low resolution
- Required ~6 h data taking

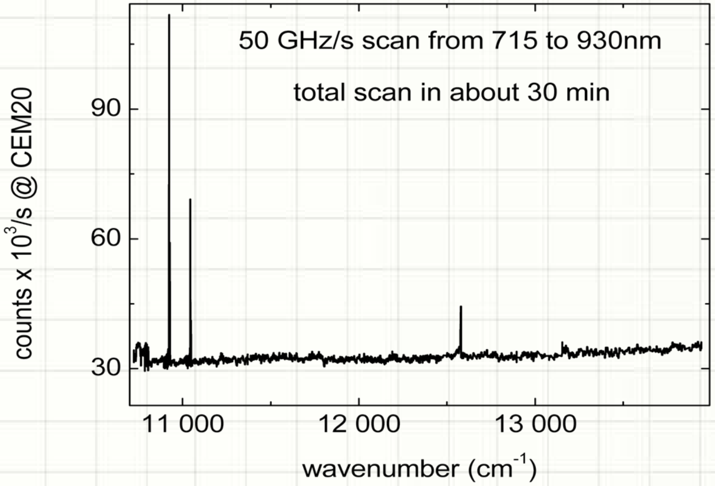
IPthreshold(At) = 75129(95) cm-1

- Higher resolution needed
- low yield due to low laser power in final step
- 3-color scheme allows use of 532 nm (50W)

At: atomic spectroscopy

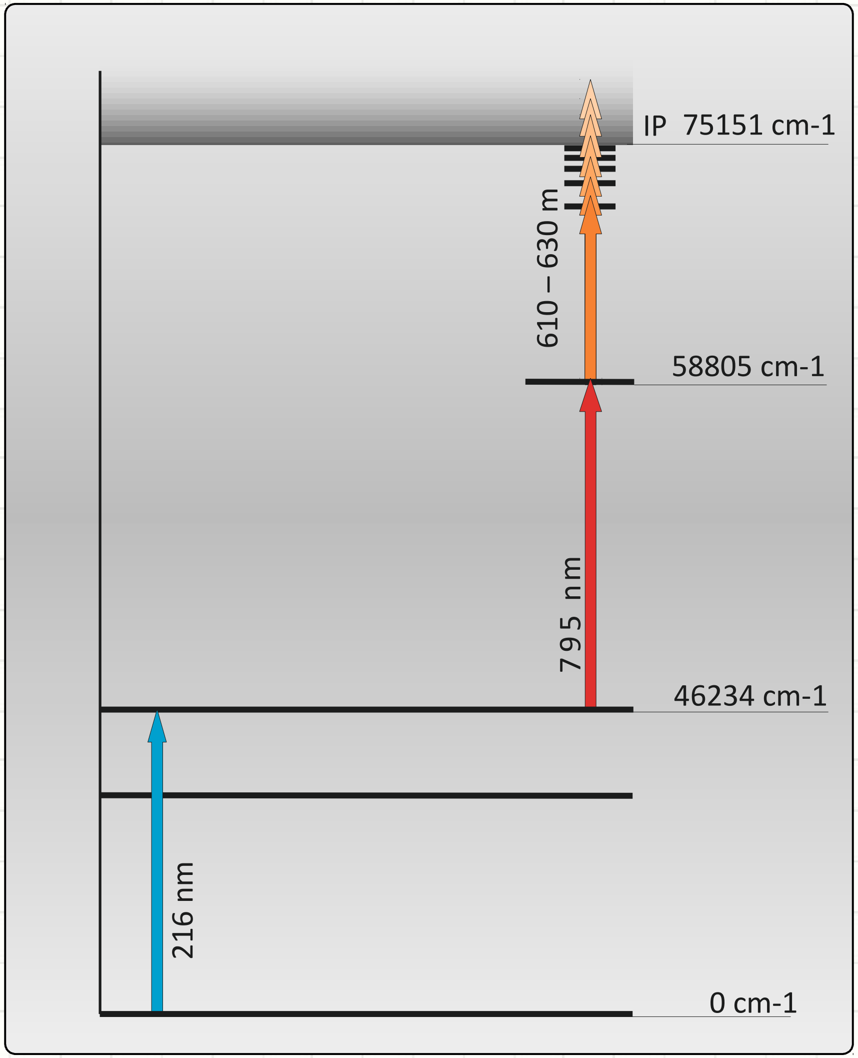


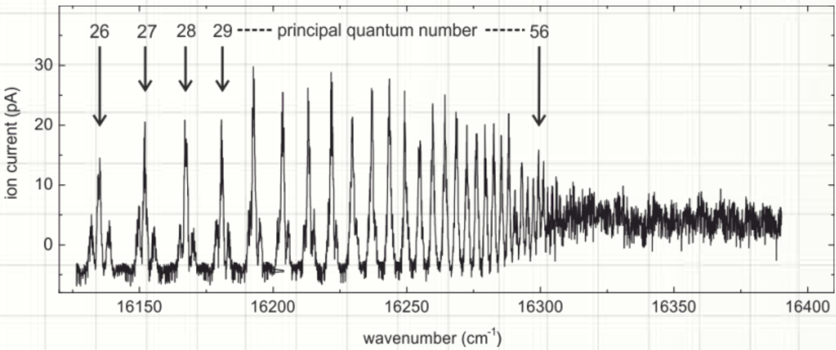
- Spectroscopy at ISAC/TRIUMF (199At)
- cw proton beam from cyclotron
- 200 nm scan: 3 new transitions
- Verified at ISOLDE/CERN (205At)

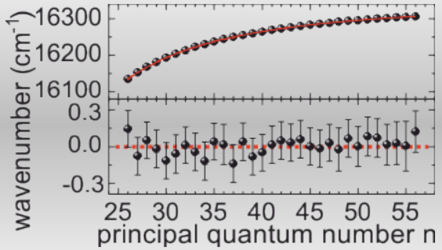


- 6 transitions, 4 new energy levels available
- Up to 150 pA of 205At
- Continuously measurable with Faraday cup

At: atomic spectroscopy







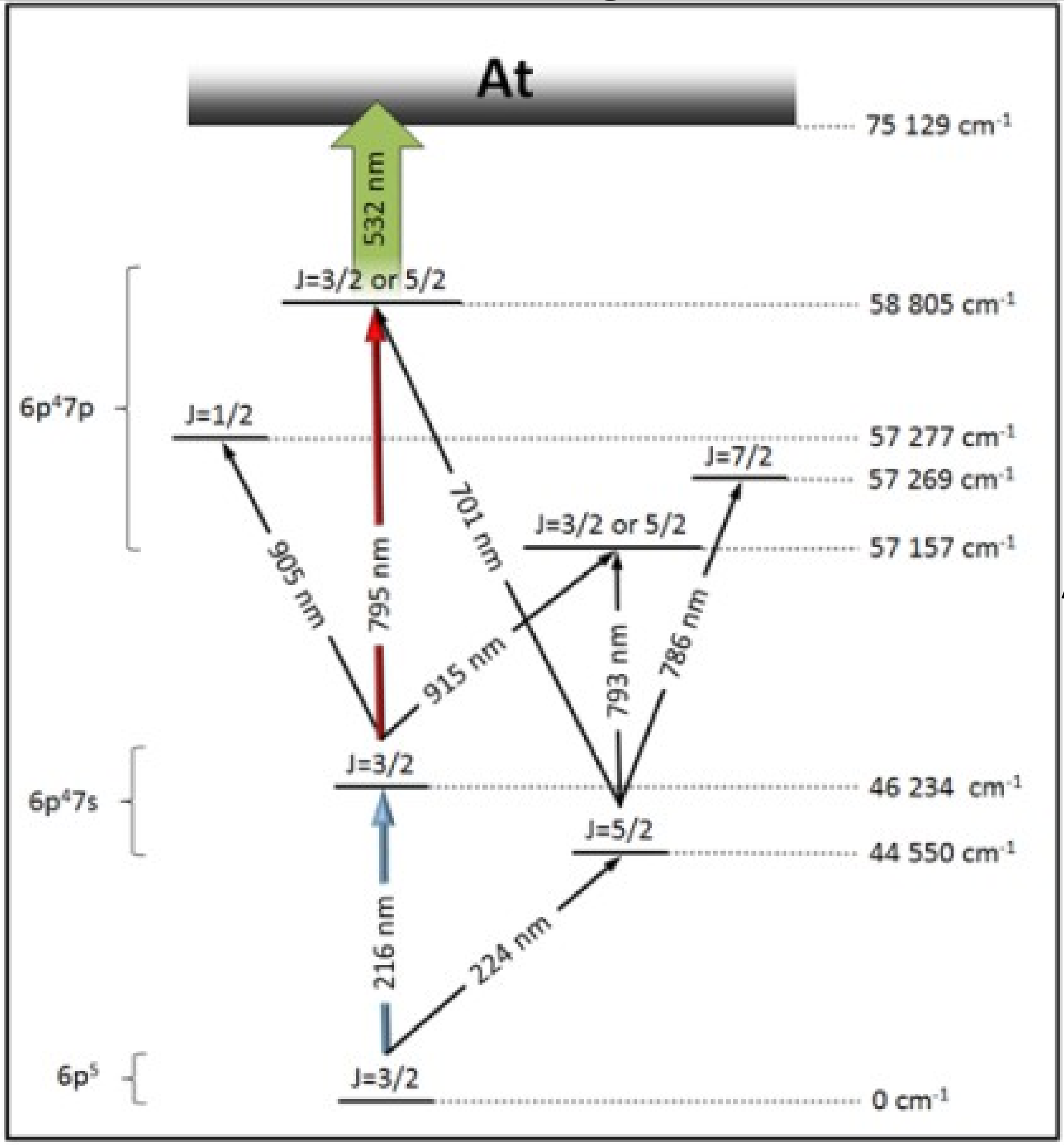
Rydberg-Ritz formula

$$\nu_n = \mathrm{IP} - \frac{\mathrm{R_M}}{(n-\delta)^2}$$

IPRydberg(At) = 75151(1) cm-1

IPthreshold(At) = 75129(95) cm-1

At: atomic spectroscopy



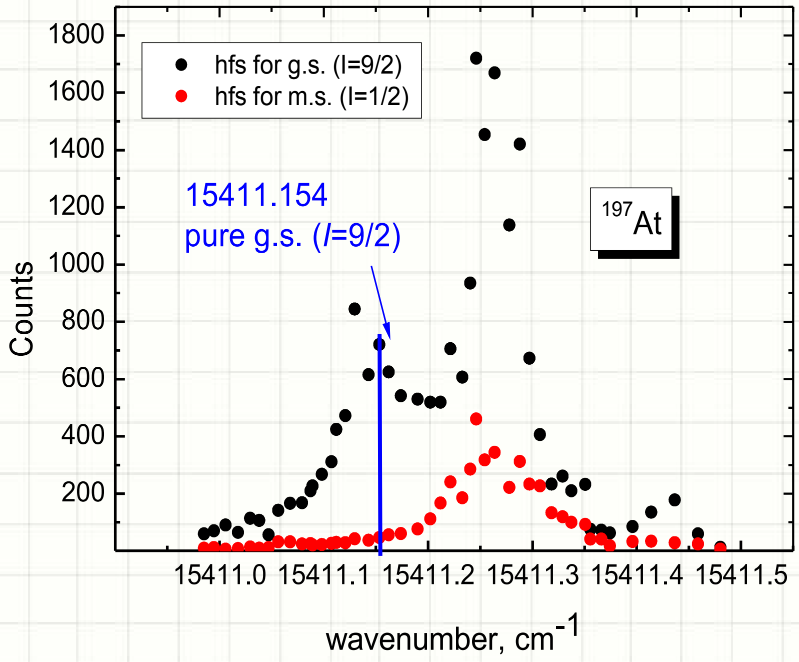
6 photoionization schemes were tested

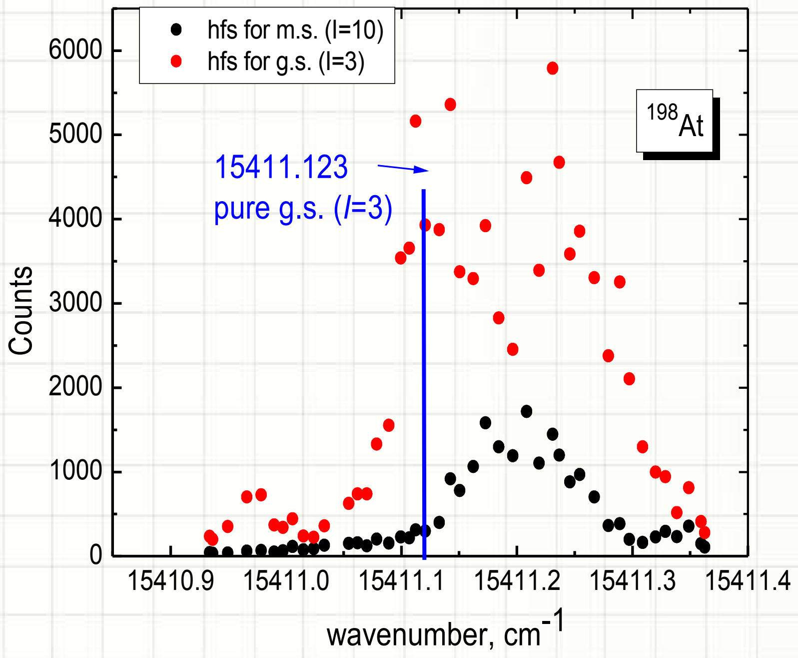
Atomic spectroscopy is Possible at 1st and 2nd steps

Isomer selectivity

1st step transition

197,198At

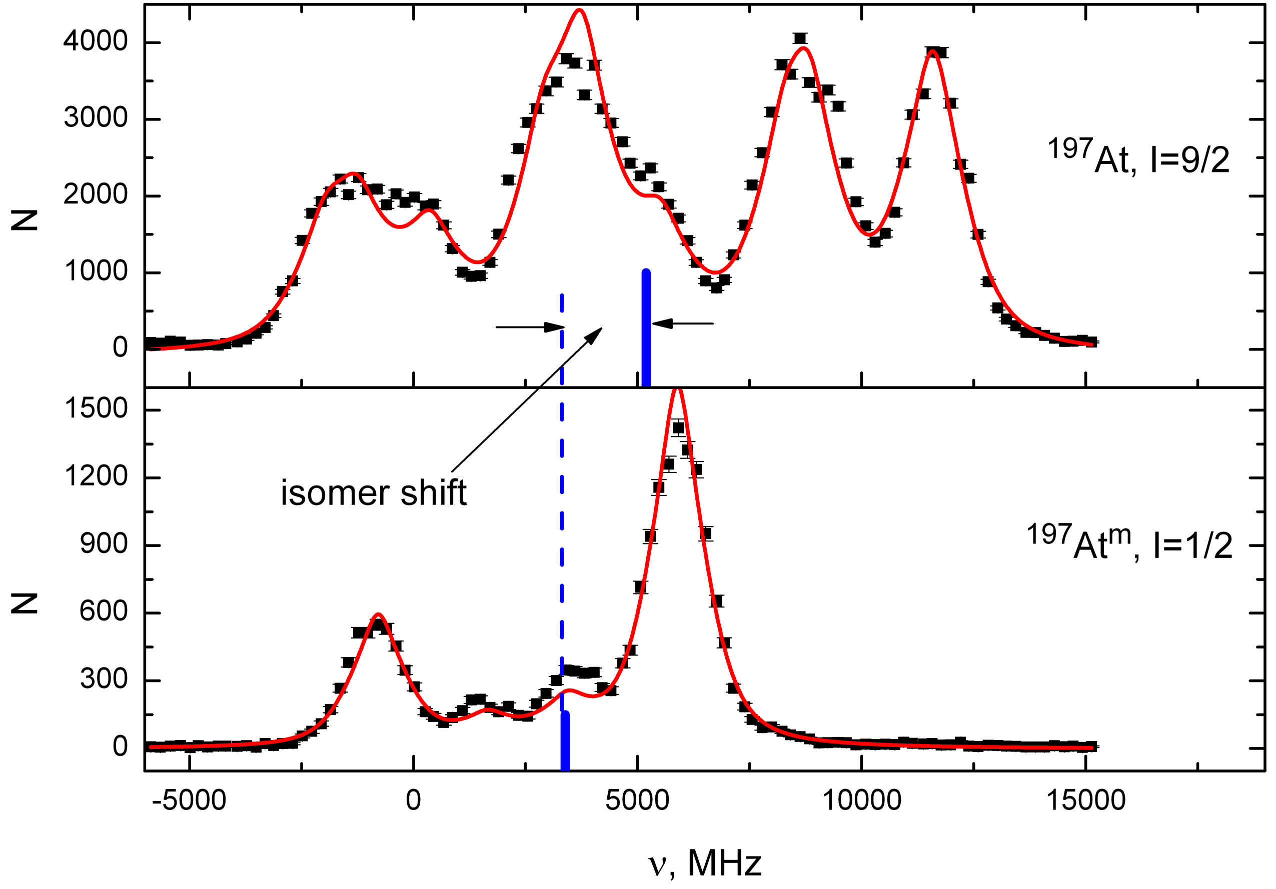




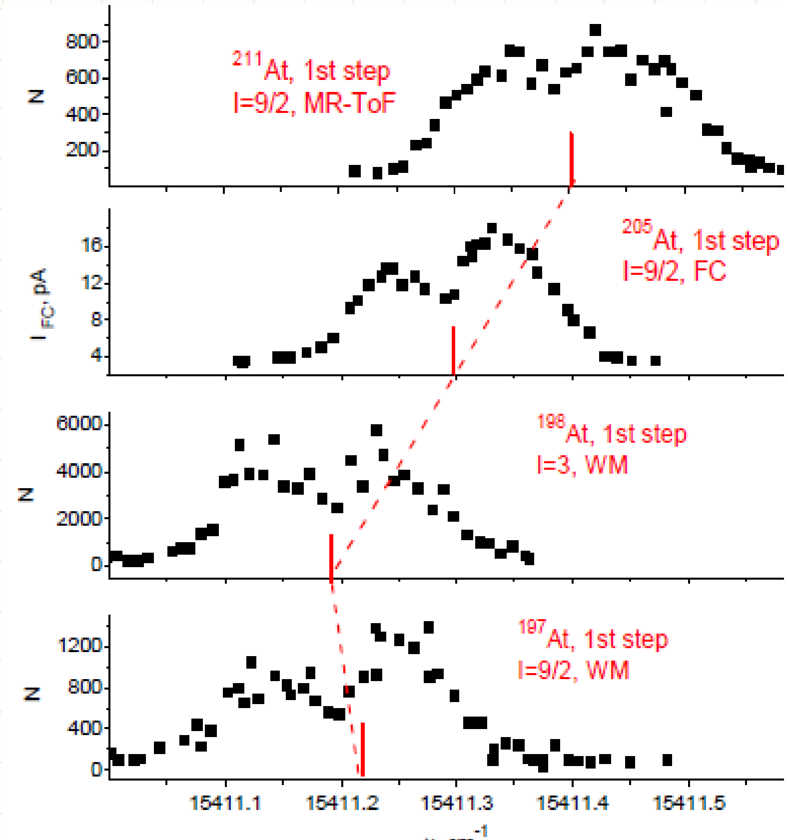
Isomer selectivity enable us to measure masses of 197g,198gAt and obtain nuclear spectroscopic information for pure g.s.

Isomer selectivity

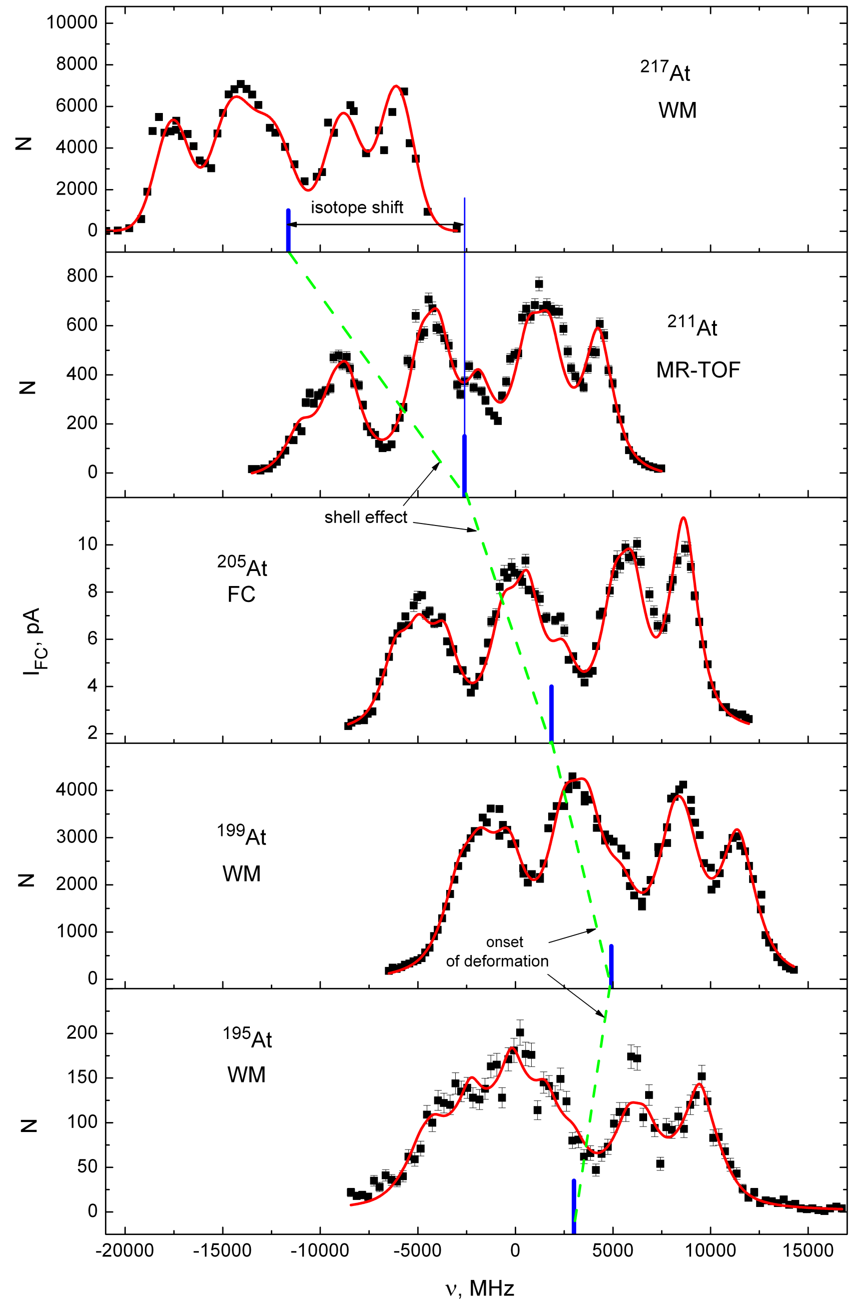
2nd step transition



Isotope shifts



1st step



2nd step

1st step scanning is better for $\Delta\langle r2\rangle$ extraction
2nd step scanning is better for hfs resolution
(Q and μ determination)

Nuclear radii and electromagnetic moments from atomic hfs parameters

Isotope shift $\delta\nu A,A'$

$$\delta\nu A,A' = F\,\lambda A,A' + MS = F\,\lambda A,A' + NMS + SMS$$

Rms charge radius

$$\lambda A,A' = \delta\langle r2\rangle A,A' + C2\,\delta\langle r4\rangle A,A' + \ldots = 0.93\,\delta\langle r2\rangle A,A'$$

Relative line position → hyperfine constants *A* & *B* → *mI, QS*

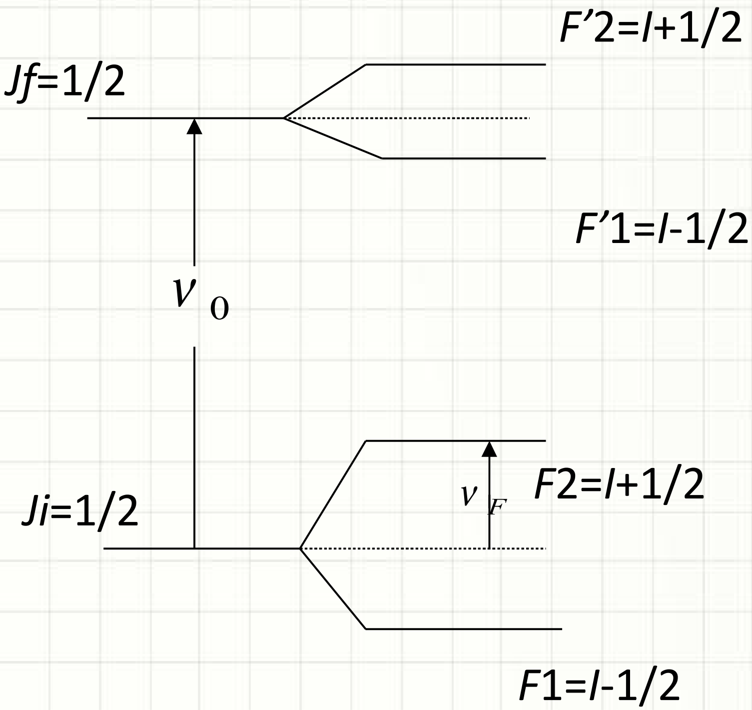
$$\nu_{F_i,F_f} = \nu_0 + \nu_{F_f} - \nu_{F_i}$$

$$\nu_F = A\cdot\frac{K}{2} + B\cdot\frac{0.75\cdot K\cdot(K+1) - I\cdot(I+1)\cdot J\cdot(J+1)}{2\cdot(2I-1)\cdot(2J-1)\cdot I\cdot J}$$

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

$$\vec{F} = \vec{I} + \vec{J},\quad F = |I-J|,|I-J|+1,\ldots,I+J$$

$$A \propto \mu,\quad B \propto Q$$



Hyperfine splitting constants and electromagnetic moments

Relative line position → hyperfine constants *A* & *B* → *mI*, *QS*

$$\nu_{F_i,F_f} = \nu_0 + \nu_{F_f} - \nu_{F_i}$$

$$\nu_F = A\cdot\frac{K}{2} + B\cdot\frac{0.75\cdot K\cdot(K+1) - I\cdot(I+1)\cdot J\cdot(J+1)}{2\cdot(2I-1)\cdot(2J-1)\cdot I\cdot J}$$

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

$$\vec{F} = \vec{I} + \vec{J}, \quad F = |I-J|, |I-J|+1, \ldots, I+J$$

$$A \propto \mu, \quad B \propto Q$$

$$A = \frac{\mu_I B_e(0)}{IJ},$$

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

$$\nu_0, \nu_{F_f}, \nu_{F_i}:$$

$$A, \quad A', \quad B, \quad B' \quad (J, \quad J')$$

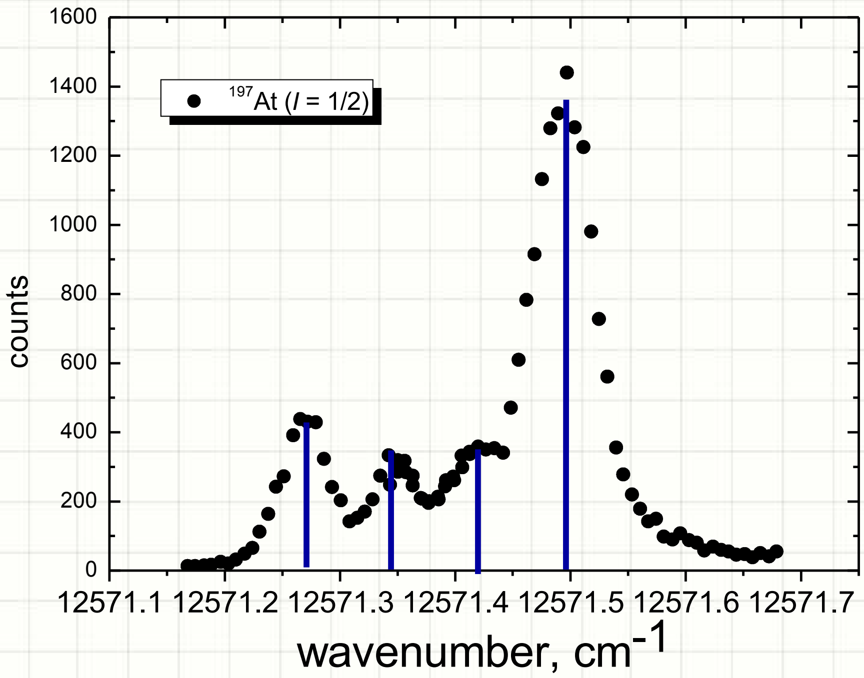
$$\mu = \mu_{\mathrm{ref}}\frac{I\,A}{I_{\mathrm{ref}}A_{\mathrm{ref}}}(1+\Delta)$$

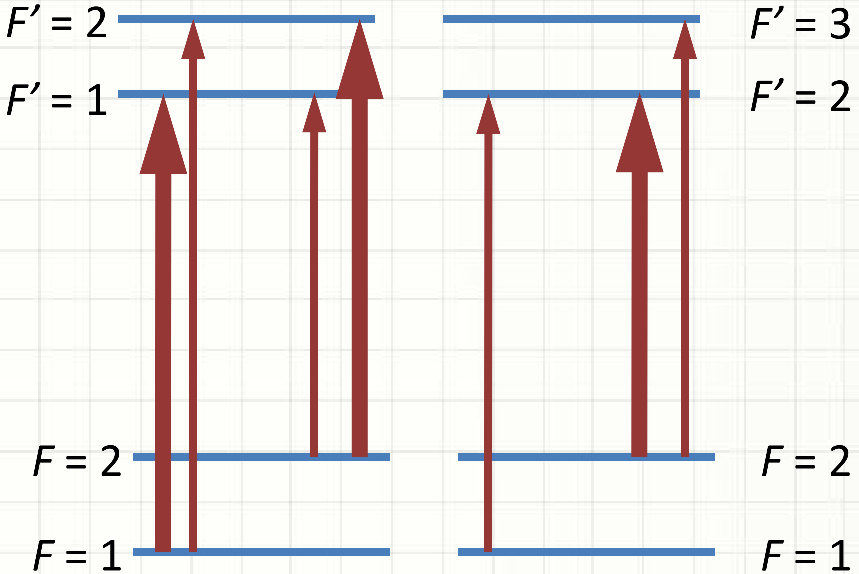
$$\frac{A}{A'} = ? \qquad \frac{B}{B'} = ?$$

$$F, \quad SMS, \quad \mu_0, \quad Q_S^0 \quad = ?$$

Atomic spin determination

Second step transition

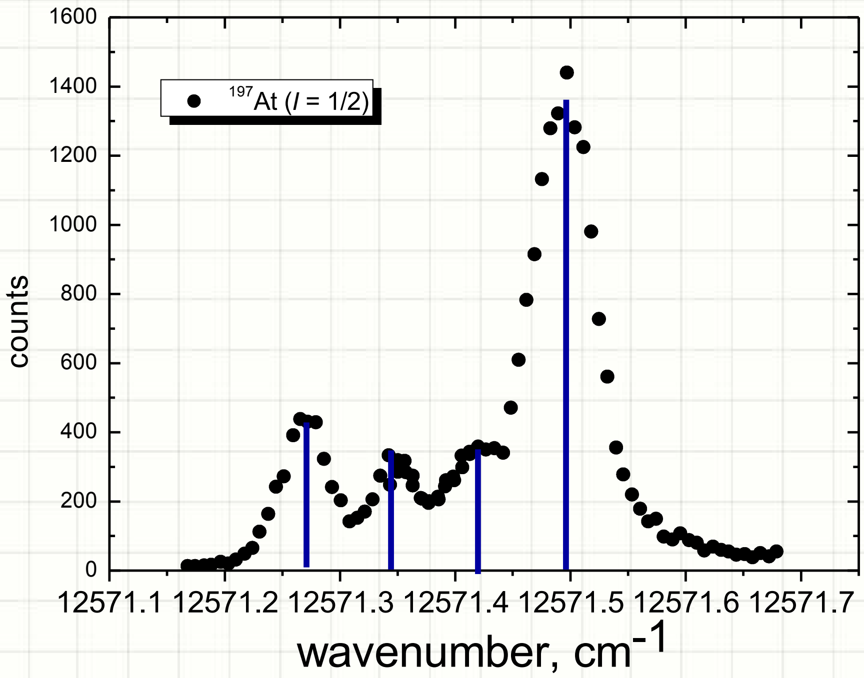


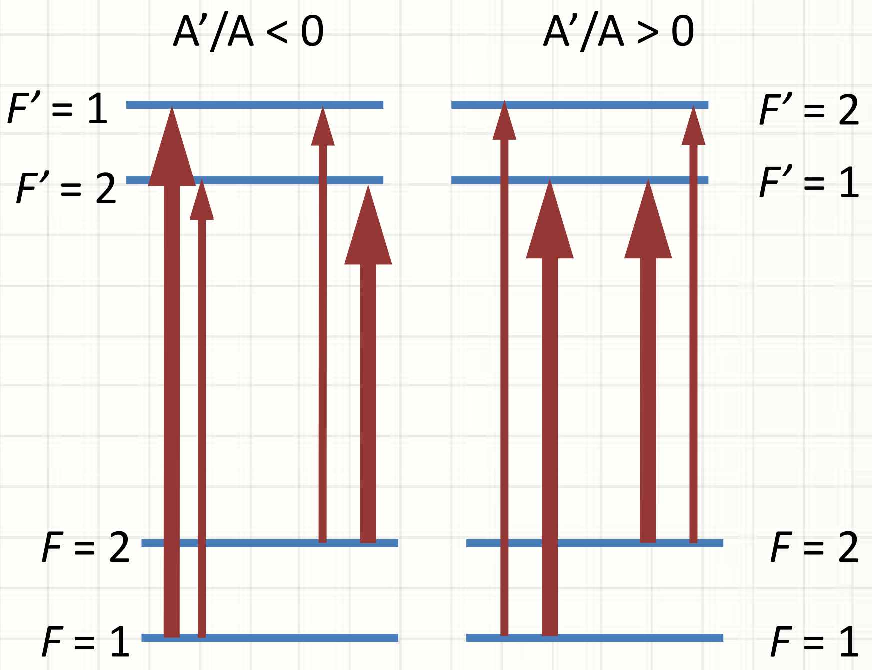


$I = 1/2$

$J' = 3/2$

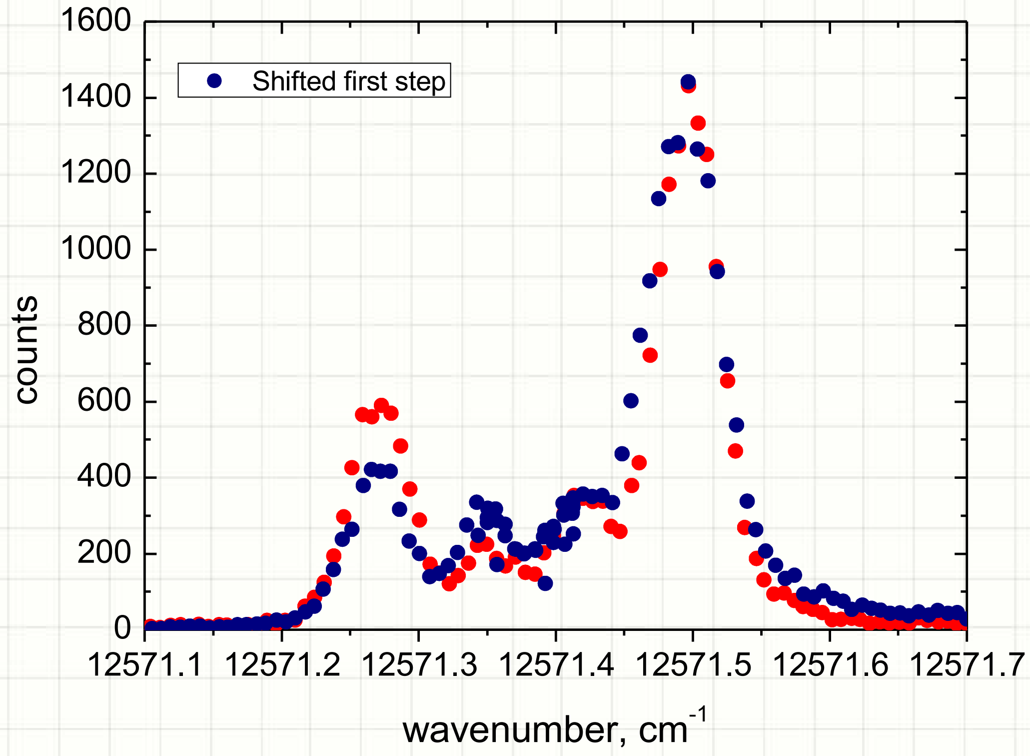
Ratio of hfs constants *A'/A*





A'/A < 0

Ratio of hfs constants *A'/A*



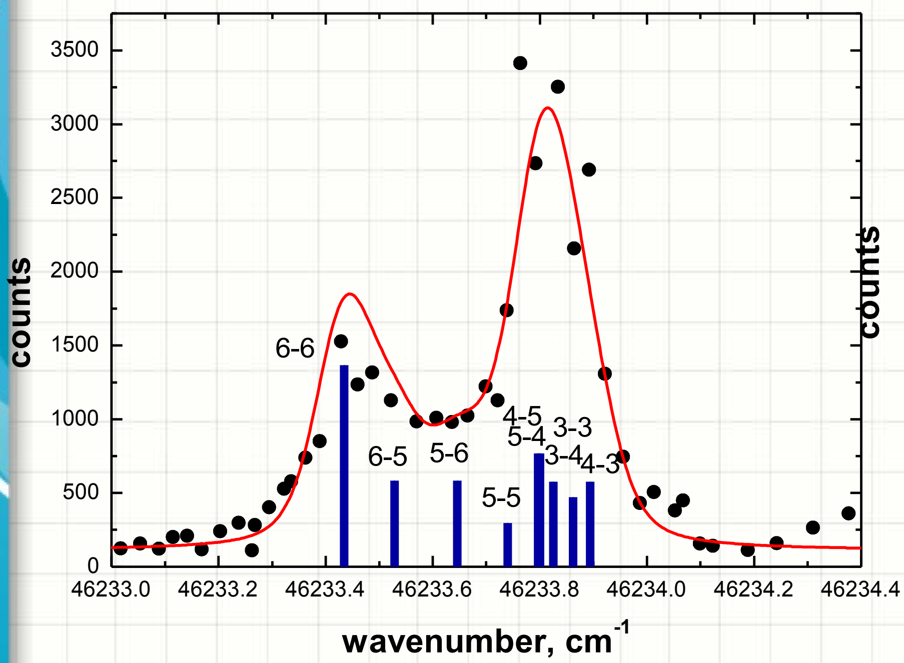
A'/A = -1.7

or

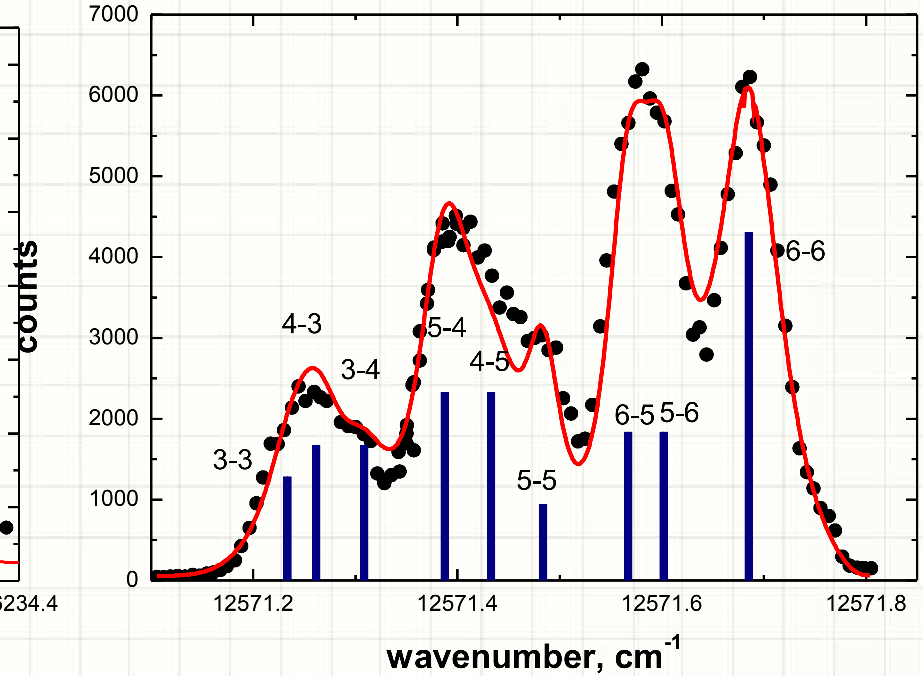
A'/A = -0.6 ?

A'/A = -1.7

Atomic spectra of 197At (*I* = 9/2)



1st transition



2nd transition

hfs intensities

$$N_i(v) = C_1 \int N_0^G(v')\, P_i\left(I^{L'}(v - v')\right) dv' + C_0$$

To take into account the saturation of transitions, pumping processes between hyperfine structure (hfs) components and a population redistribution of the hfs levels the number of photoions *Nion* for each frequency step was calculated by solving the rate equations for the given photoionization scheme:

$$\begin{cases} \dfrac{dN_F}{dt} = \sum\limits_k W_{F'_k F} N_{F'_k} - \sum\limits_k W_{F F'_k} N_F - W_{F,ion} N_F \\ \vdots \\ \dfrac{dN_{ion}}{dt} = \sum\limits_k W_{F'_k,ion} N_{F'_k} \end{cases}$$

$$W_{FF'} \sim S^*_{FF'} I(v + \Delta v^{FF'} - v'), \quad S^*_{FF'} = S_{FF'}/(2F+1)$$

Amplitudes of the components:

$$S(F_i \rightarrow F_f) = \frac{(2F_f + 1) \times (2F_i + 1)}{2I + 1} \times \begin{Bmatrix} J_f & F_f & I \\ F_i & J_i & 1 \end{Bmatrix}^2$$

hfs intensities

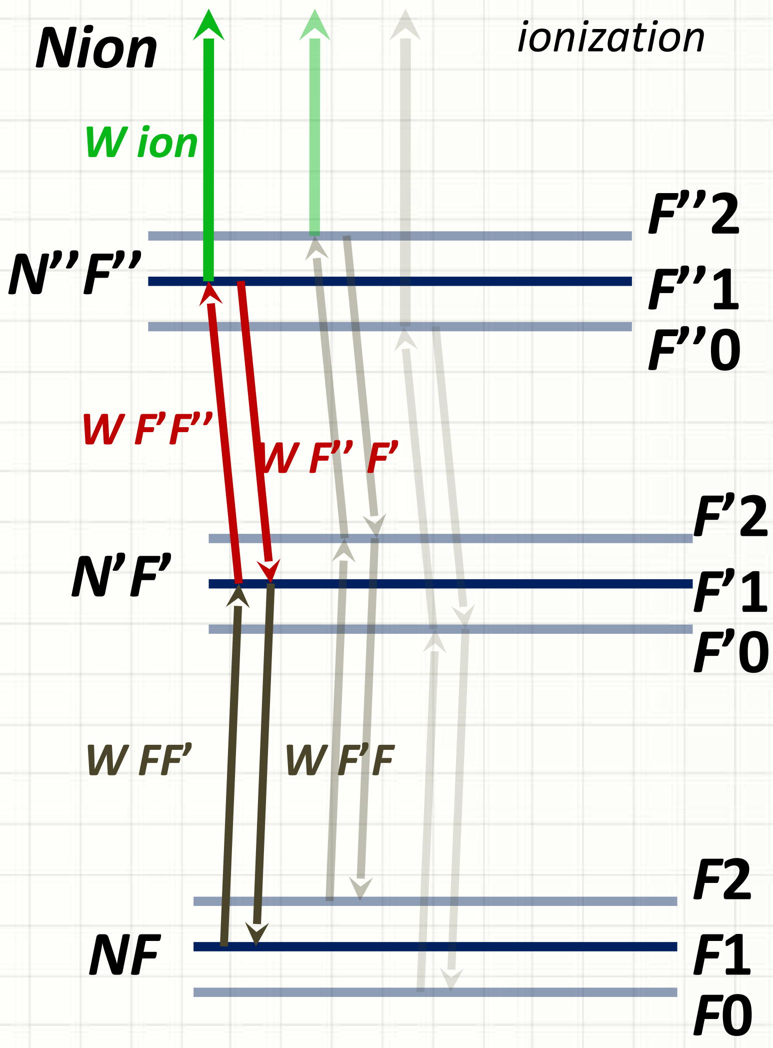
$$dN_{ion} = W_{ion} N''_{F''} dt + \ldots.$$

$$dN''_{F''} = -N''_{F''}(W_{ion} + W_{F''F'} + \ldots)dt + $$
$$+ N'_{F'} W_{F'F''} dt + \ldots$$

$$dN'_{F'} = -N'_{F'}(W_{F'F''} + W_{F'F} + \ldots)dt +$$
$$+ (N''_{F''} W_{F''F'} + N_F W_{FF'} + \ldots)dt$$

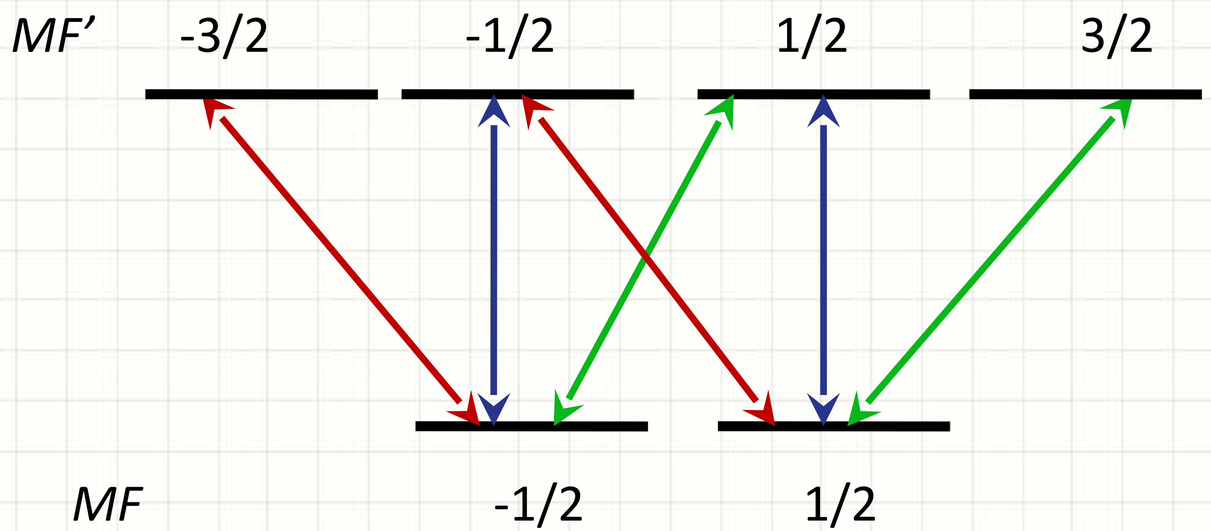
$$dN_F = -N_F(W_{FF'} + \ldots)dt +$$
$$+ (N'_{F'} W_{F'F} + \ldots)dt$$

$$\frac{W_{FF'}}{W_{F'F}} = \frac{2F'+1}{2F+1}$$



Rate equations for the polarized light

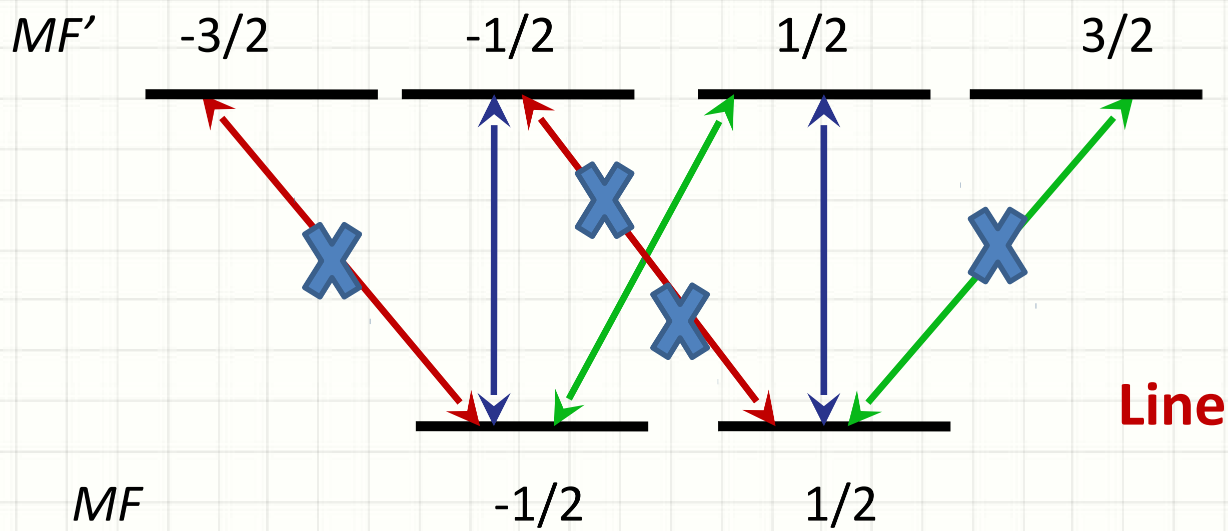
$F = 1/2 \quad \rightarrow \quad F' = 3/2$



$$(2F+1)(2F'+1)\begin{pmatrix} F & 1 & F' \\ -M_F & Q & M'_F \end{pmatrix}^2 \begin{Bmatrix} F & F' & 1 \\ J' & J & I \end{Bmatrix}^2, \quad Q = MF - M'F$$

Rate equations for the polarized light

$F = 1/2 \rightarrow F' = 3/2$



Linear polarization

$$(2F+1)(2F'+1)\begin{pmatrix} F & 1 & F' \\ -M_F & Q & M'_F \end{pmatrix}^2 \begin{Bmatrix} F & F' & 1 \\ J' & J & I \end{Bmatrix}^2, \quad Q = MF - M'F$$

King plot

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

$$\mu^{A,A'} = \frac{AA'}{A'-A},$$

$$\mu^{A,A'}\delta\nu_j^{A,A'} = \frac{F_j}{F_i}\mu^{A,A'}\delta\nu^{A,A'} + M_j - \frac{F_j}{F_i}M_i,$$

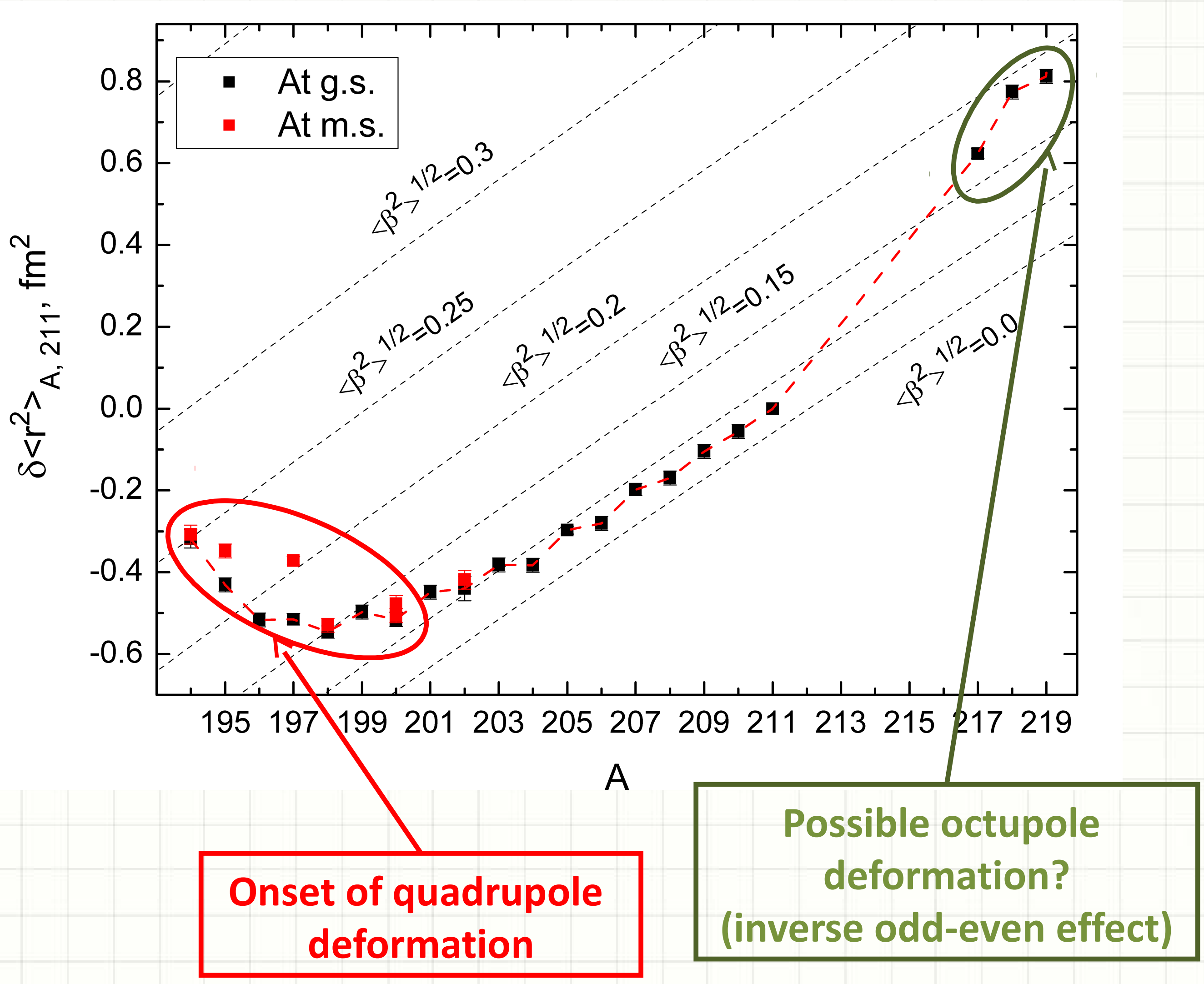
Gradient:

$$F_j/F_i$$

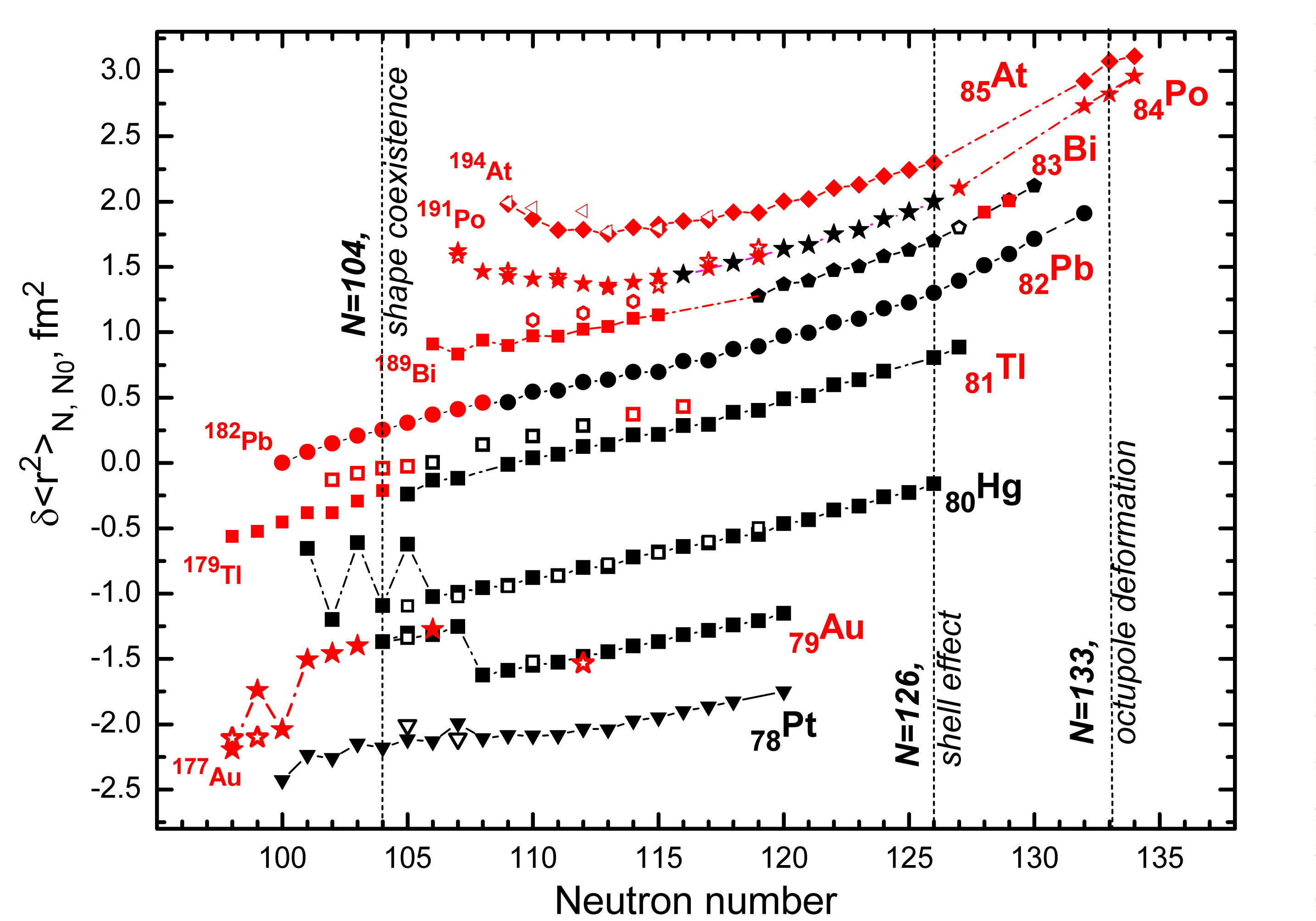
Intercept:

$$M_j - (F_j/F_i)M_i.$$

At charge radii



Charge radii in Pb-region (Z = 82)



Charge radii of At and Po

Nuclear deformation

Charge radii and deformation:

$$\langle r^2 \rangle_A \approx \langle r^2 \rangle_A^{sph} \left(1 + \frac{5}{4\pi} \langle \beta_2^2 \rangle_A \right)$$

Quadrupole moment and deformation:

$$Q_S = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} Q_0,$$

K is the projection of the nuclear spin on the symmetry axis of the nucleus.

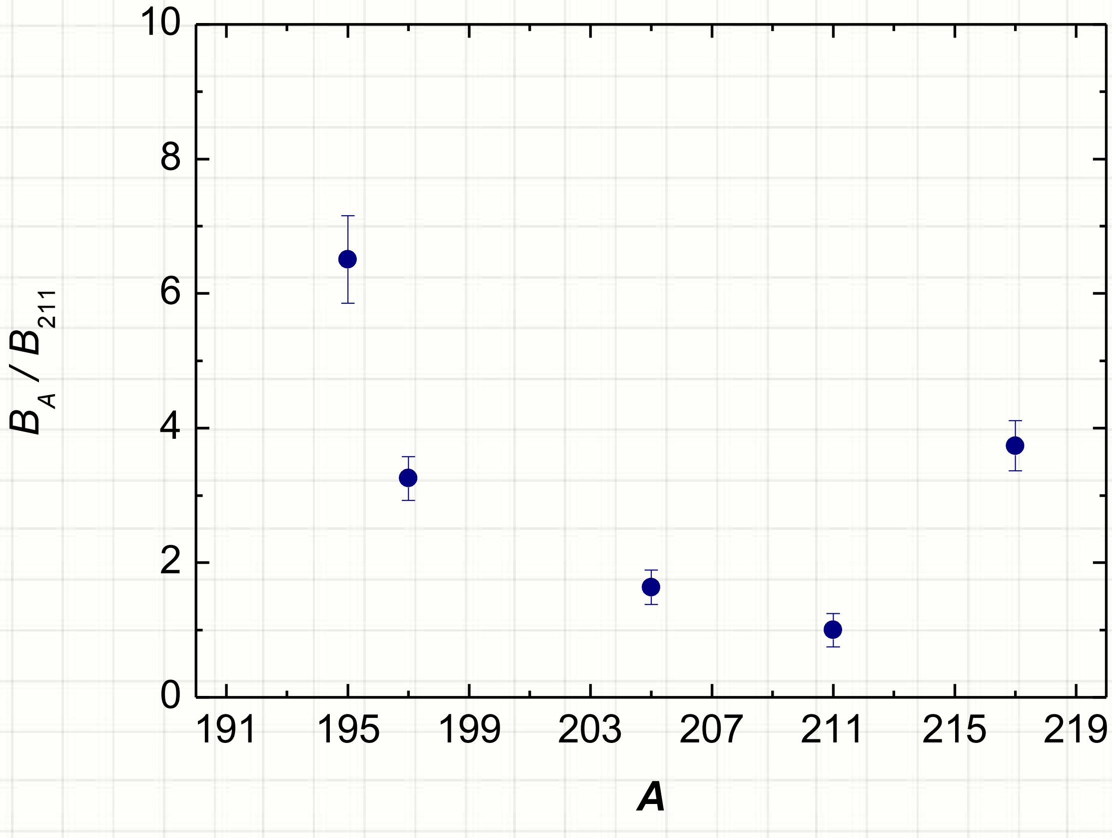
$$Q_0 \approx \frac{3}{\sqrt{5\pi}} eZR_0^2 \left(\beta_2 + \frac{2}{7}\sqrt{\frac{5}{\pi}}\beta_2^2 + \dots \right),$$

*R*o =1.2*A*1/3 fm.

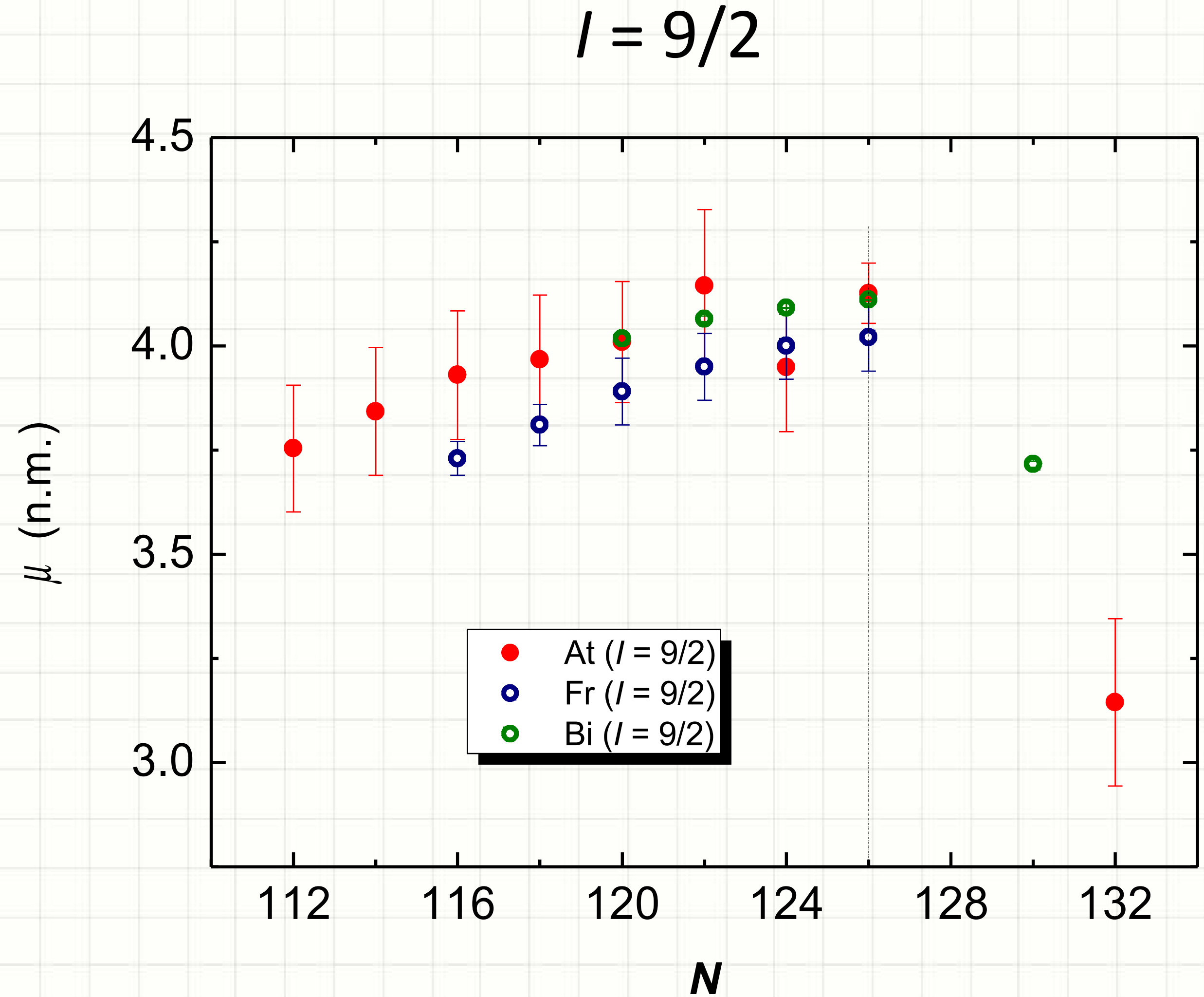
Isotope shift (charge radii): $\langle \beta_2^2 \rangle$ Quadrupole moments: $\langle \beta_2 \rangle$

Quadrupole moments (spectroscopic)

$$Q_s = Q_{s,\mathrm{ref}} \frac{B}{B_{\mathrm{ref}}},$$

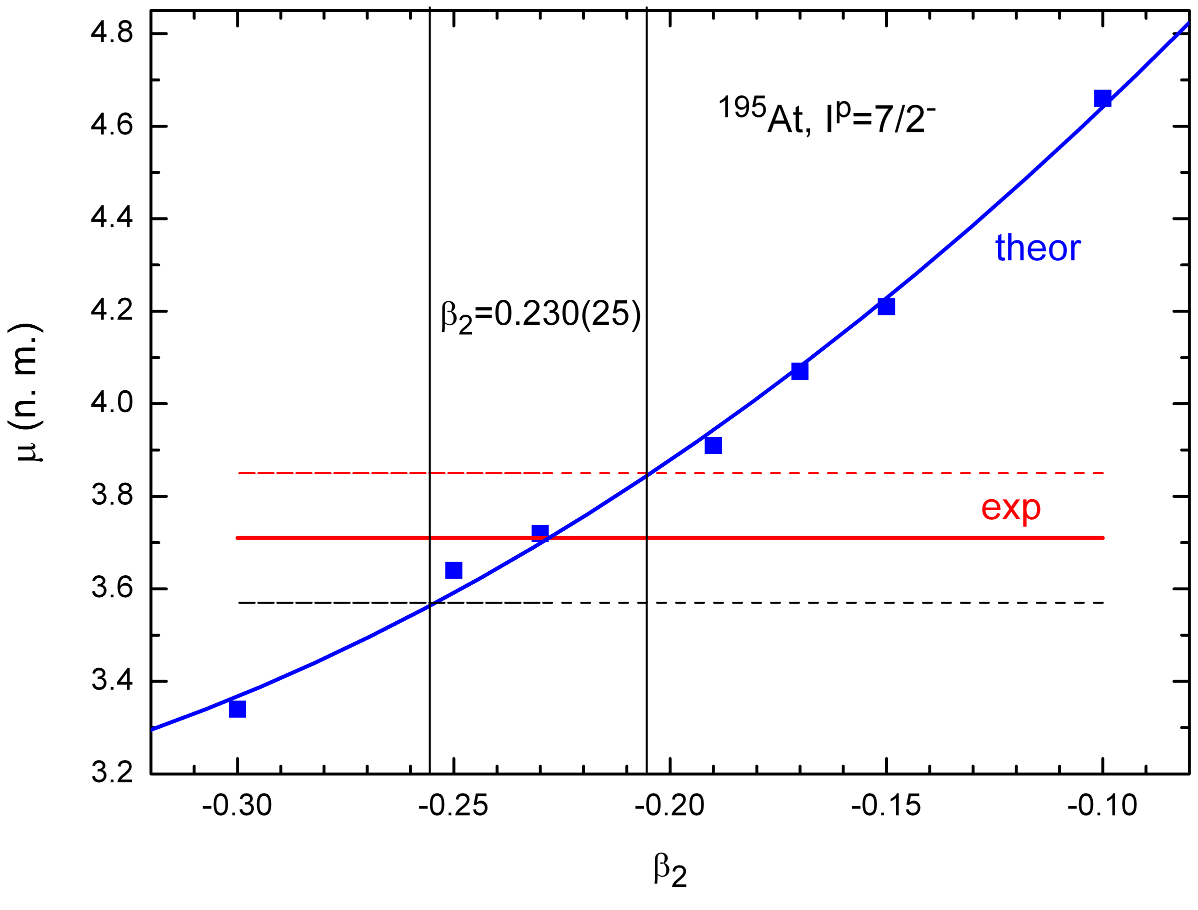


Magnetic moments



Magnetic moment of 195At: comparison to theory

Nilsson model + Coriolis interaction



Conclusions

- 29 isotopes/isomers of At were investigated.
- Valuable atomic spectroscopic information was obtained (new atomic levels and transition, IP, atomic spin, IS, hyperfine splitting constants)
- 6 very effective photoionization schemes were established
- From the measured IS and hfs constants changes in the mean scquare charge radii and electromagnetic moments were deduced
- Early onset of quadrupole deformation was observed in the light At isotopes
- Shell effect at N= 126
- Octupole deformation of 218At

Coming soon…

April 2015:
IS598: In-source laser spectroscopy of mercury isotopes