Prospects for Laser Spectroscopy of Superheavy Elements

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Outline

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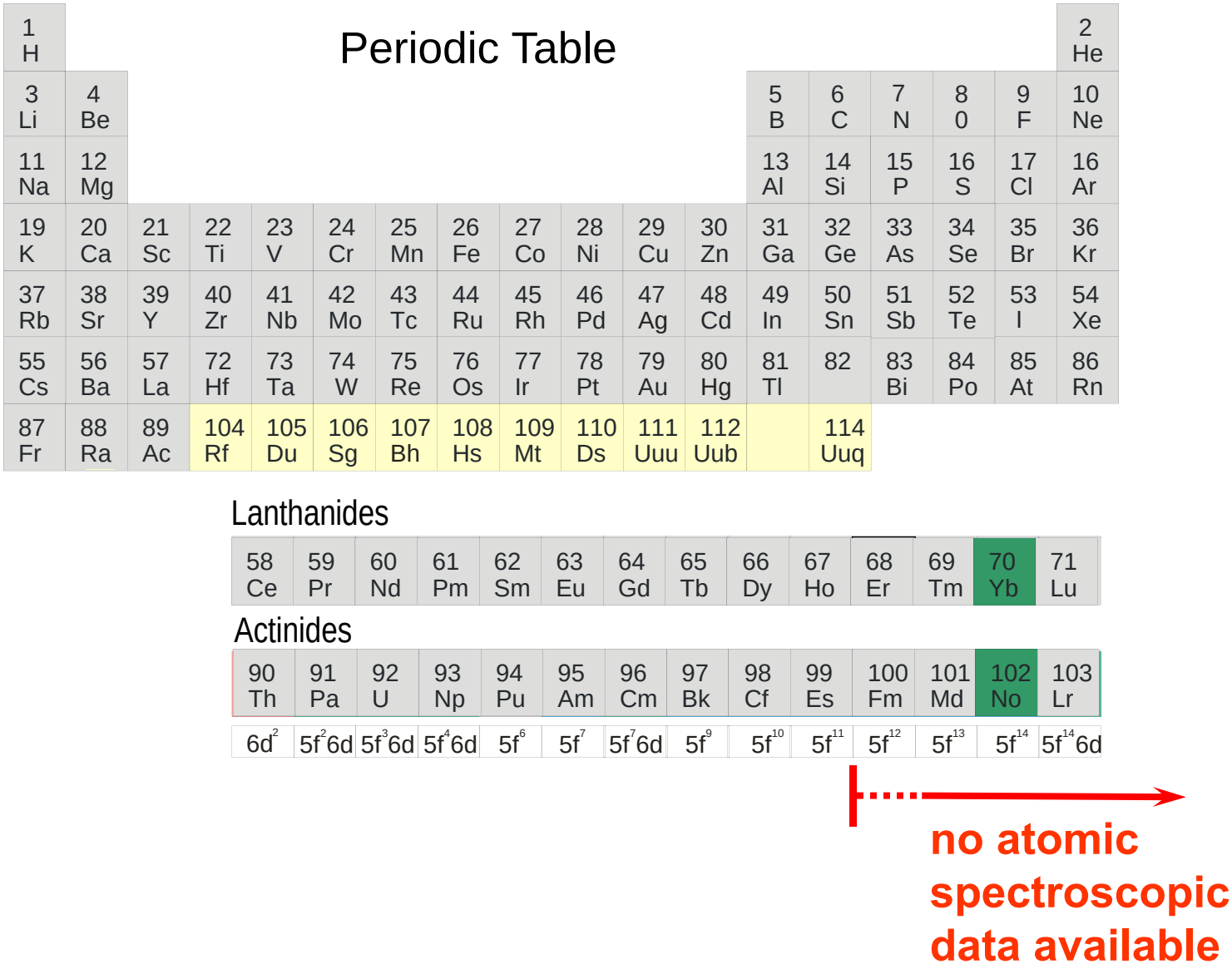
2. How Sensitive is Optical Spectroscopy?
3. Remarks on Laser Induced Fluorescence (LIF) Spectroscopy in a Buffer Gas Trap
4. RAdioactive Decay Detected Resonance Ionization Spectroscopy (RADRIS)
   Optical Spectroscopy at Americium Fission Isomers (Z = 96)
5. Ion-Guide-Detected Resonance Ionization Spectroscopy (IGRIS)
   Investigation of the Atomic Level Scheme of Fermium (Z = 100)
6. RADRIS with the Ion Collection and Atom Re-Evaporation Method
   Status of Laser Spectroscopy at Nobelium (Z = 102)
7. Conclusion

Methods

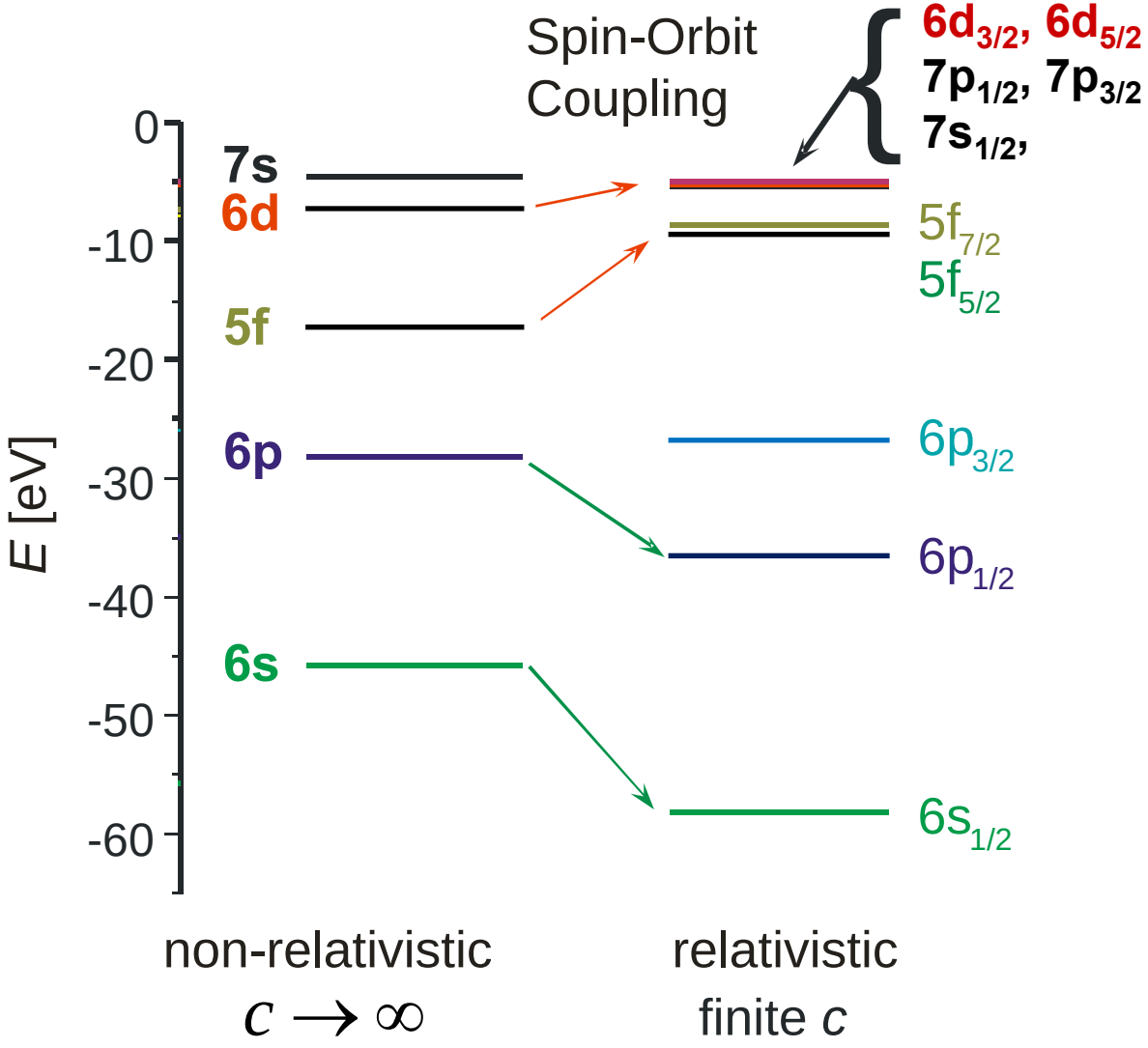
no levels known

1. Introduction and Motivation

Why Atomic Spectroscopy of Heavy Elements?



Relativistic Effects for Atomic Level Scheme of Uranium

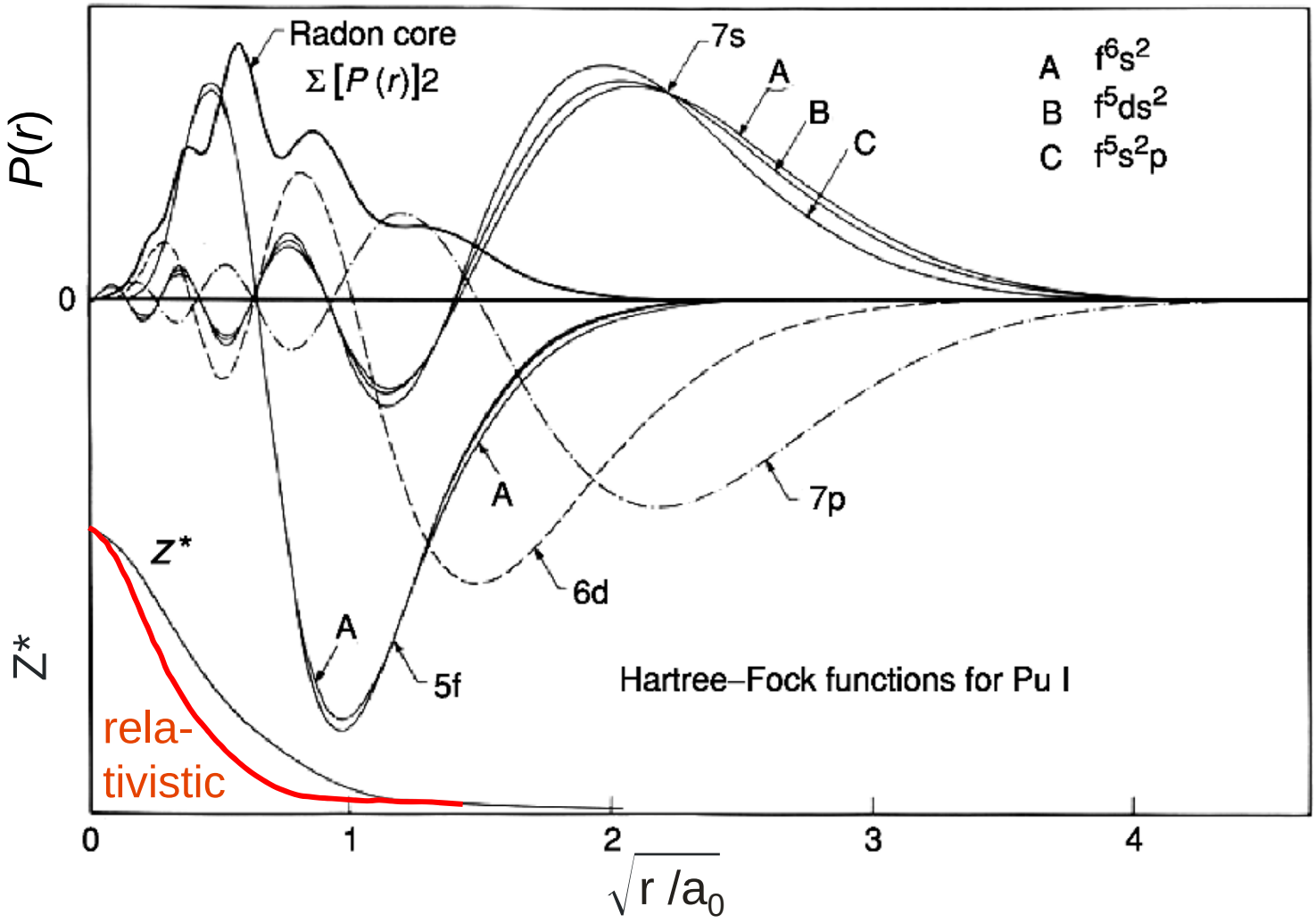


Destabilization of d, f Orbitals

Stabilization of $s_{1/2}$, $p_{1/2}$ Orbitals

Radial Wave Functions of Relevant Orbits in Pu

Non-relativistic Hartree-Fock calculations
taken from E. F. Worden , Jean Blaise, and Mark Fred and N. Trautmann and J.-F. Wyart
The Chemistry of the Actinide and Transactinide Elements, Third Edition (2008)



Nuclear Ground-State Properties by Atomic Physics Techniques

Hyperfine structure interaction

1. Magnetic dipole hfs

$$A = \frac{\mu_I < H_e(0) >}{IJ} \Rightarrow \text{Nuclear magnetic moment } \mu_I$$

2. Electric quadrupole hfs

$$B = eQ_S < \varphi_{jj}(0) > \Rightarrow \text{Spectroscopic quadrupole moment } Q_S$$

3. Coupling

$$\vec{J} + \vec{I} = \vec{F} \Rightarrow \text{Nuclear spin } I$$

Isotope shift

$\delta \langle r^2 \rangle^{A,A'} \Rightarrow$ change of mean square charge radius

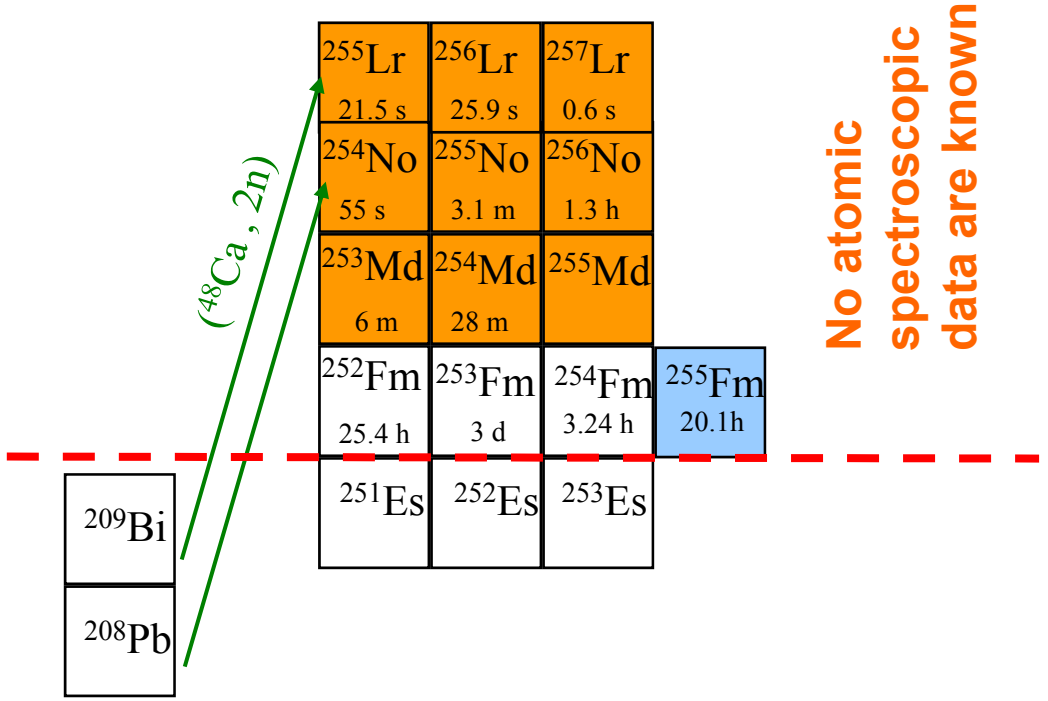
Requirements for Optical Spectroscopy at Trans-Einsteinium Elements

On-line: Z > 100 Nuclear reactions
targets : Pb,U,Pu,Cm,Cf, Es
beams : p,d,α,HI (Ca)

Problem: at σ ~ μb small production rates ~1/s

Off-line: Z ≤ 100 (Fm) breeding of material in high flux isotope reactors

Problem: Experiments at Fm with typically 10^{10} atoms only



⇨ Ultra-sensitive Laser-Spectroscopic Methods

2. How Sensitive is Optical Spectroscopy?

How Sensitive is Optical Spectroscopy?

$$\sigma_r(\omega_0) = \frac{\lambda^2}{2\pi}\frac{g_k}{g_i} \approx 10^{-10}\ \mathrm{cm}^2$$

$\Rightarrow$ Transition rate per atom

$$P_{ik} = \frac{d\dot{N}}{dA}\cdot\sigma_r(\omega_0) = \frac{1}{\hbar\omega}\frac{dP}{dA}\cdot\sigma_r(\omega_0)$$

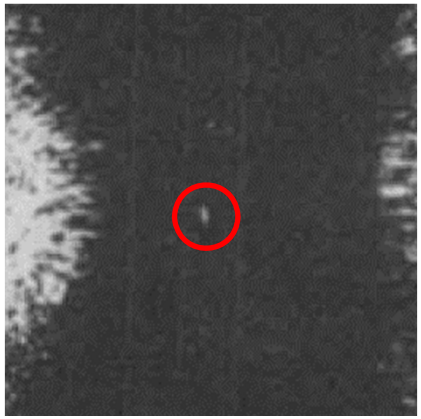
Power of tuneable cw dye lasers $P \approx 100$ mW ... 1 W

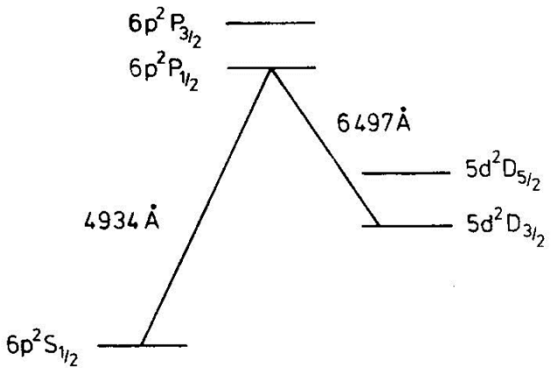
$\Rightarrow$ Flux of photons

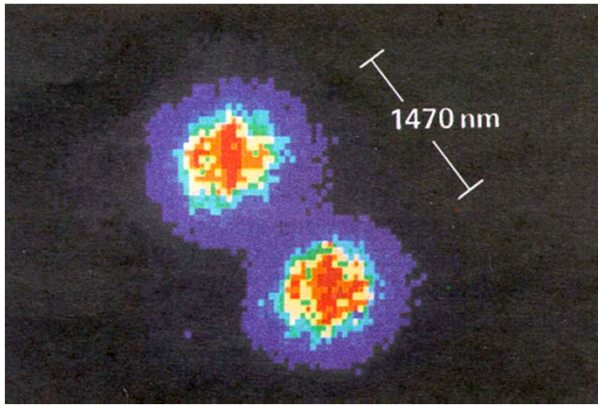
$$\frac{d\dot{N}}{dA} \approx 10^{17}...10^{18}\ /\ (\mathrm{s\ cm}^2) \Rightarrow P_{ik} \approx 10^{8}\ /\ (\mathrm{s\ atom})$$

"In principle" only 1 atom required

First example: Ba^+ stored in an ion trap



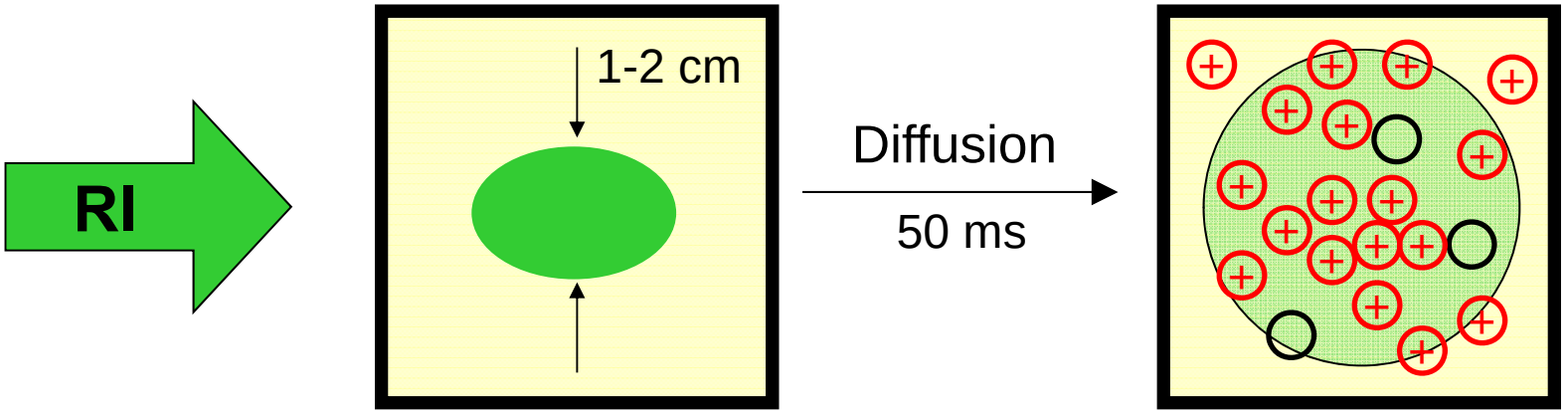




(Toschek, Dehmelt, Neuhauser et al., 1980)

R.G.Voe et al., PRL 76 (1996) 2049

Buffer Gas Trap



Radioactive Ions from Separator
$T_{1/2}$ >1 ms

Buffer Gas Cell

He, Ar at ≈ 100 mbar

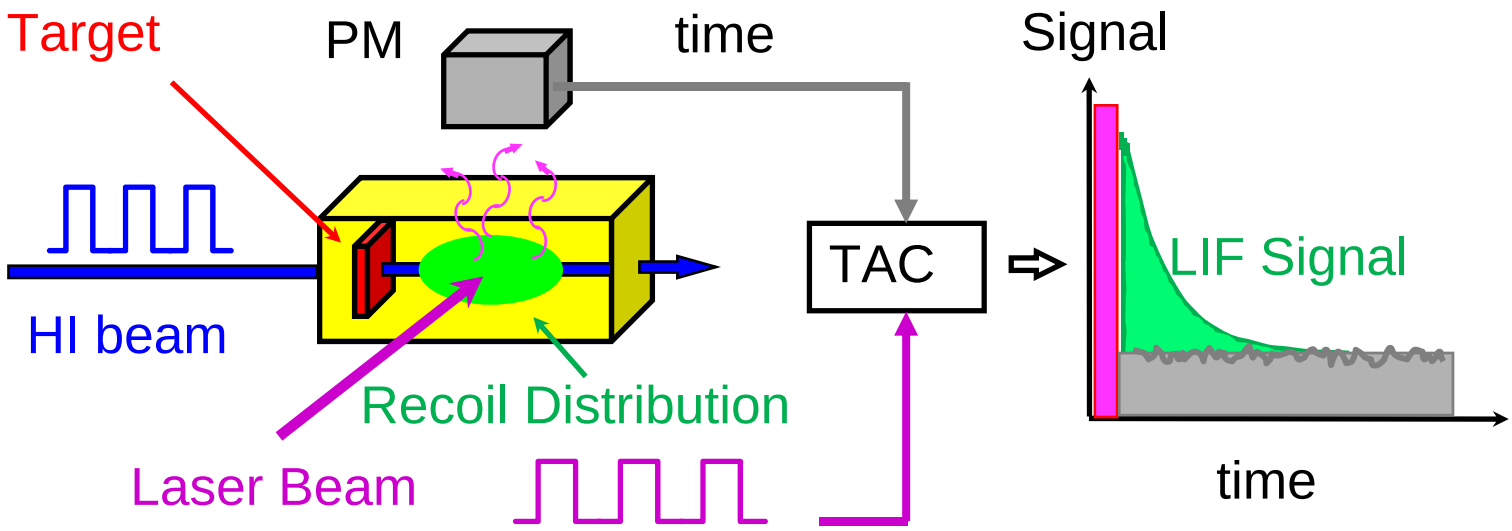
⊕ 85% charged

○ 15% neutral

- Laser Spectroscopy at Neutral Fraction
- Ion Chemistry and Drift Time Measurements at Charged Fraction
- Cooling and Bunching and Transfer to Traps for Mass Measurements

3. Remarks on Laser Induced Fluorescence (LIF) Spectroscopy in a Buffer Gas Trap

Laser Induced Fluorescence (LIF) Spectroscopy

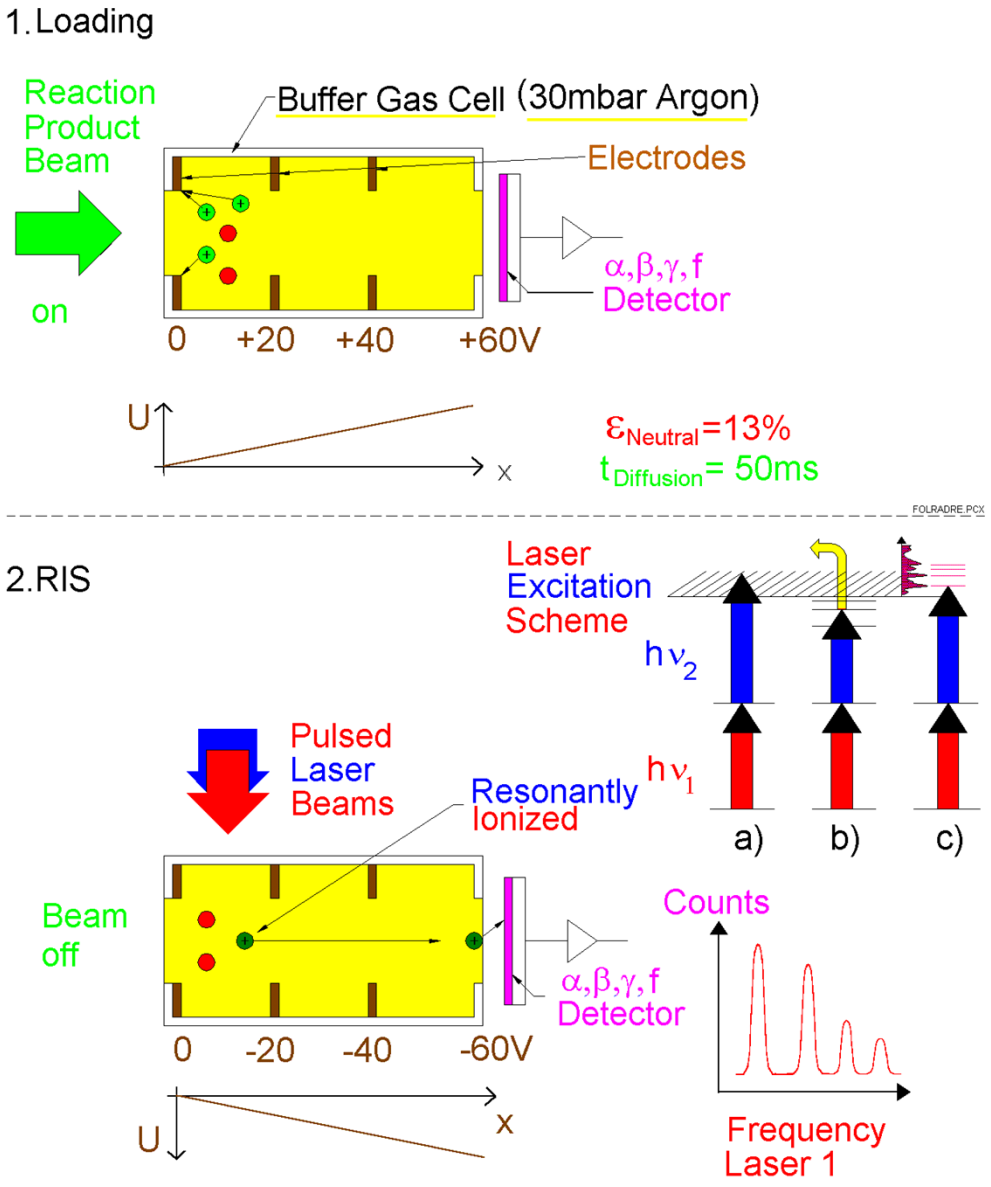


G. D. Sprouse et al.,
Laser Spectroscopy of Light Yb Isotopes On-Line in a Cooled Gas Cell.
Phys. Rev. Lett. **63** (1989) 1463
Sensitivity: Target production rate about 10^3/s

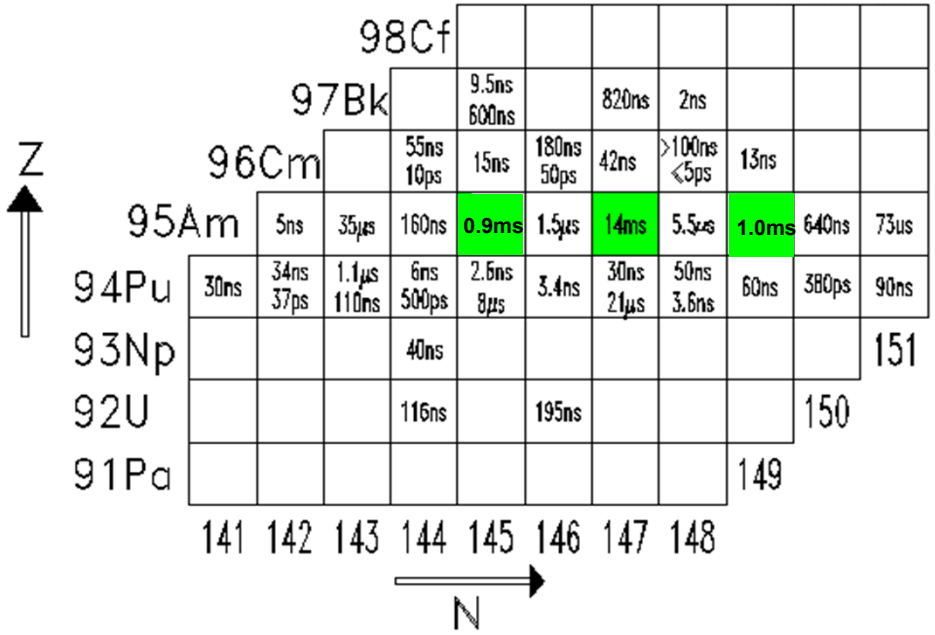
4. RAdioactive Decay Detected Resonance Ionisation Spectroscopy (RADRIS)

Optical Spectroscopy at Americium Fission Isomers (Z = 96)

RAdioactive Decay Detected Resonance Ionisation Spectroscopy (RADRIS)



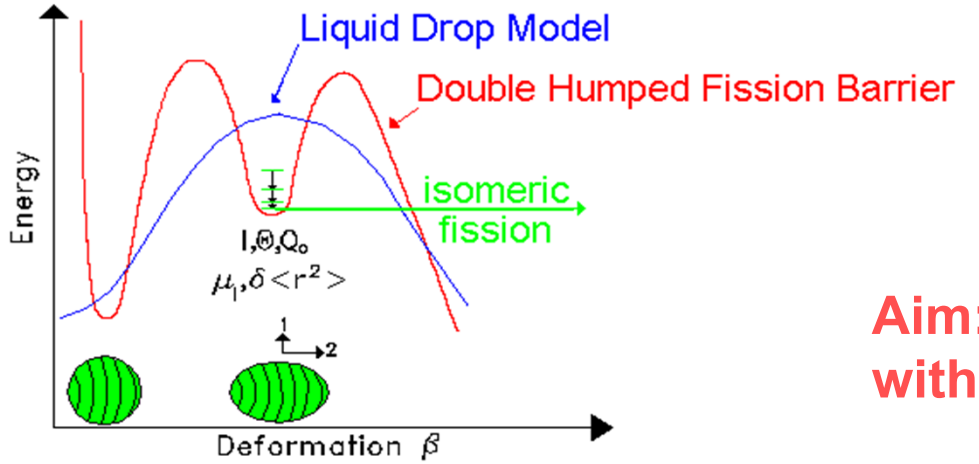
Americium Fission Isomers



^{240f}Am ($T_{1/2}$= 0.9 ms)
^{242f}Am ($T_{1/2}$=14 ms)
^{244f}Am ($T_{1/2}$=1 ms)

Dubna 1962

- conversion electron spectroscopy
- lifetime measurements of excited states (charge plunger method)
- g-factor measurements
- γ-ray spectroscopy
- optical spectroscopy



Aim: δ $\langle r^2 \rangle$, Q_{20}, I, g with Optical Spectroscopy

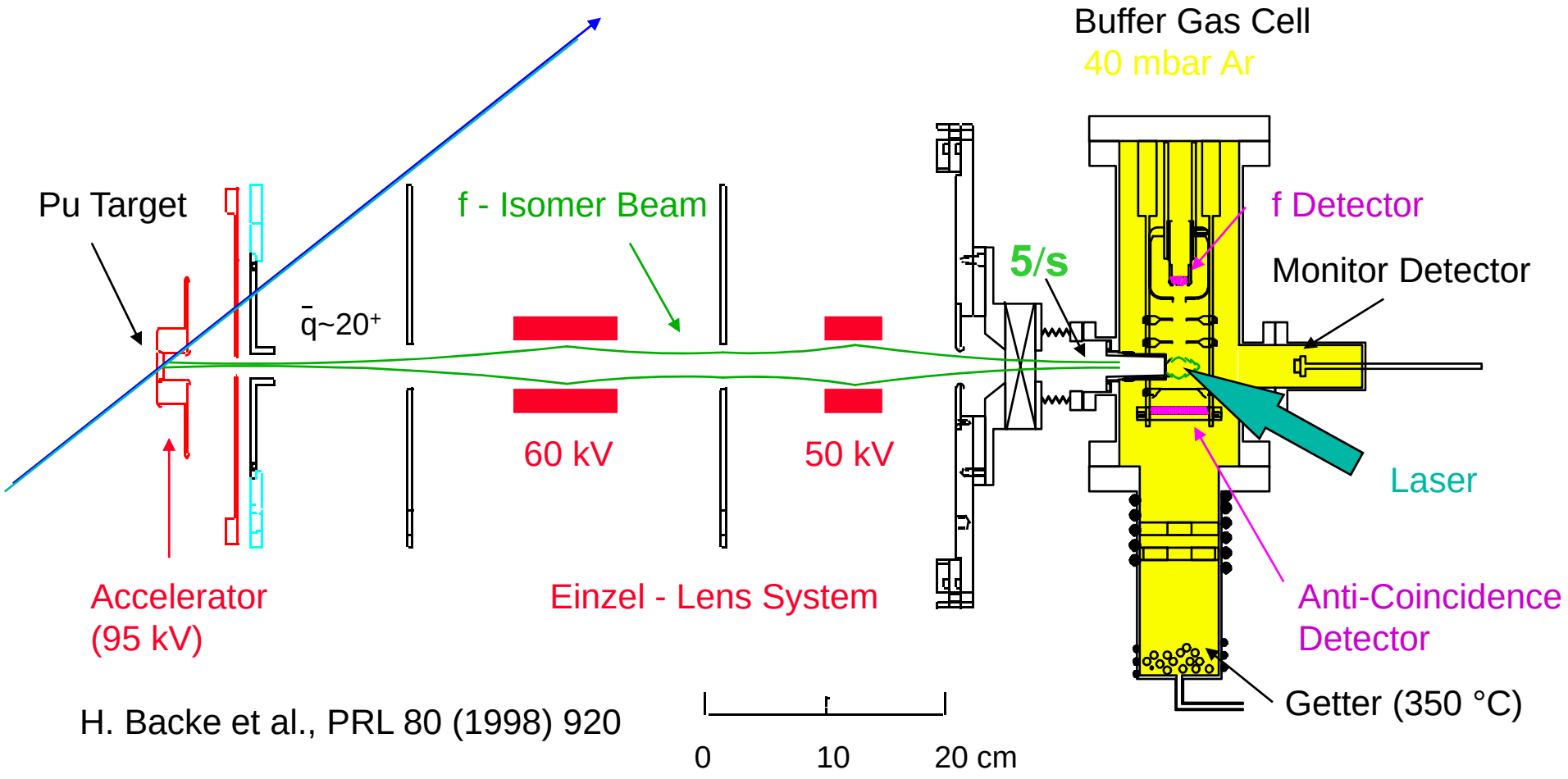
Experimental Setup

^{242}Pu (d,2n) ^{242f}Am $T_{1/2}$=14ms d Beam 6ms on / 6ms off 12 MeV, I=3μA

^{242}Pu (p,3n) ^{240f}Am $T_{1/2}$=0.9ms p Beam 2ms on / 2ms off 24 MeV, I=3μA

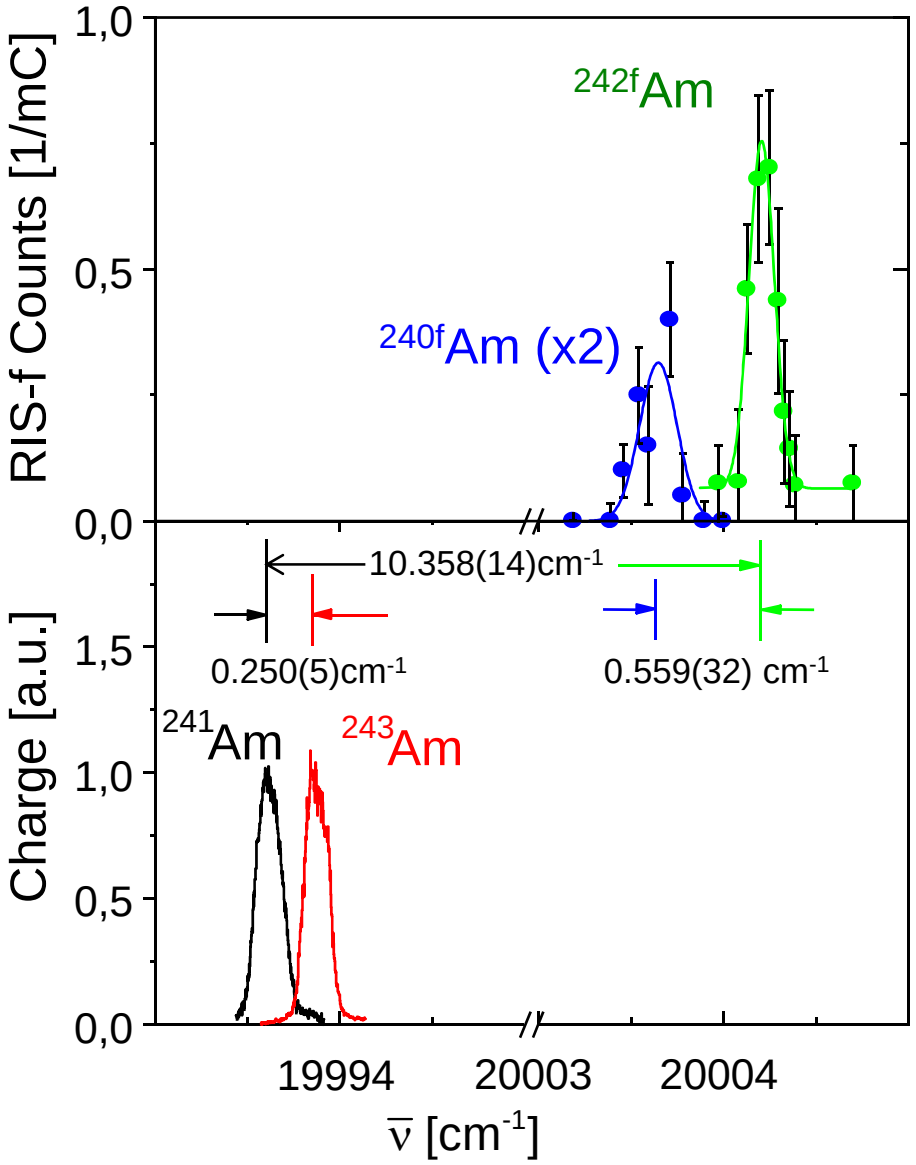
^{244}Pu (d,2n) ^{244f}Am $T_{1/2}$=1ms d Beam 2ms on / 2ms off 14 MeV, I=2μA

σ =(8±3)μb



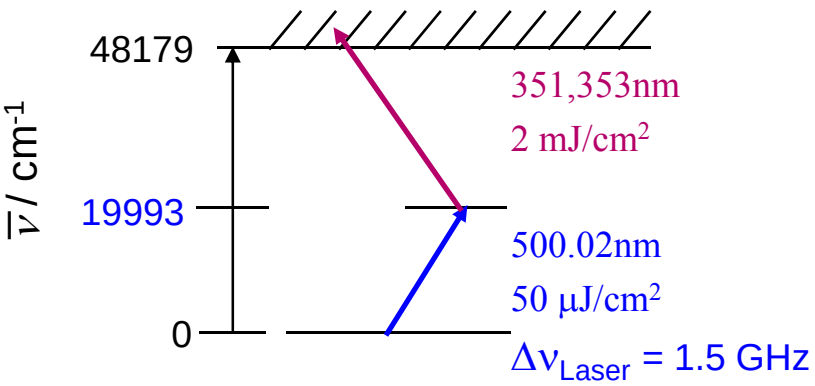
H. Backe et al., PRL 80 (1998) 920

Isotope Shift Measurement in the Second Potential Minimum



^{242}Pu(d,2n)^{242f}Am, σ =8 μb, 12 MeV

^{242}Pu(p,3n)^{240f}Am, σ =8 μb, 24 MeV



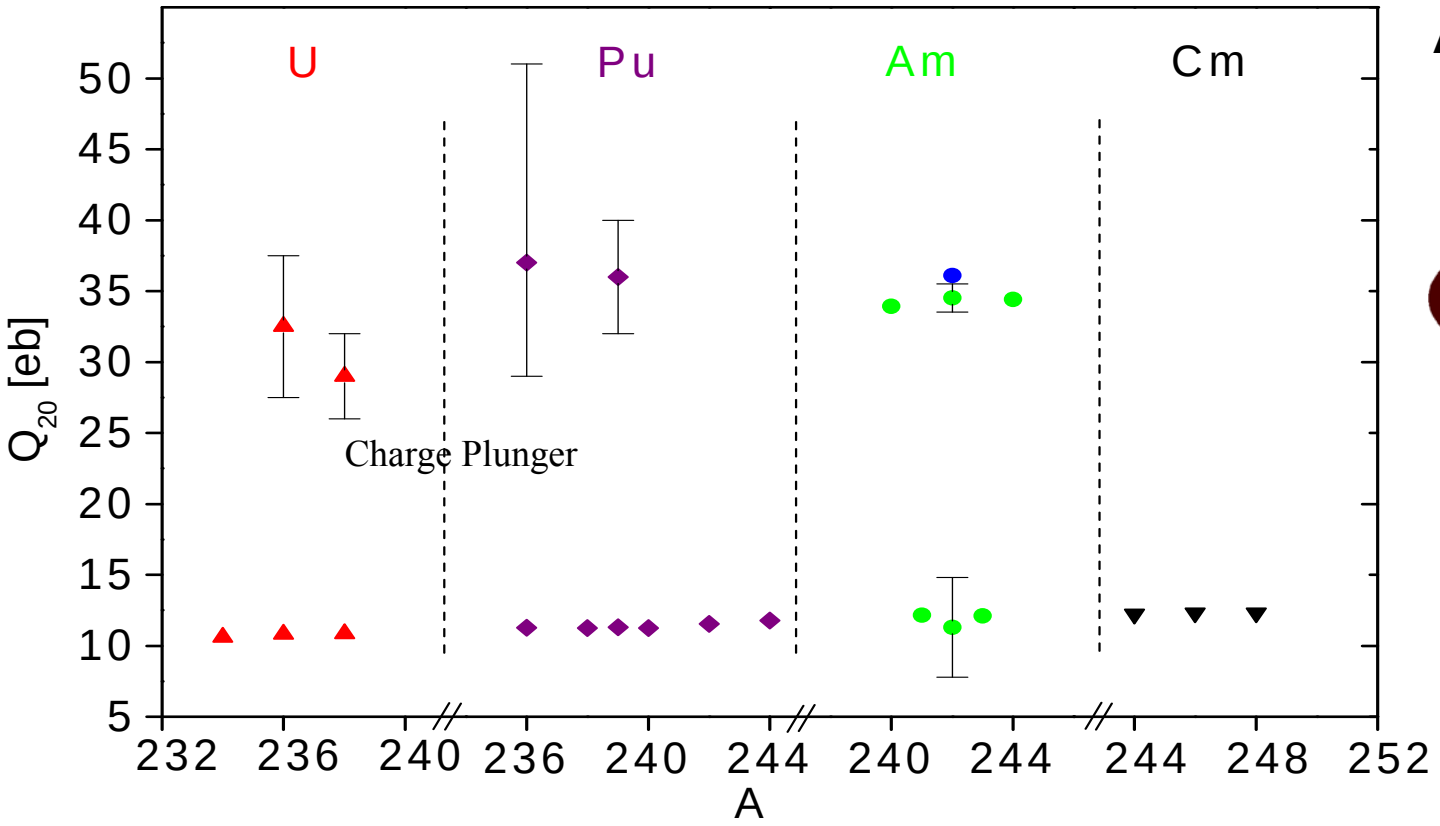
$$X_{exp}(^{242f}\mathrm{Am}) = \frac{IS^{242f,241}}{IS^{243,241}} = 41.4\ (8)$$

$$X_{exp}(^{240f}\mathrm{Am}) = \frac{IS^{240f,241}}{IS^{243,241}} = 39.2\ (8)$$

At variance with

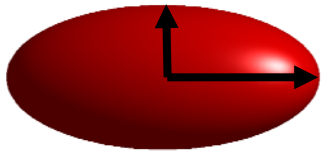
X^{240f} = 26.8 (2.0) (Bemis et al.)

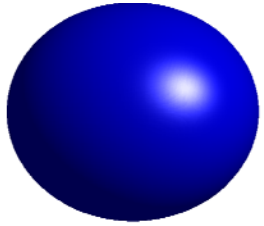
Quadrupole Moments of Fission Isomers



Axes ratio 1:1.9

$\beta = 0.69$





5.Ion-Guide-Detected Resonance Ionization Spectroscopy (IGRIS)

Investigation
of the Atomic Level Scheme
of Fermium (Z = 100)

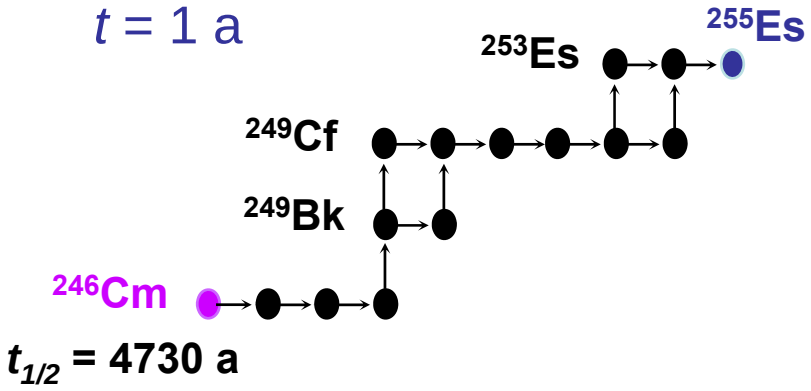
Production of ^{255}Fm

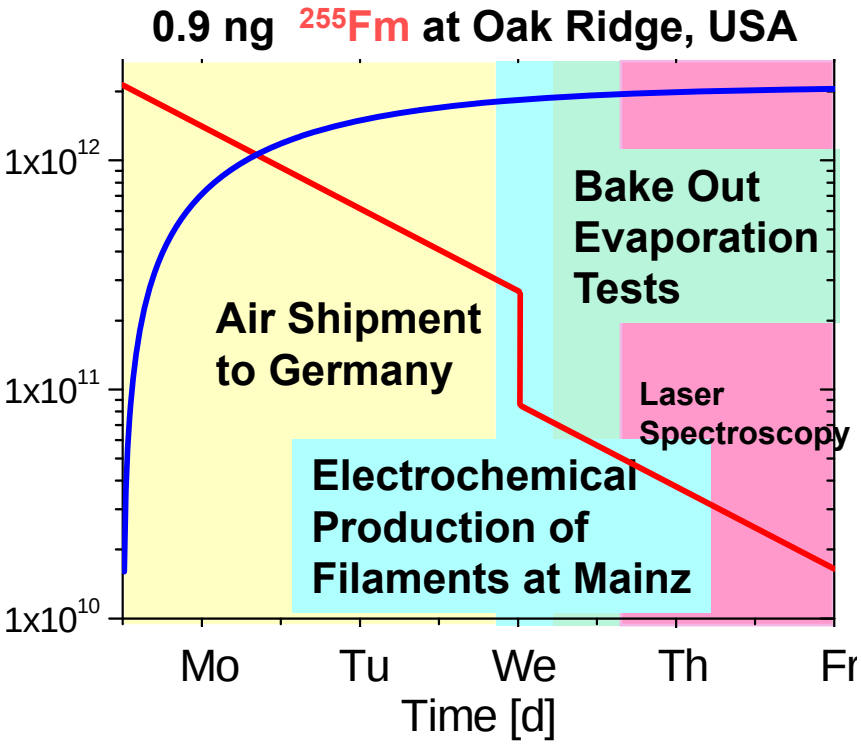
High Flux Isotope Reactor
Oak Ridge National Laboratory

- Breeding of ^{255}Es (Z = 99)

$\Phi_n = 2.6 \cdot 10^{15}/cm^2 \cdot s$

t = 1 a

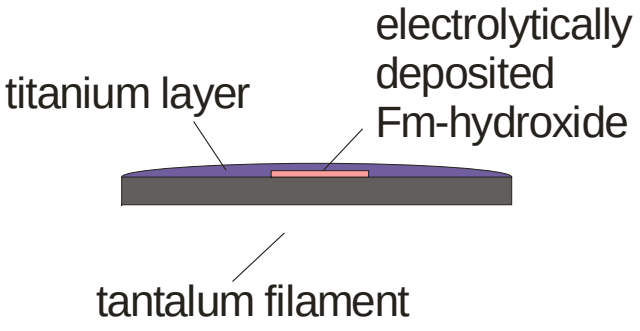




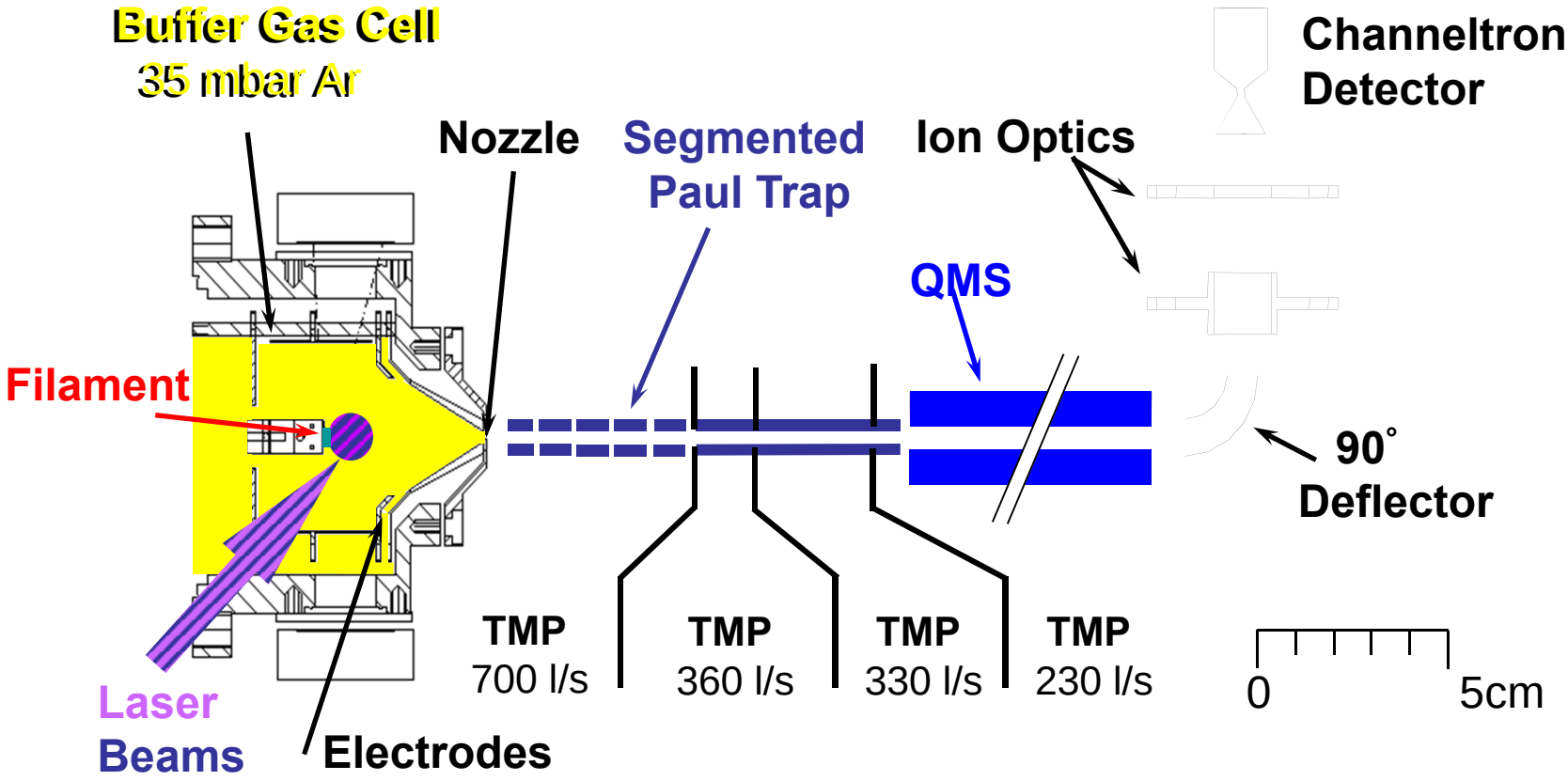
- Chemical Separation of Es,

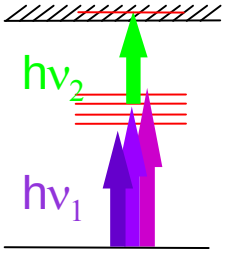
- Waiting for ^{255}Es $\xrightarrow[t_{1/2} = 39.8\ d]{\beta^-}$ ^{255}Fm decay

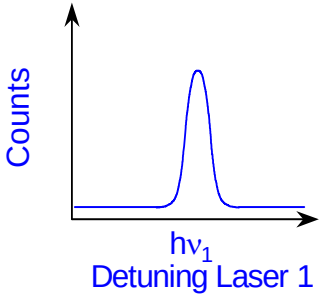
- Chemical Extraction of ^{255}Fm ($t_{1/2}$= 20.1 h)

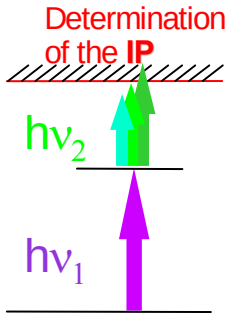


Ion-Guide Detected Resonance Ionization Spectroscopy with Mass Selective Ion Detection

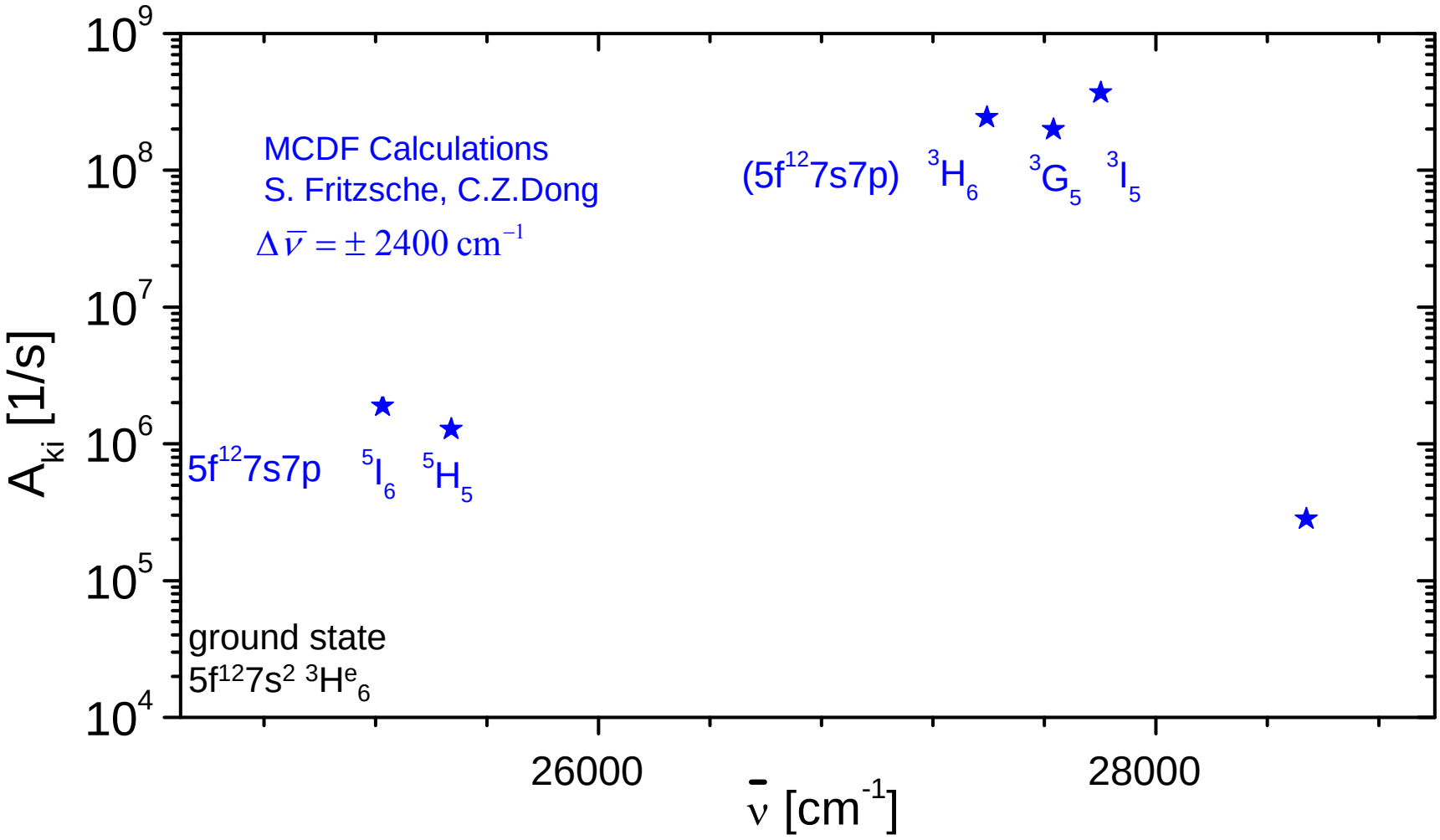




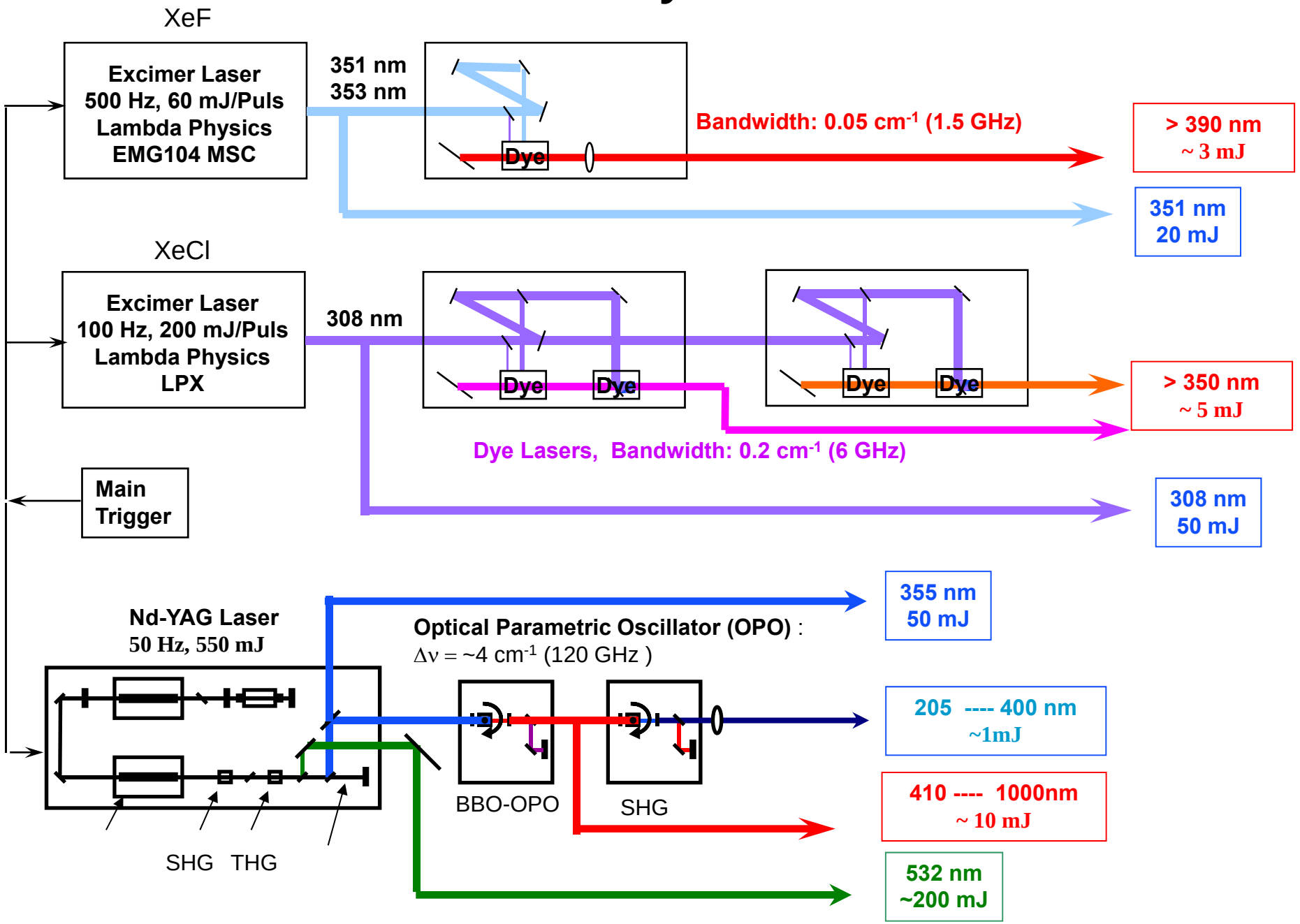




Theoretical Level Predictions for Fermium

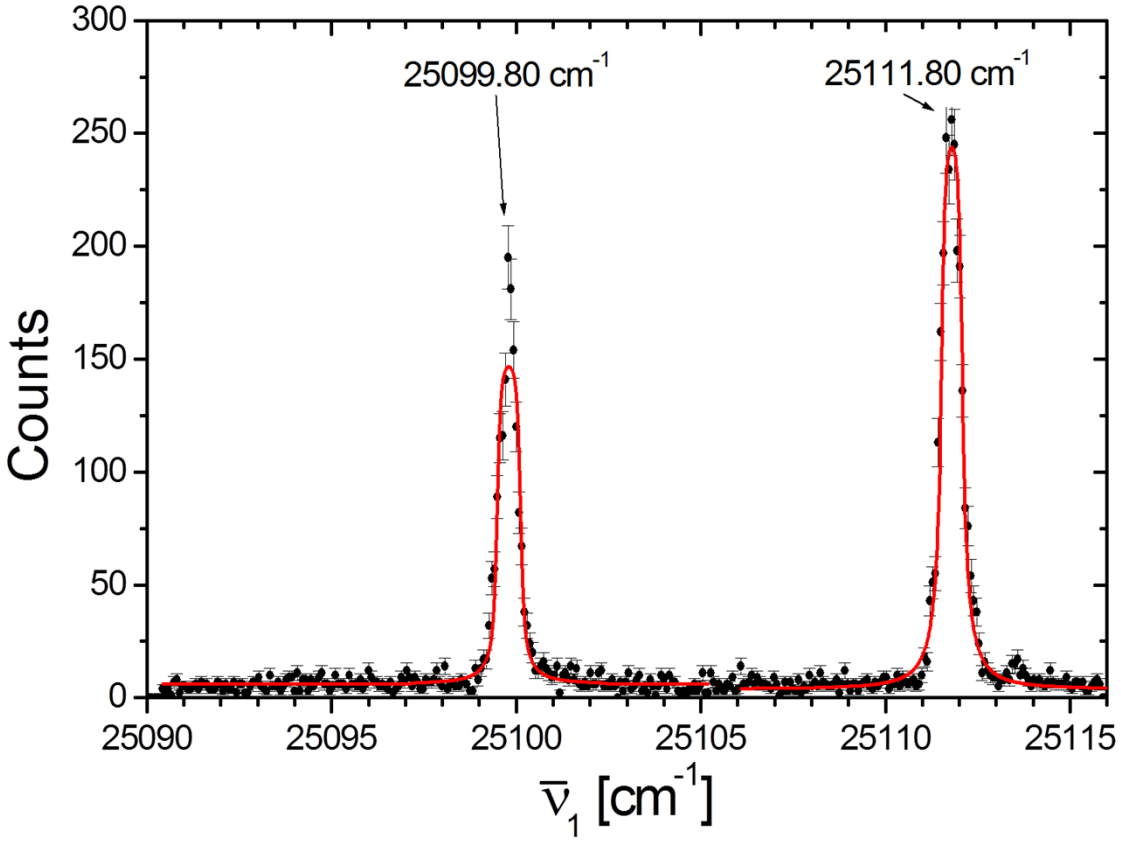


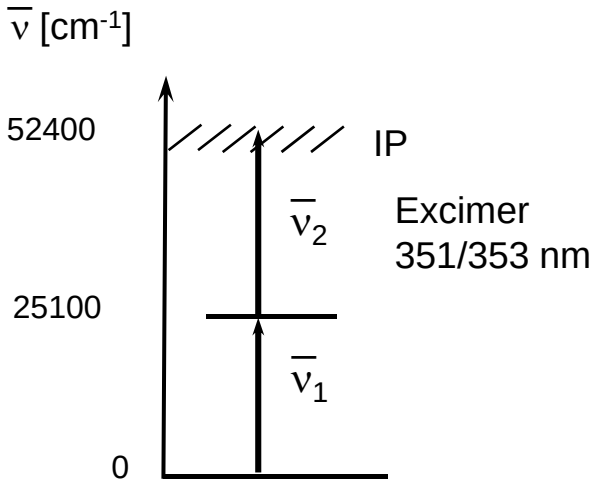
Laser Systems



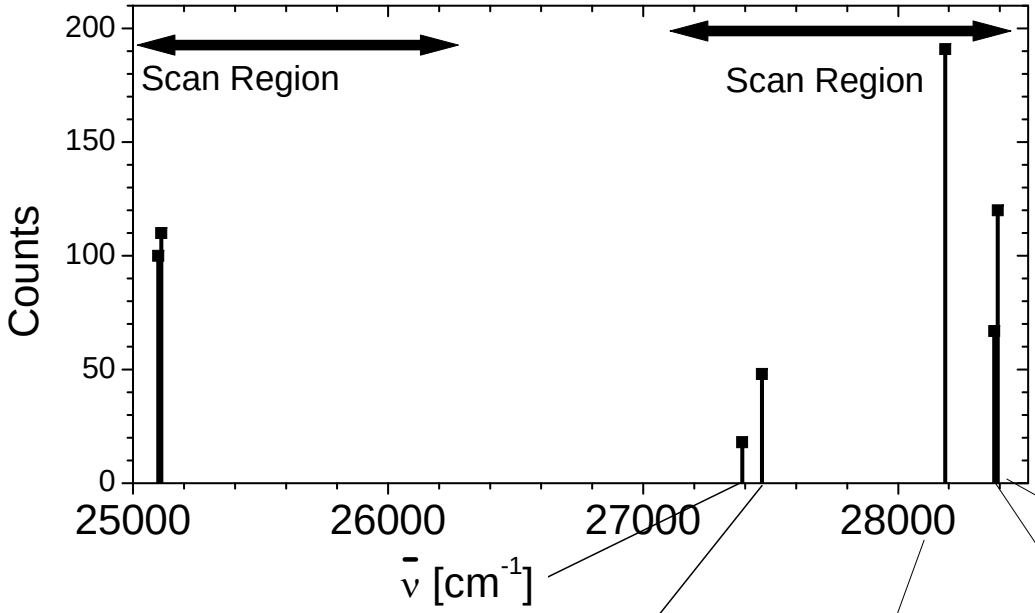
The First Optical Transition ever Observed for Fermium (Z = 100)

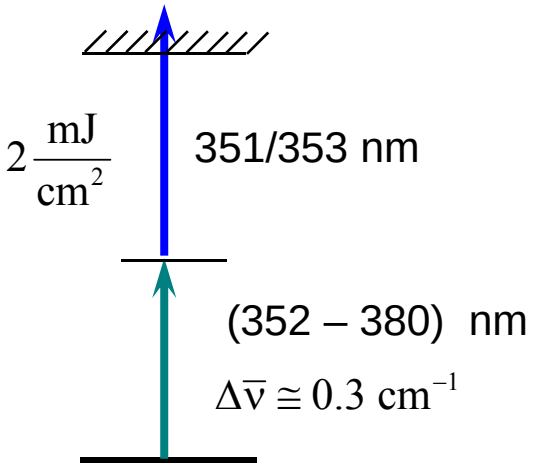
M. Sewtz et al., Phys. Rev. Letters **90** (2003) 163002

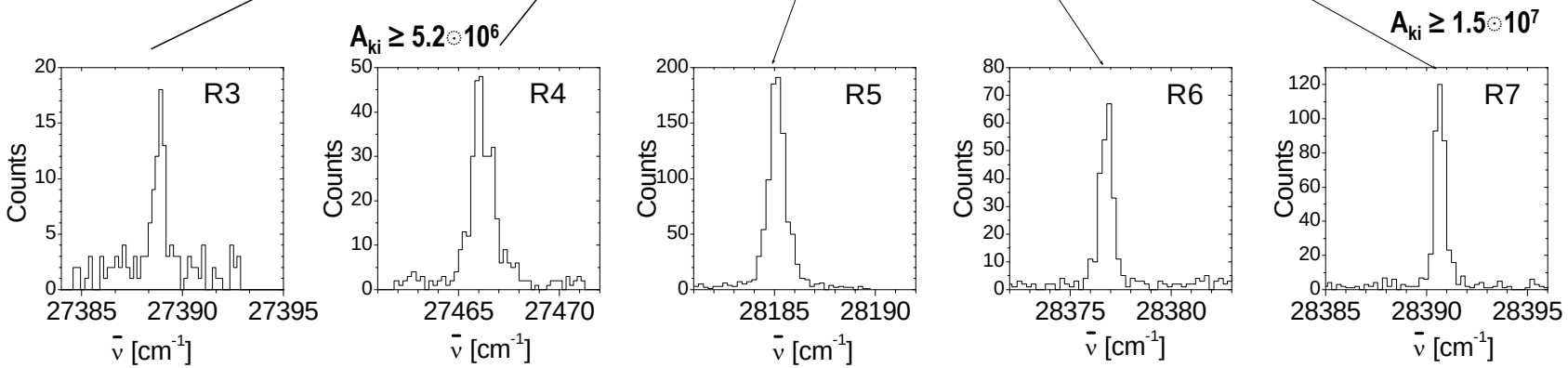




Summary of Level Search







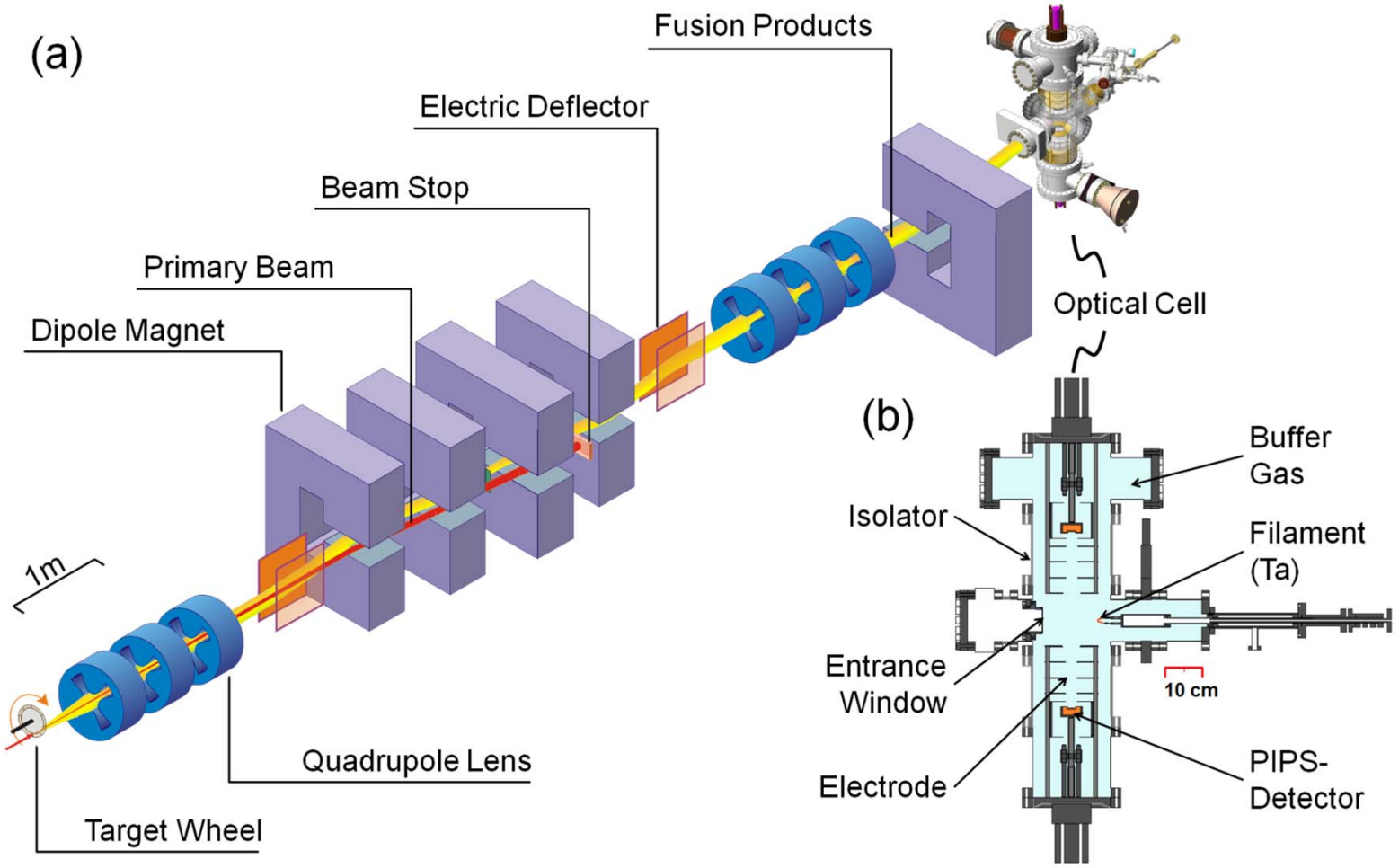
6. RADRIS with the Ion Collection and Atom Re-Evaporation Method

Status of Laser Spectroscopy at Nobelium (Z = 102)

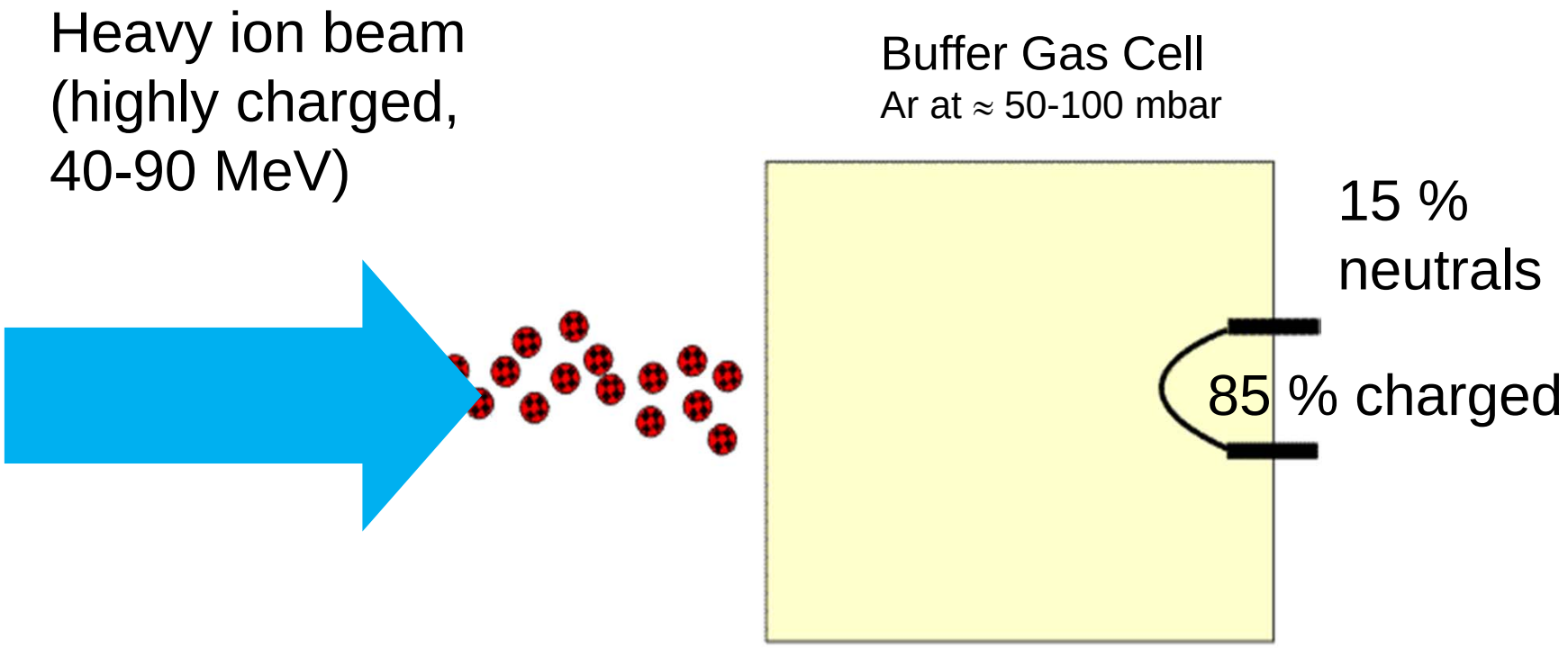
Experimental Setup

^{208}Pb (^{48}Ca,2n) ^{254}No ($t_{1/2}$=55 s, α decay)

$\sigma \sim 3.4\ \mu b$: 5 Ions/s



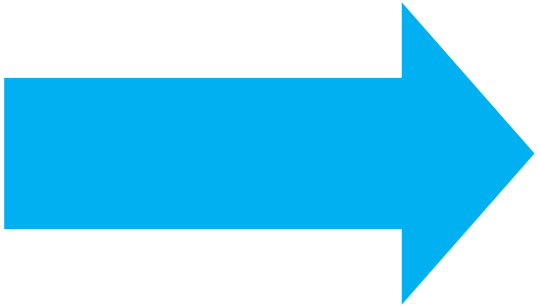
The Ion Collection and Atom Re-Evaporation Method (ICARE)



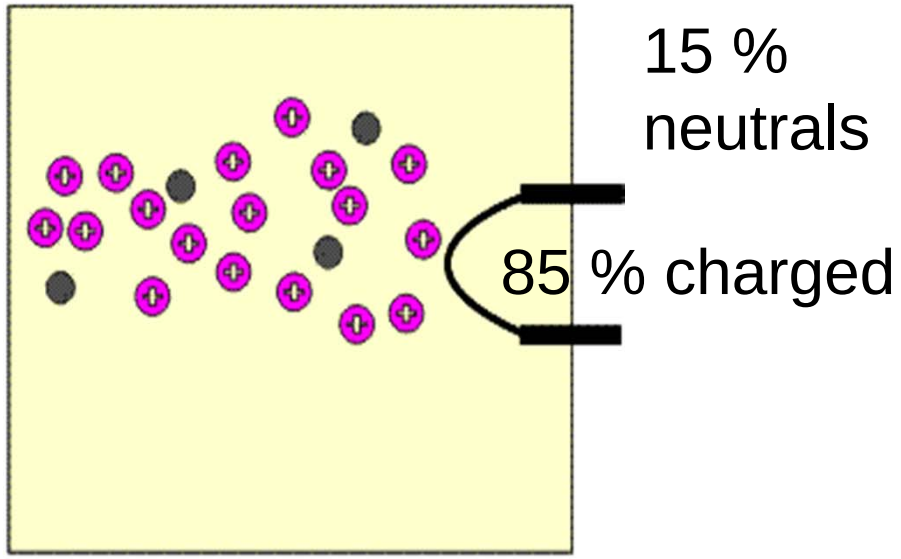
Method take advantage of the
85 % charged fraction

The Ion Collection and Atom Re-Evaporation Method (ICARE)

Heavy ion beam
(highly charged,
40-90 MeV)



Buffer Gas Cell
Ar at ≈ 50-100 mbar



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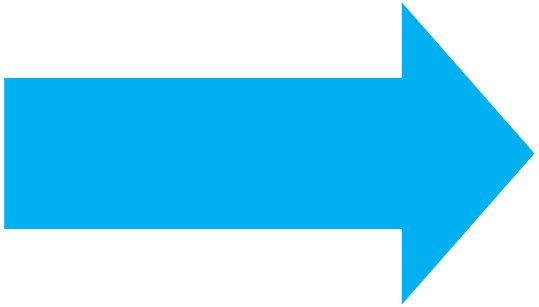

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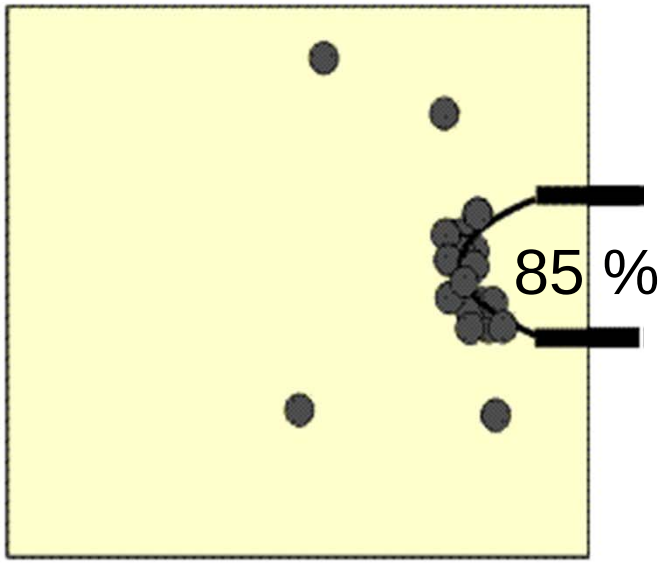
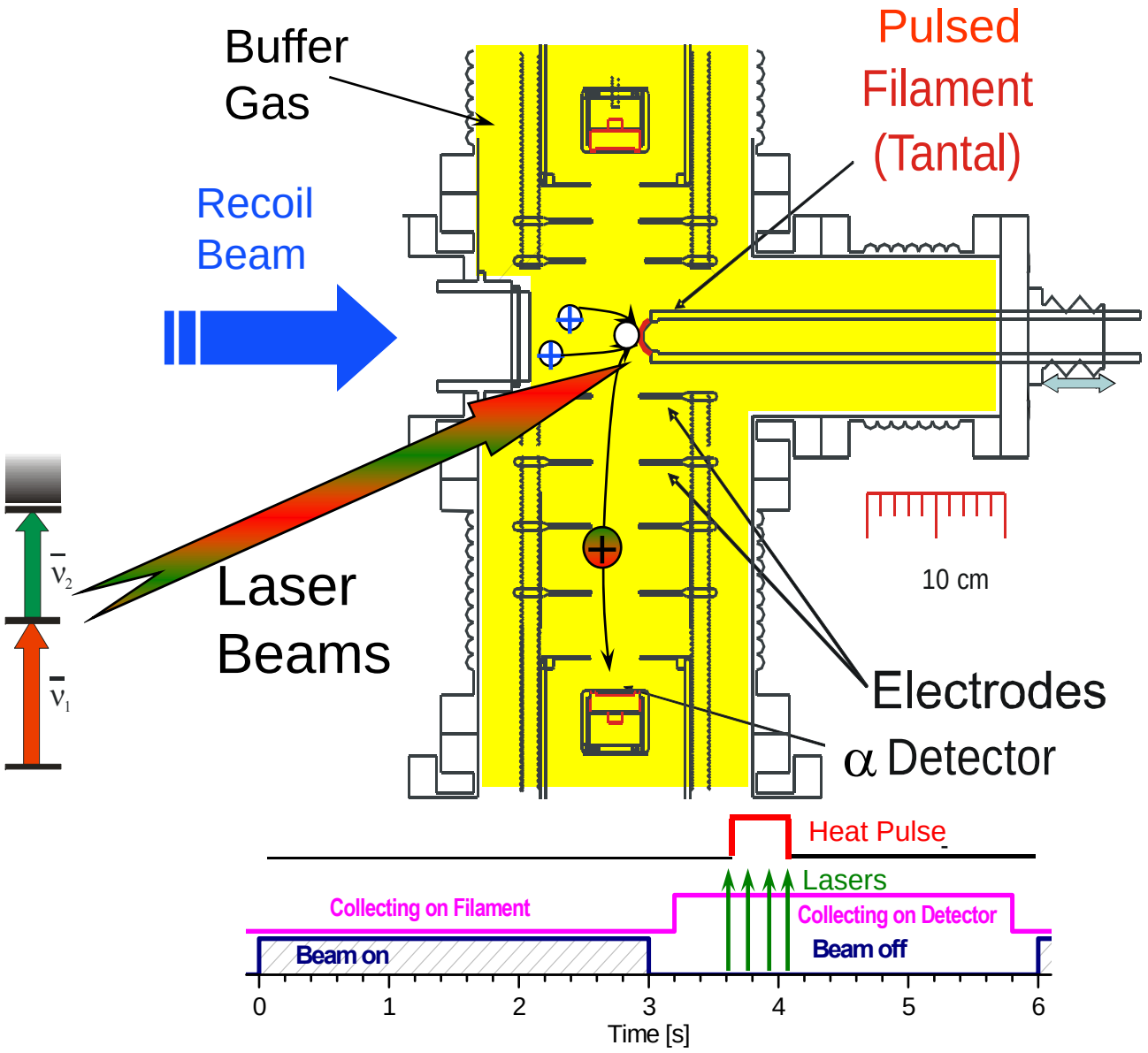


15 %
neutrals

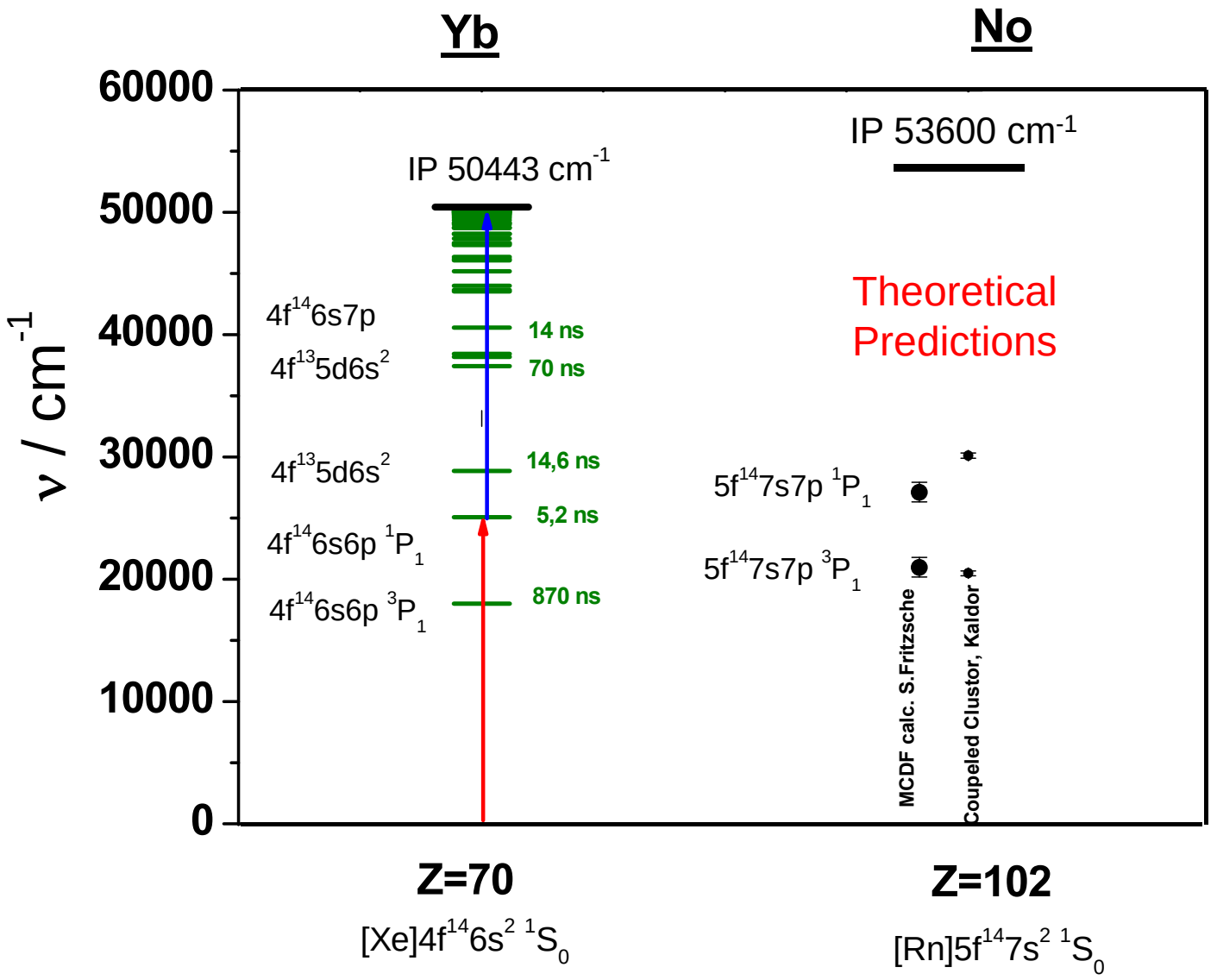
85 % charged

Method take advantage of the
85 % charged fraction

Radioactive Decay Detected Resonance Ionization with the ICARE Method

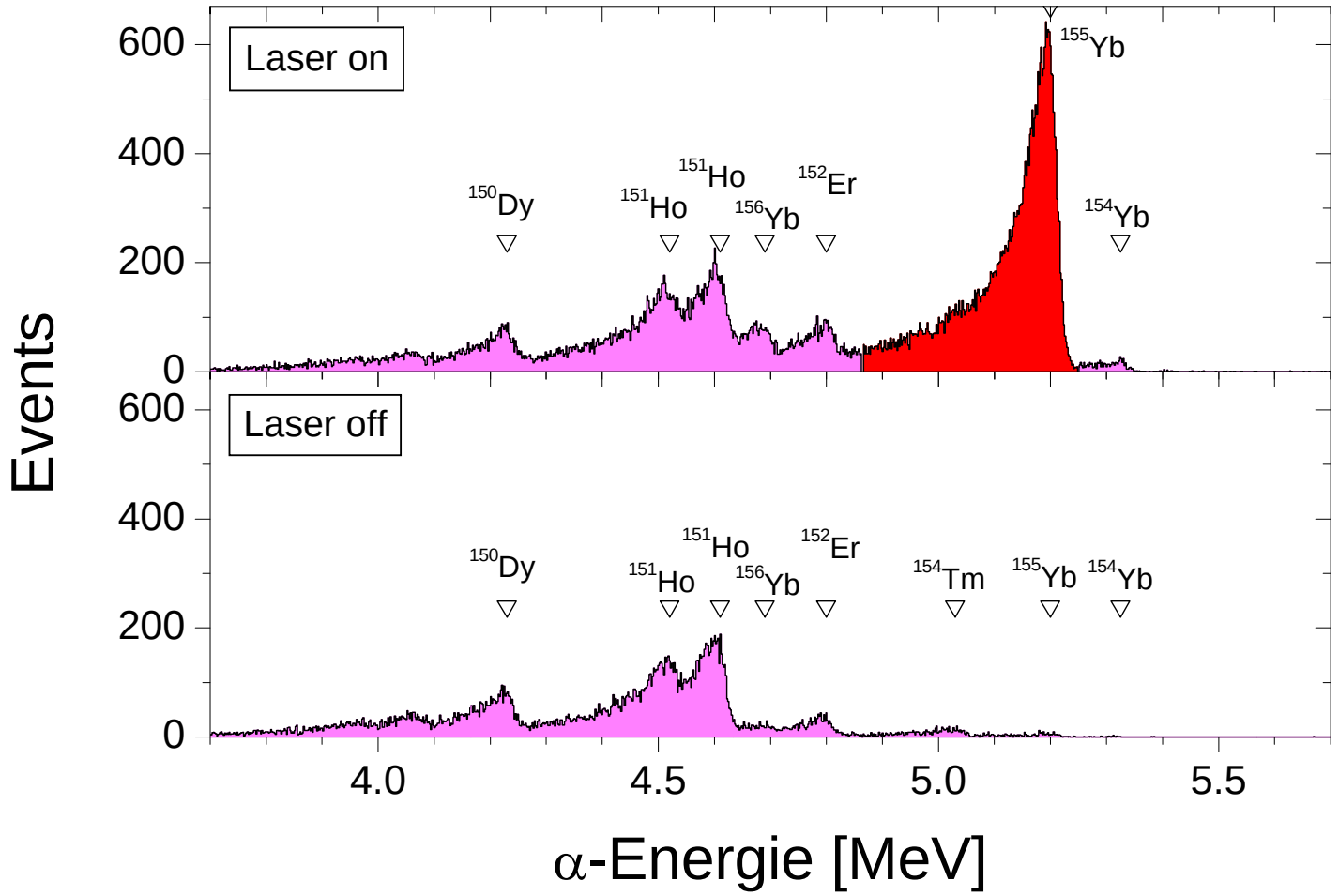


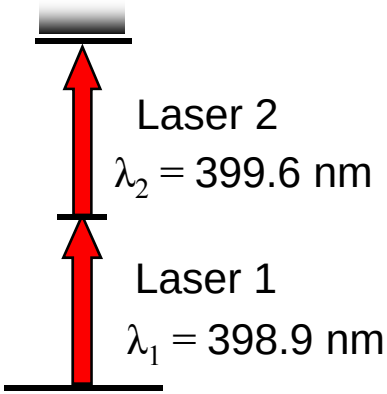
Nobelium as Chemical Homolog of Ytterbium



Test of the Method at ^{155}Yb (Z=70)

^{107}Ag(^{52}Cr, p3n)^{155}Yb ($t_{1/2}$=1.75 s, α - decay);
σ = 15 mb, ρd = 0.455 mg/cm^2, 4·10^4 Ions/s





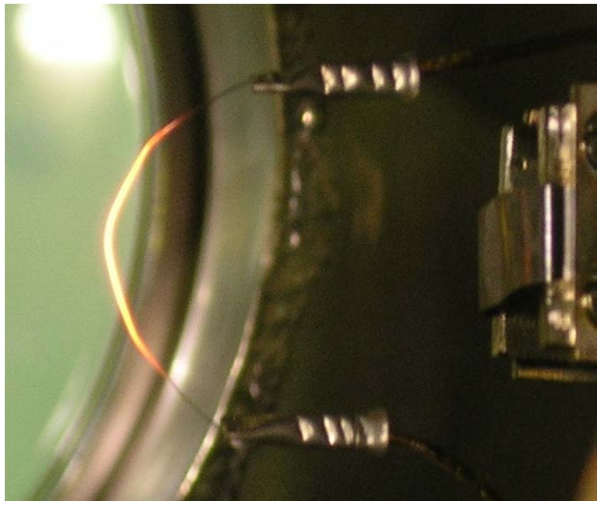
$$\frac{\text{Signal}}{\text{Background}} = \frac{30}{1}$$

Efficiency

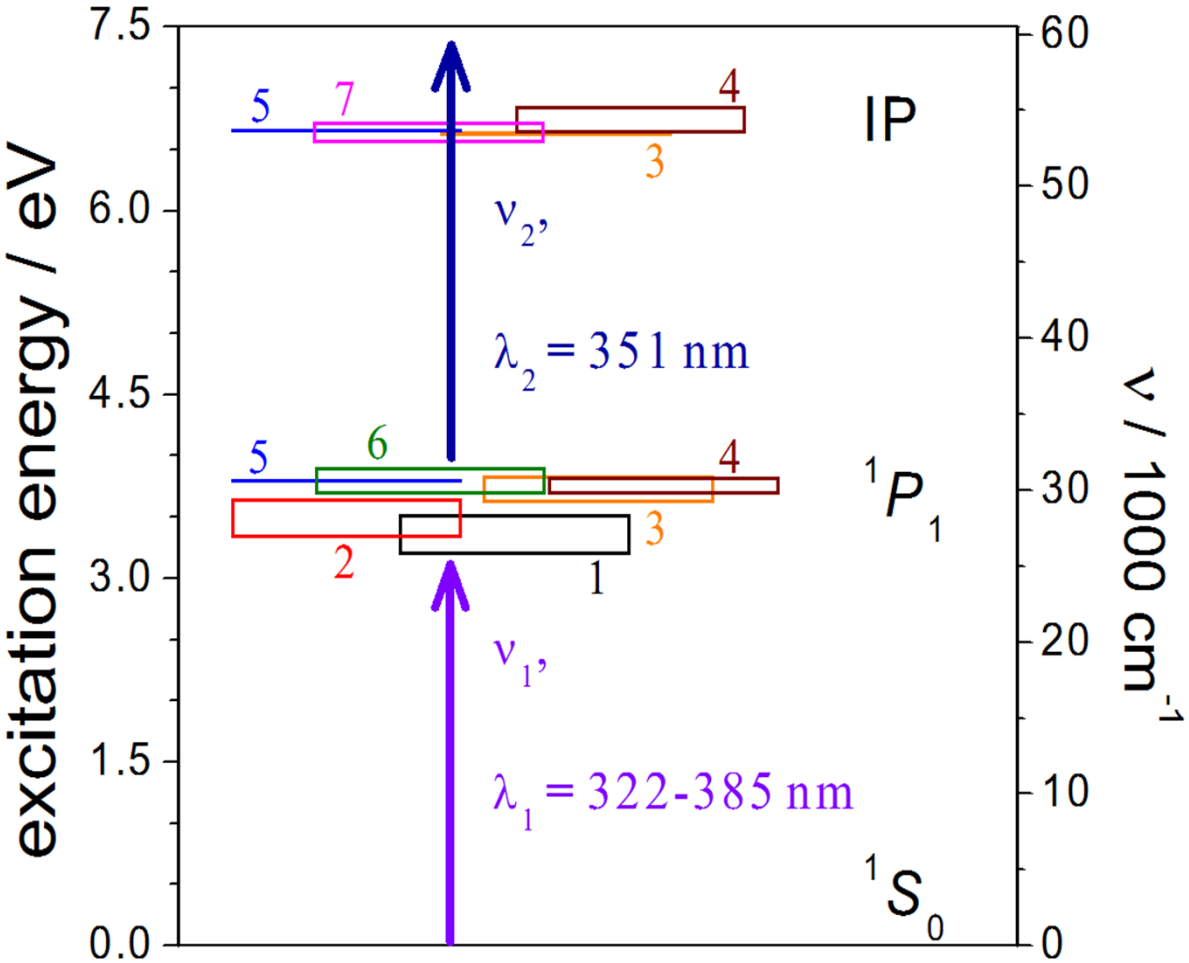
$$\frac{N_{Yb}^{RIS}}{N_{Yb}^{Target}} = 0.8 \cdot 10^{-2}$$

$$= \varepsilon_{SHIP} \cdot \varepsilon_{Cell} \cdot \varepsilon_{Ion} \cdot \varepsilon_{Collect} \cdot \varepsilon_{Decay} \cdot \varepsilon_{Evap} \cdot \varepsilon_{RIS} \cdot \varepsilon_{Transp.} \varepsilon_{\alpha Det}$$

$$0.5 \cdot 0.7 \cdot 0.85 \cdot 0.8 \cdot 0.59 \cdot 0.16 \cdot 1 \cdot 0.36$$



Predictions for the $^1P_1$ – level



[1,2] (MCDF) S. Fritzsche, Eur. Phys. J. D 33, 15 (2005)

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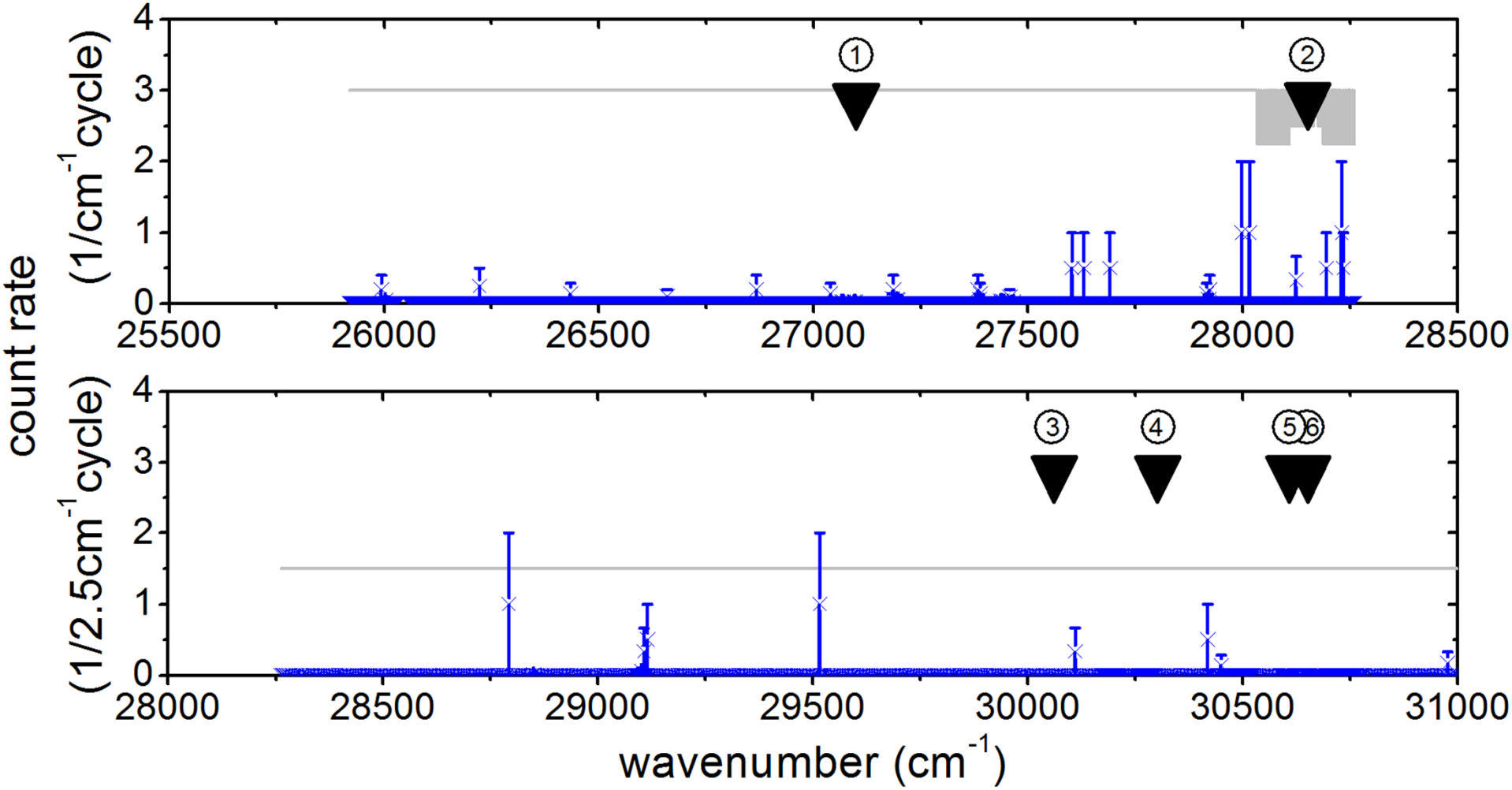
Multi-Configuration Dirac Fock (MCDF)

Intermediate Hamiltonian Fock-space coupled-cluster (IHFSCC)

Relativistic coupled cluster (RCC)

Search for an Atomic Level



7. Conclusions

- Resonance Ionization Spectroscopy (RIS) in gas cells is a powerful laser spectroscopic method at samples in the order of only 10^{10} atoms or production rates as low as 1/s.

• $^{240\text{-}244f}$Am	0.9–14 ms	on-line	10^6 - 10^7	RADRIS
• ^{255}Fm	20.1 h	off-line	few 10^{10}	IGRIS

Prospects

• ^{254}No	55 s	on-line	10^6 - 10^7	RADRIS

- Method has been tested with an on-line laser spectroscopy experiment at the chemical homologue ^{155}Yb. An overall efficiency of ~ 1% has been measured.
- The experiment at ^{254}No at GSI for an atomic level search is well prepared but is difficult and requires a lot of beam time.
- Activities are also underway at KU Leuven (Belgium) within the Heavy Element Laser Ionization Project (HELIOS) to be performed at the SPIRAL-2 facility at GANIL (France).

no atomic nlevels known

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