Hyperfine-resolved laser spectroscopy of highly charged I^{7+} ions

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Outline

- Motivation
- Fine-structure and metastable states of Pd-like I^{7+}
- Hyperfine structure of Pd-like I^{7+}
- Brief of experimental observation and theoretical results
- Summary

Introduction

Hyperfine structure

Nuclear electron interactions induce particularly small splitting in atomic energy levels, defined as hyperfine structure.

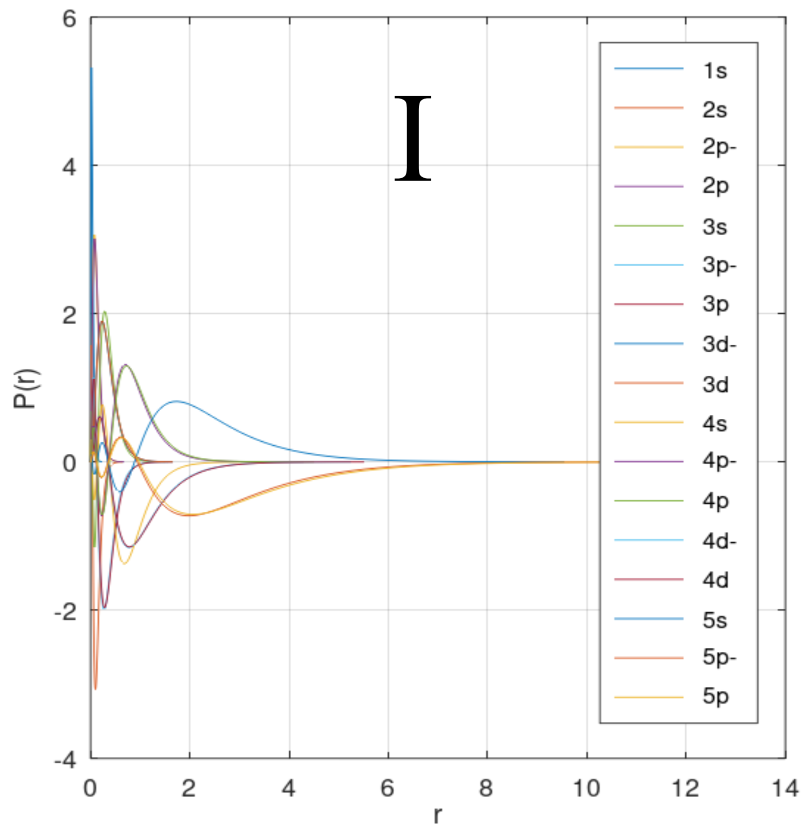
For **non-zero Nucleus spin** $F = |J-I| — |J+I|$

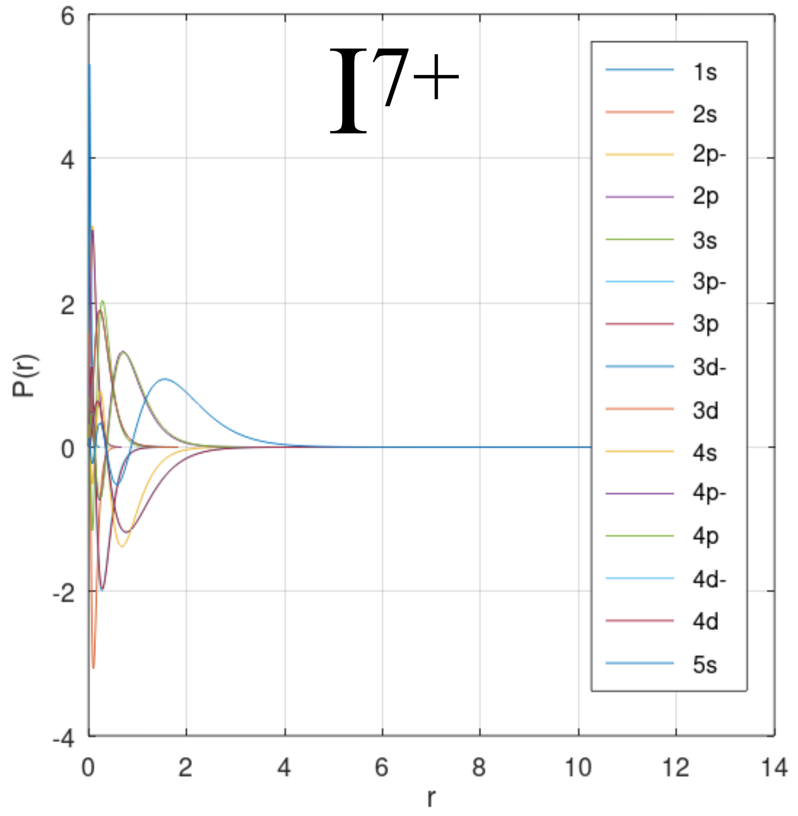
↓ total angular momentum of e-

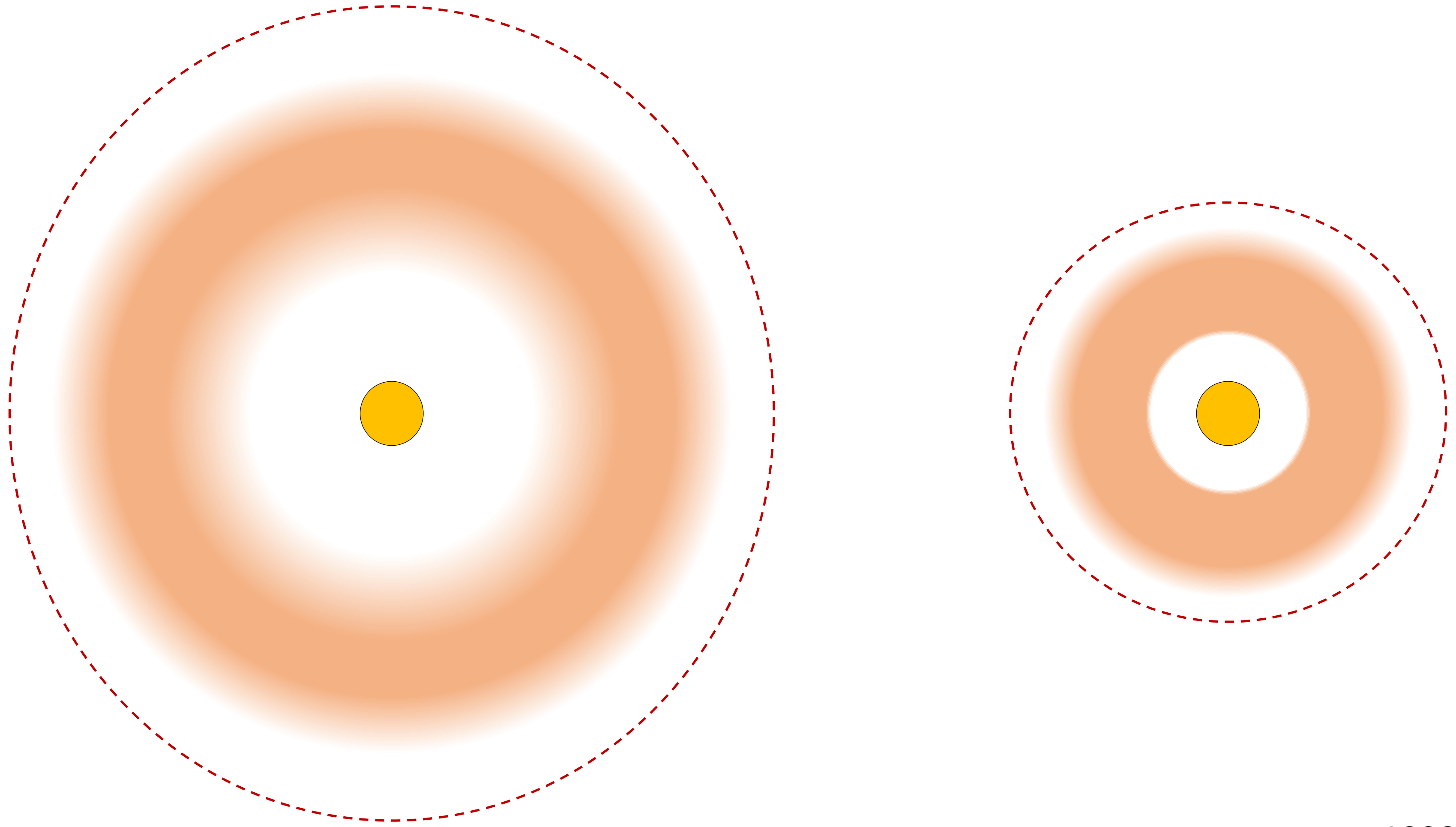
↘ nuclear spin

HFS in Highly charged ion(HCI)

Highly charged ions (HCIs), enhanced hyperfine interactions owing to contracted electron clouds.







Motivation

- Hyperfine resolved spectroscopy of HCI's play an important role in many studies

HFS in H-, He-, Li-, and Be-like ions have been widely performed

They have successfully contributed to

- Tests of relativistic and quantum electrodynamics (QED) atomic theories
- Investigations of nuclear properties

Present interest

HFS in many-electron HCIs

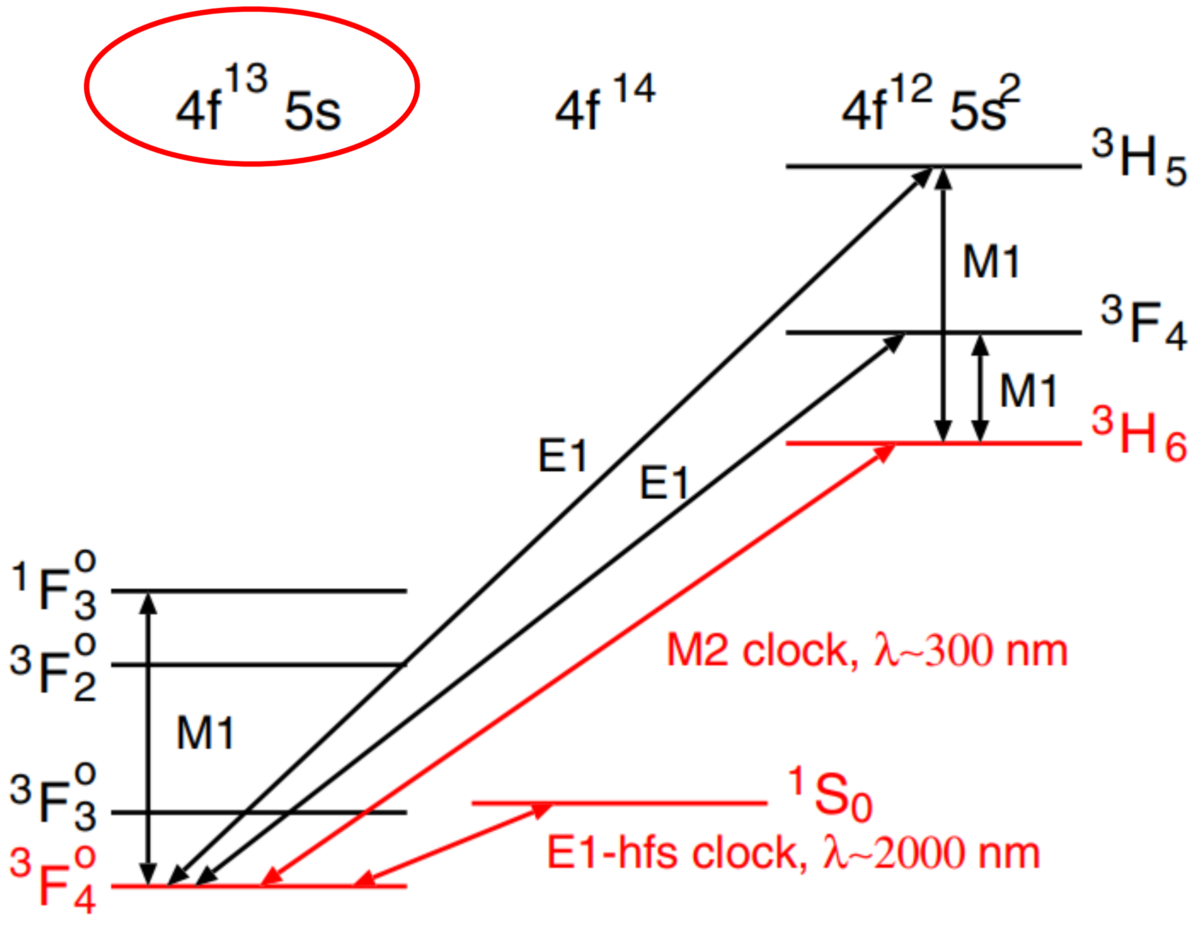
Toward the HCI clock (Good probe for fundamental physics)*

- Proposed atomic clocks are based on Hyperfine-structure resolved excitation (**Viz. Ho^{14+} , Ir^{17+}**)
- Natural width of a clock transition involves hyperfine-mixing

*M. G. Kozlov, *et al.*, Rev. Mod. Phys. 90, 045005 (2018).

Specific electron configuration with a 5s valence electron

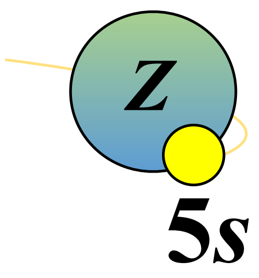
Ir^{17+}



J. C. Berengut, et al., Phys. Rev. Lett. 106, 210802 (2011).
A. Windberger, et al., Phys. Rev. Lett. 114, 150801 (2015).
V. A. Dzuba, et al., Hyp. Int. 236, 79 (2015).

Large HFS constant ??

Ho^{14+}



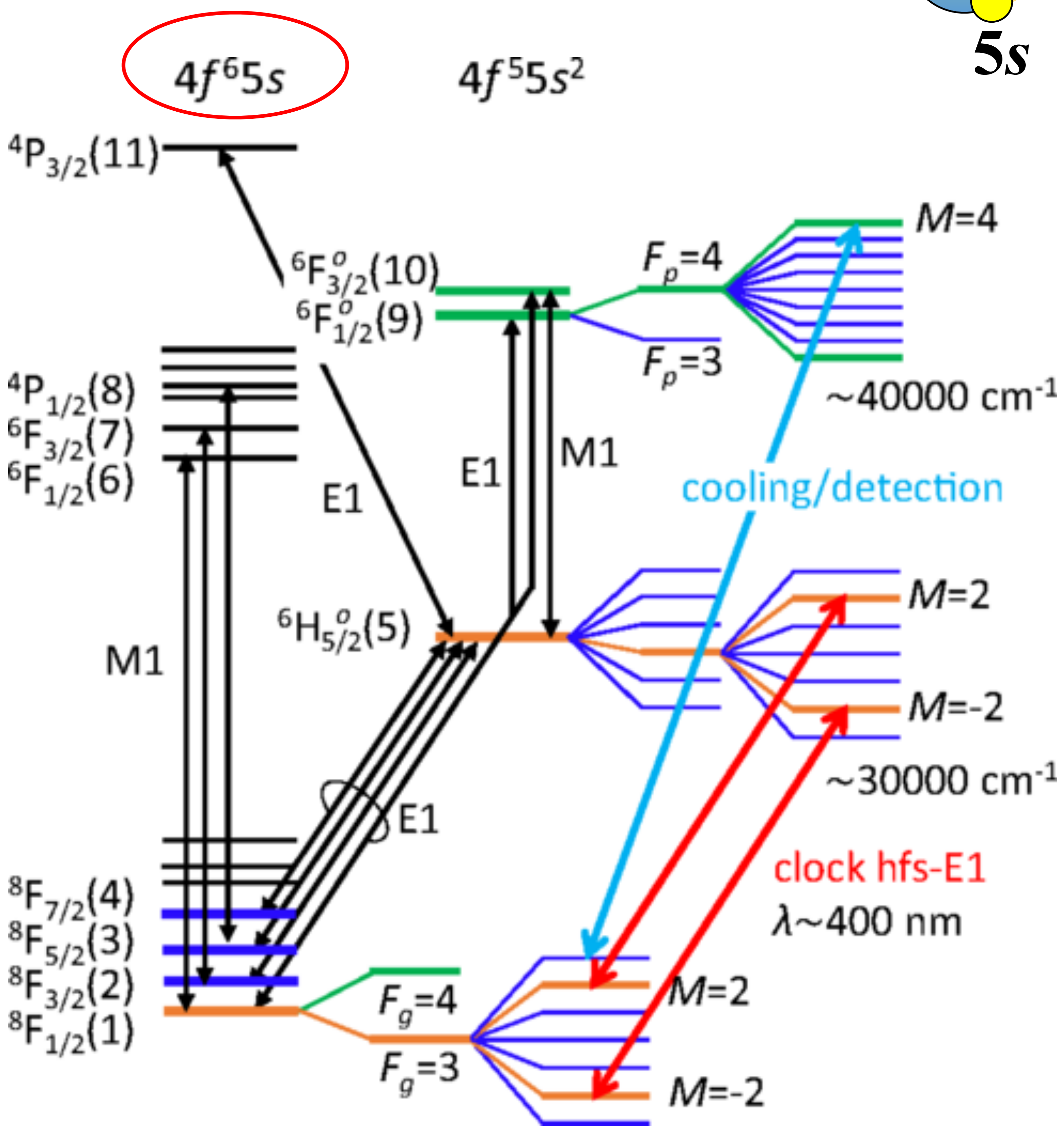
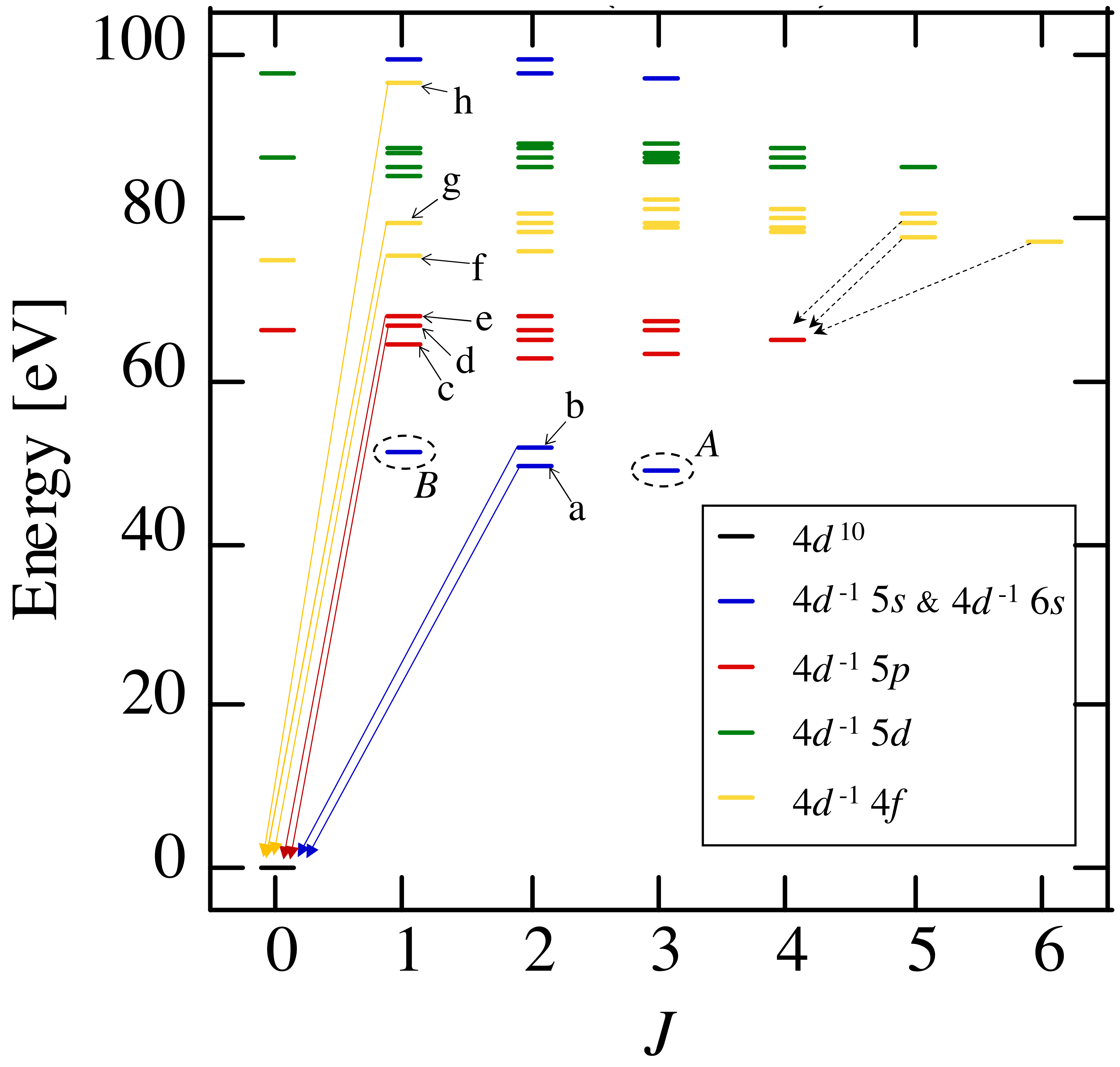


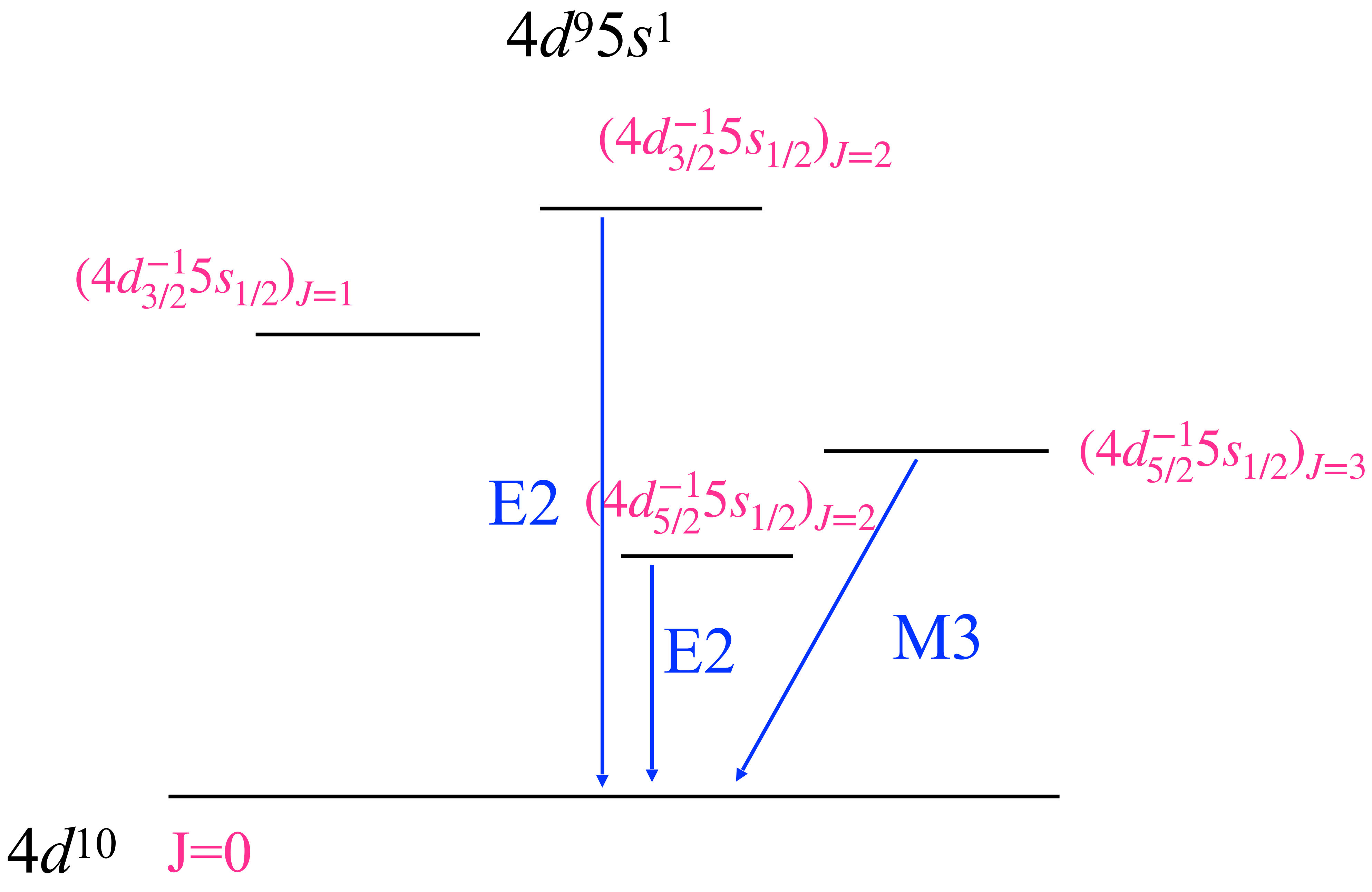
TABLE III. Magnetic-dipole and electric-quadrupole hfs constants A and B for the ground and clock states of $^{165}Ho^{14+}$.

State		A (GHz)	B (GHz)
$4f^65s$	$^8F_{1/2}$	96.5	0
$4f^55s^2$	$^6H^o_{5/2}$	3.53	−6.04

V. A. Dzuba, et al., Phys. Rev. A 91, 022119 (2015).

System of Interest Pd-like $^{127}I^{7+}$



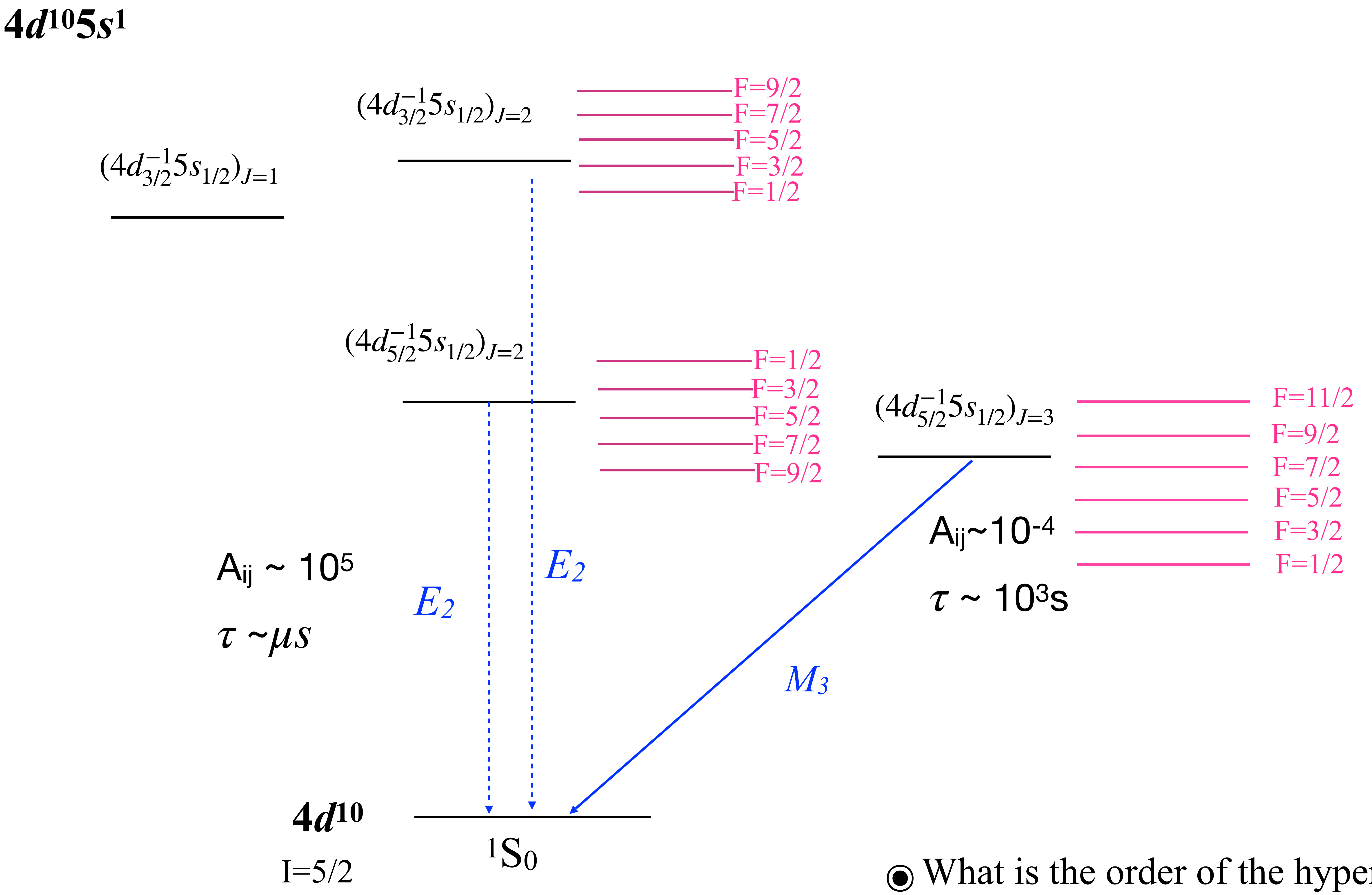


Collisional radiative Model calculations

		I (Z = 53)	
Label	Level	τ (s)	ρ (%)
A	$(4d_{5/2}^{-1}\ 5s_{1/2})_{J=3}$	$3.6 \times 10^{+3}$	17.64
B	$(4d_{3/2}^{-1}\ 5s_{1/2})_{J=1}$	3.3×10^{-2}	1.92
C	$(4d_{5/2}^{-1}\ 4f_{7/2})_{J=6}$	3.2×10^{-4}	0.13
D	$(4d_{5/2}^{-1}\ 4f_{5/2})_{J=5}$	1.9×10^{-4}	
E	$(4d_{5/2}^{-1}\ 4f_{7/2})_{J=5}$	2.3×10^{-4}	
G	$(4d^{10})_{J=0}$		80.11

Kimura *et al.*, PRA102, 032807 (2020)

Hyperfine splitting（Pd-like- $^{127}I^{7+}$）



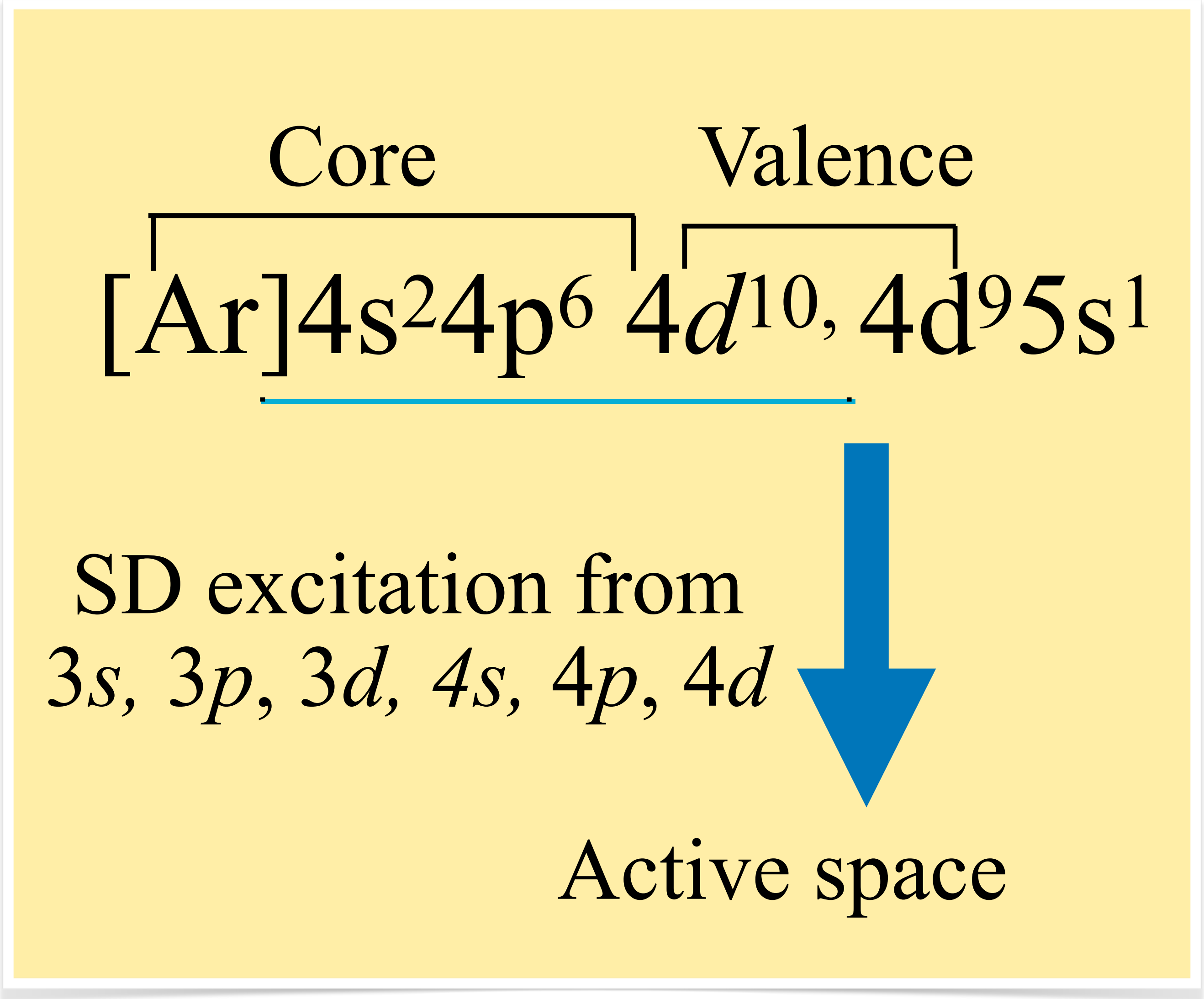
Nuclear Spin, I =5/2

Angular momentum J= 3, 2

F= |I+J| to |I-J|

- What is the order of the hyperfine splitting?
- Does hyperfine mixing will change the lifetime of the metastable states?

Multi configuration Dirac-Fock (MCDF) calculations using GRASP2018*



- Core–core and core–valence correlations with the inner orbitals were also included.
- This active space treatment led to 3,300,000 jj-coupled configurations.

$$\mathrm{DF} = \{3s^2\,3p^6\,4s^2\,4p^6\,4d^{10},\ 3s^2\,3p^6\,4s^2\,4p^6\,4d^9\,5s^1\},$$
$$\mathrm{AS1} = \mathrm{DF} + \{5p, 5d, 5f, 5g\},$$
$$\mathrm{AS2} = \mathrm{AS1} + \{6s, 6p, 6d, 6f, 6g, 6h\},$$
$$\mathrm{AS3} = \mathrm{AS2} + \{7s, 7p, 7d, 7f, 7g, 7h\},$$
$$\mathrm{AS4} = \mathrm{AS3} + \{8s, 8p, 8d, 8f, 8g, 8h\}.$$

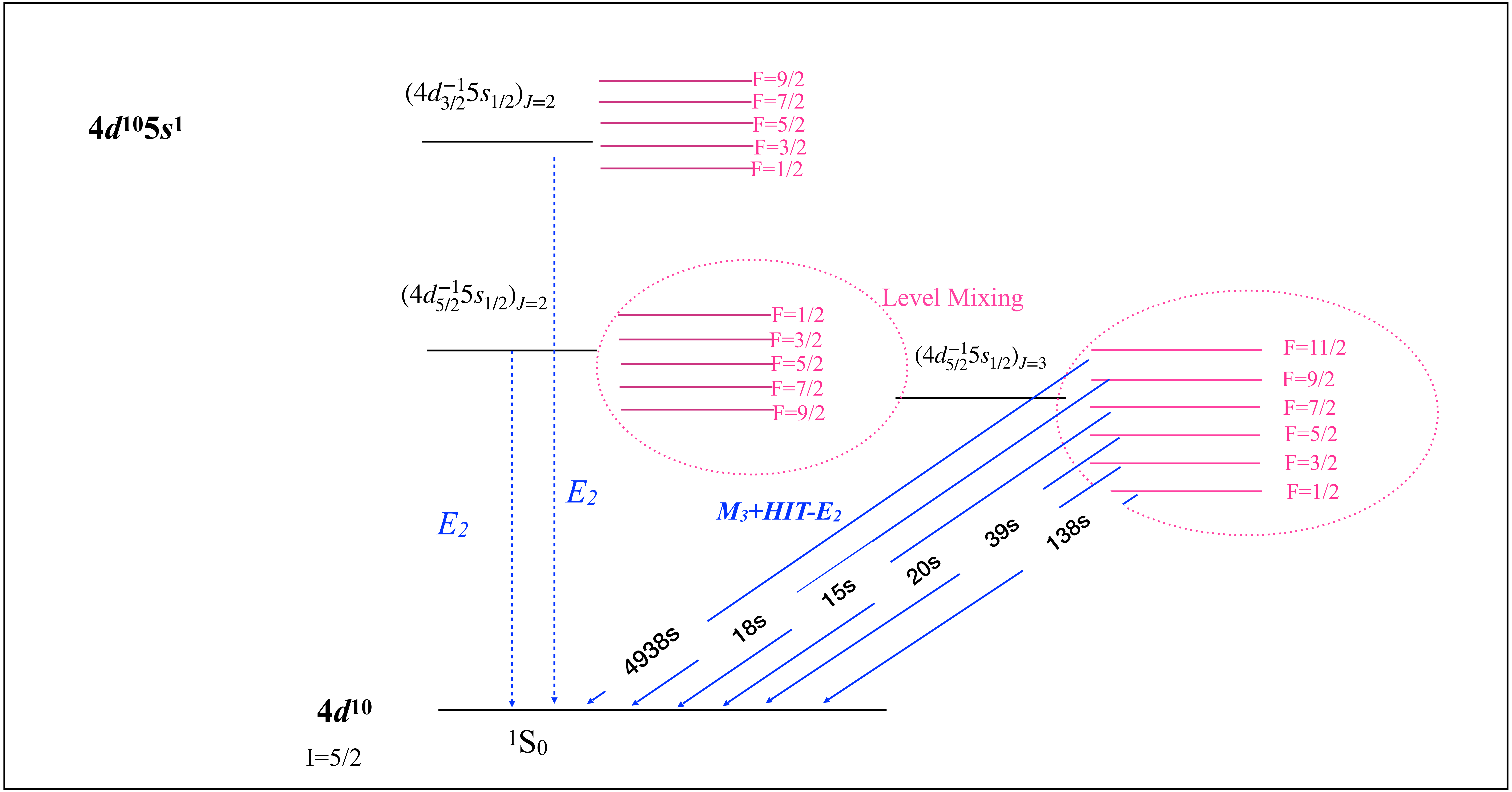
	Theory	MCDF	Breit	QED
A_{hfs} [GHz]	10.39 (± 0.05)	10.41	-1.7×10^{-2}	$+3.3\times10^{-3}$
B_{hfs} [GHz]	2.32 (± 0.02)	2.37	-4.3×10^{-2}	$+4.0\times10^{-4}$
A'_{hfs} [GHz]	15.33 (± 0.03)	15.45	-1.2×10^{-1}	$+7.5\times10^{-3}$
B'_{hfs} [GHz]	2.02 (± 0.01)	2.05	-2.8×10^{-2}	$+3.0\times10^{-4}$
k_0 [cm^{-1}]	17616 (± 22)	18016	− 418	+ 18

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

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

*C. Froese Fischer, *et. al.*, Computer Physics Communications 2019, 237, 184

Hyperfine induced transition Rates Mixing splitting（Pd-like- $^{127}I^{7+}$）

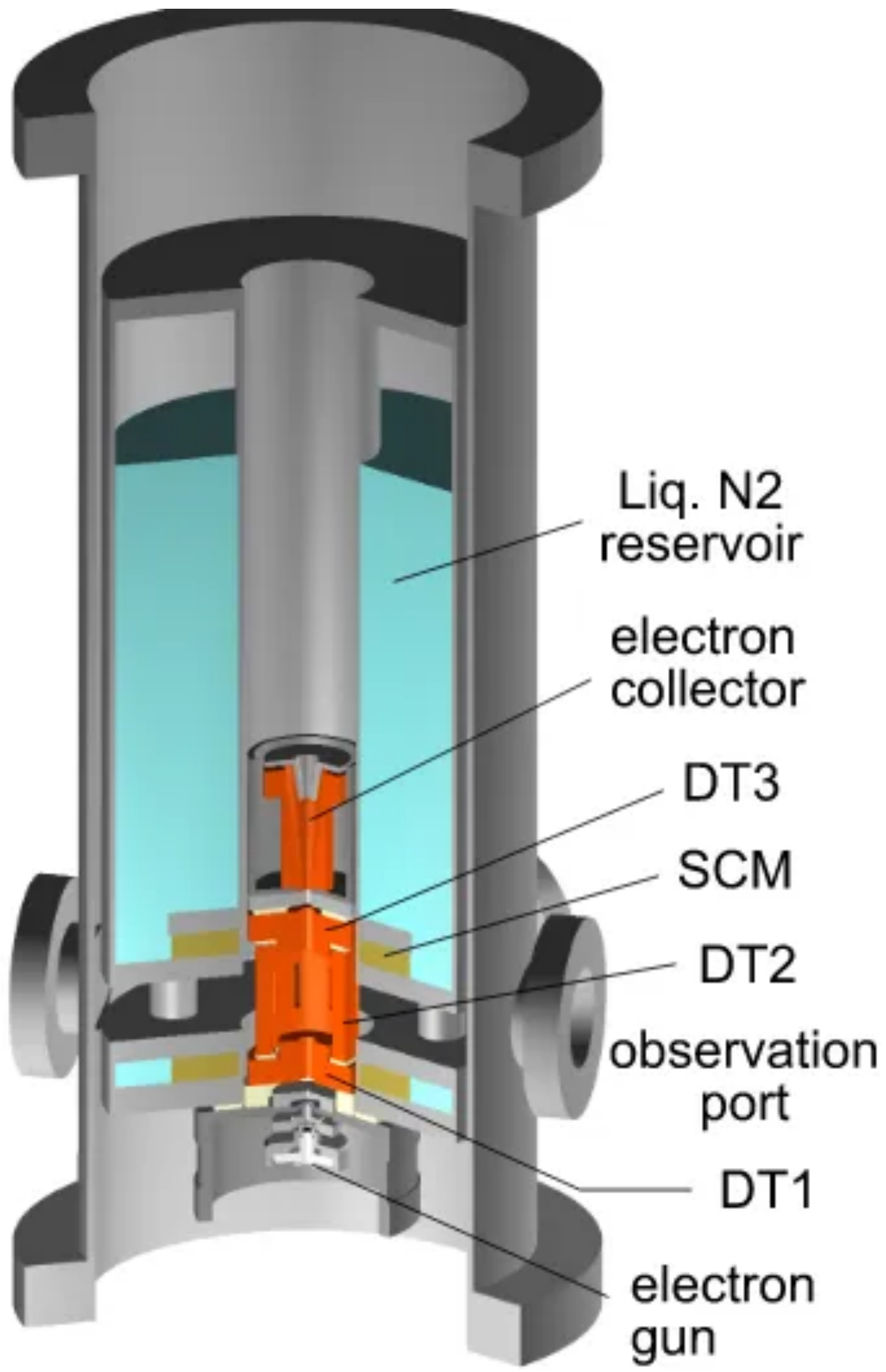


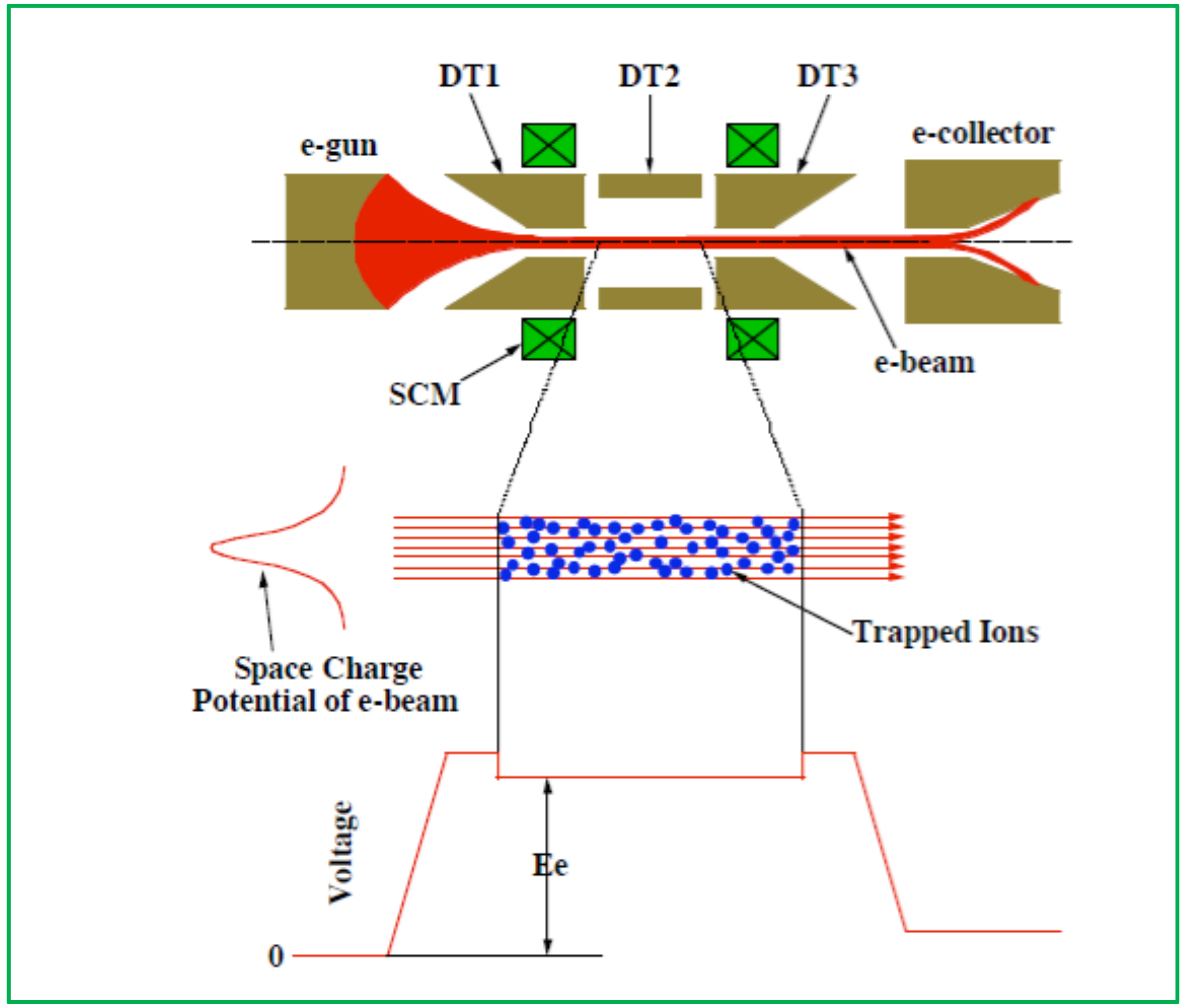
Li, W., Grumer, J., Brage, T. & Jönsson, P. Hfszeeman95-A program for computing weak and intermediate magnetic-field- and hyperfine-induced transition rates. Comput. Phys. Commun. 253, 107211 (2020)

Compact Electron Beam Ion Trap (CoBIT), UEC Tokyo

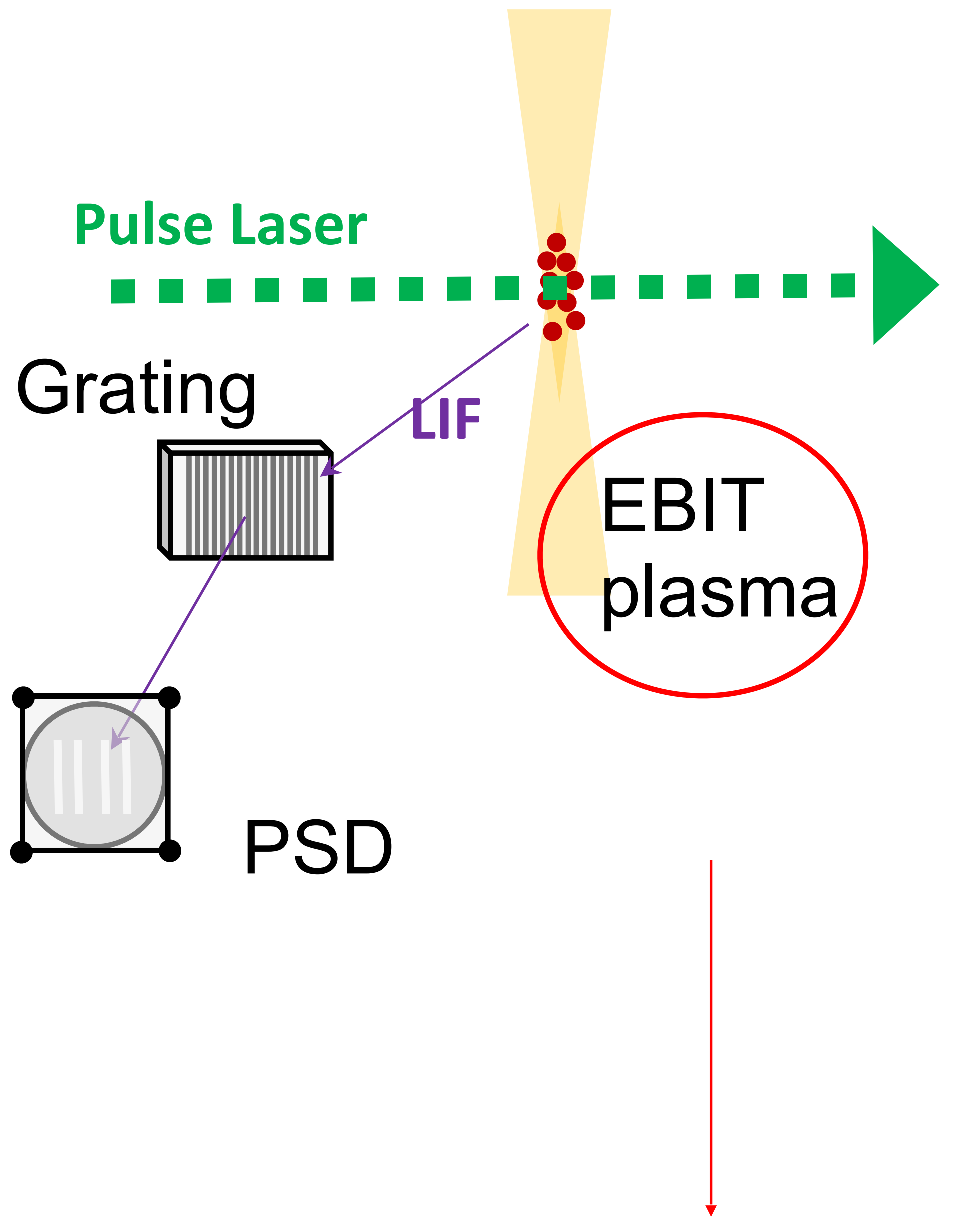
Specifications

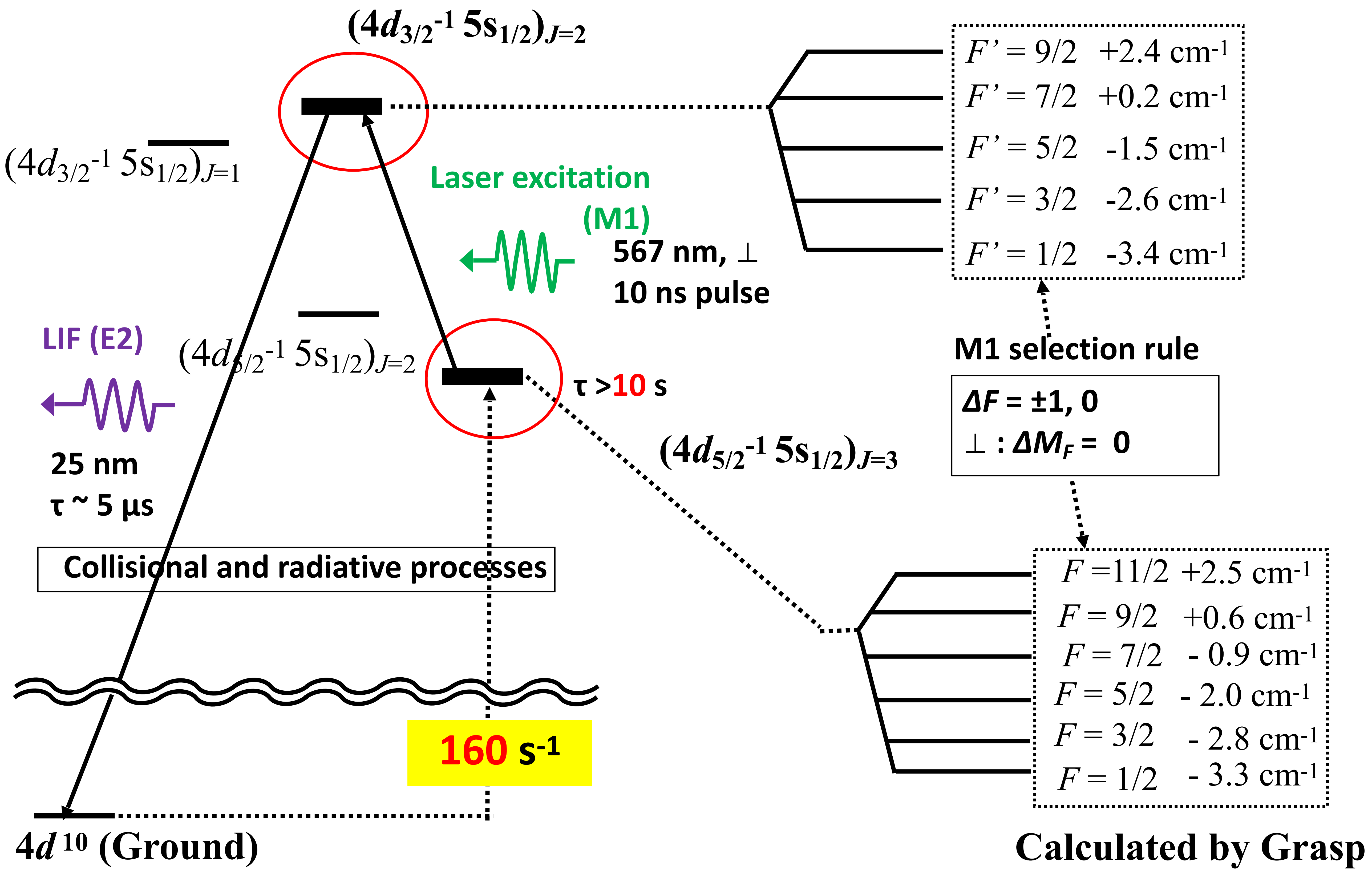
Vacuum : ~10^{-9} Pa
Beam energy : 50-2000 eV
Beam current : 1~20 mA
Magnetic field : 0.03 - 0.2 T



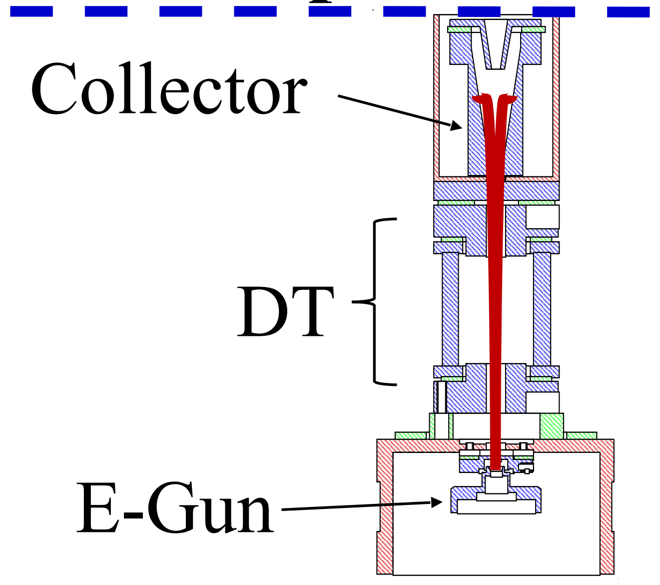


I^{7+} spectroscopy concept : Plasma-assisted laser spectroscopy





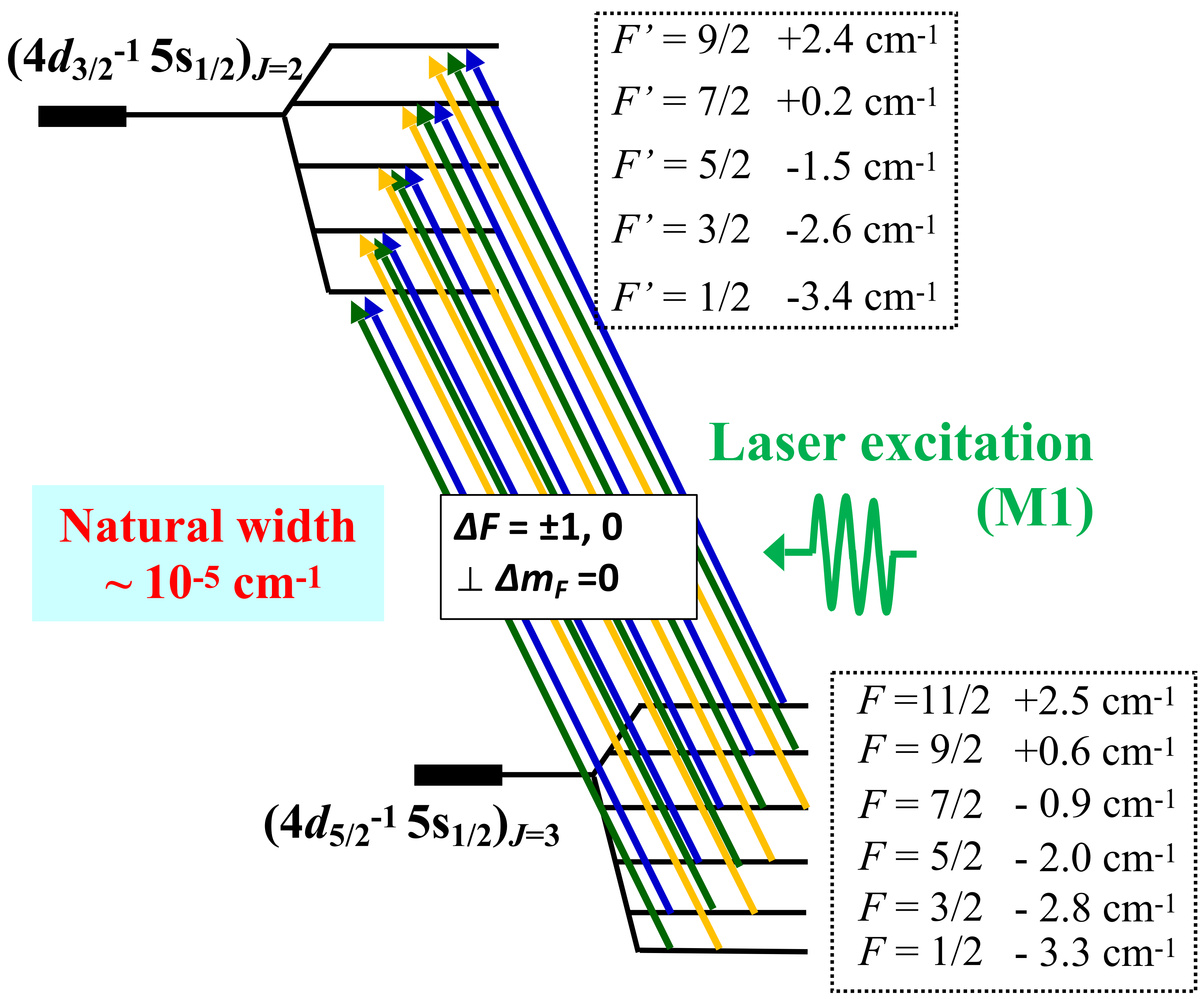
UEC compact EBIT (CoBIT)



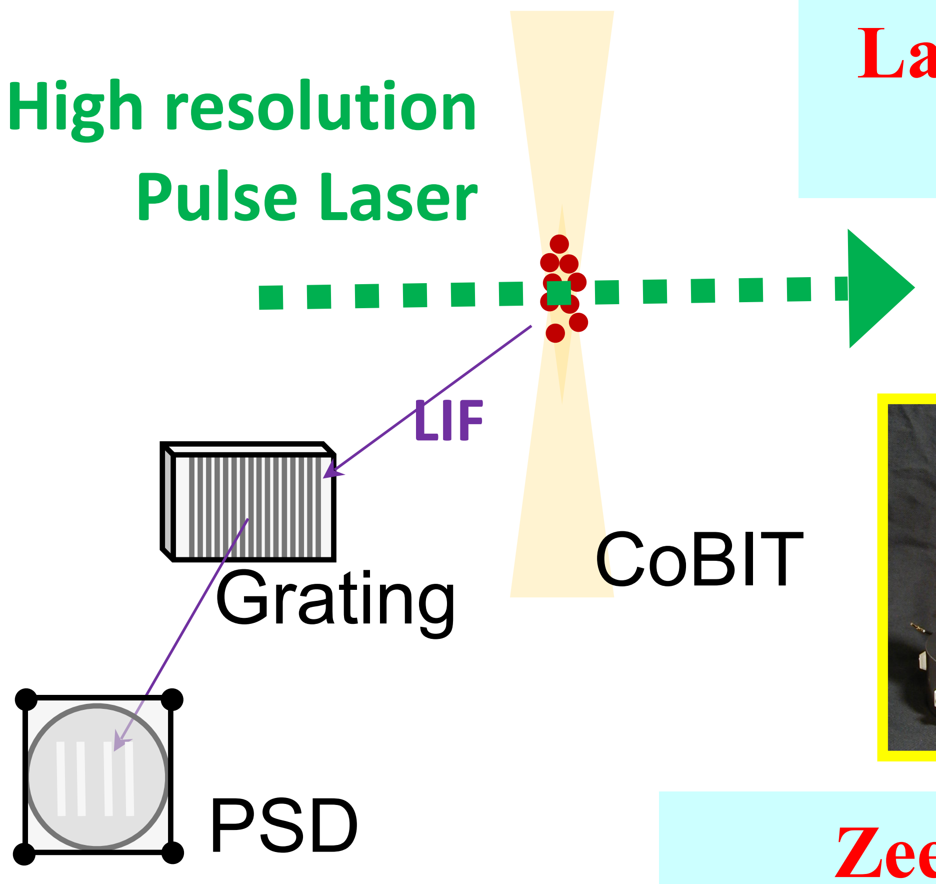
Specifications

Vacuum	:	~10^{-9} Pa
Beam energy	:	50-1000 eV
Beam current	:	1~20 mA
Magnetic field	:	0.03 - 0.2 T

Can we resolve the hyperfine-structure ??



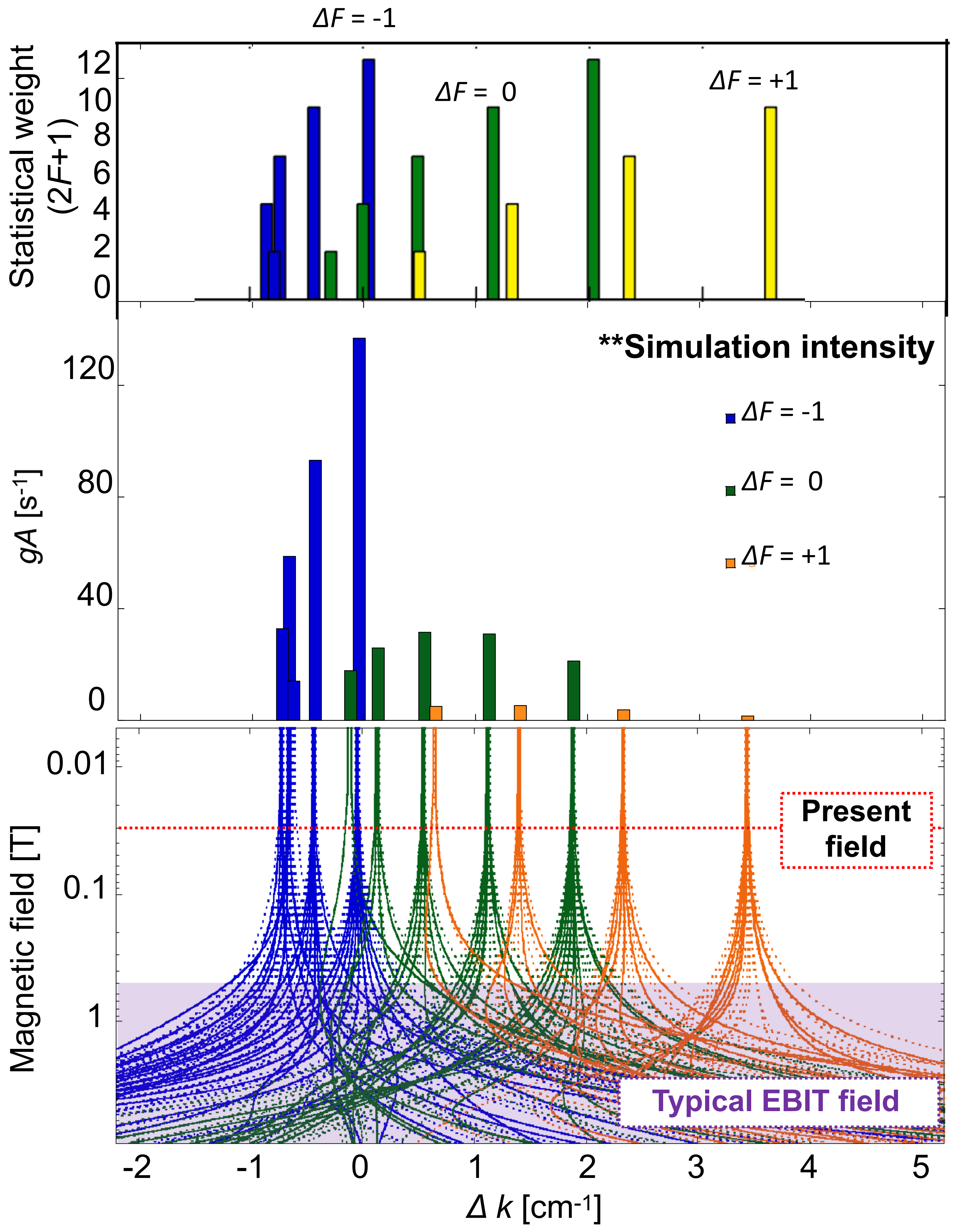
Natural width
~ 10^{-5} cm^{-1}



Laser line width
~ 0.03 cm^{-1}

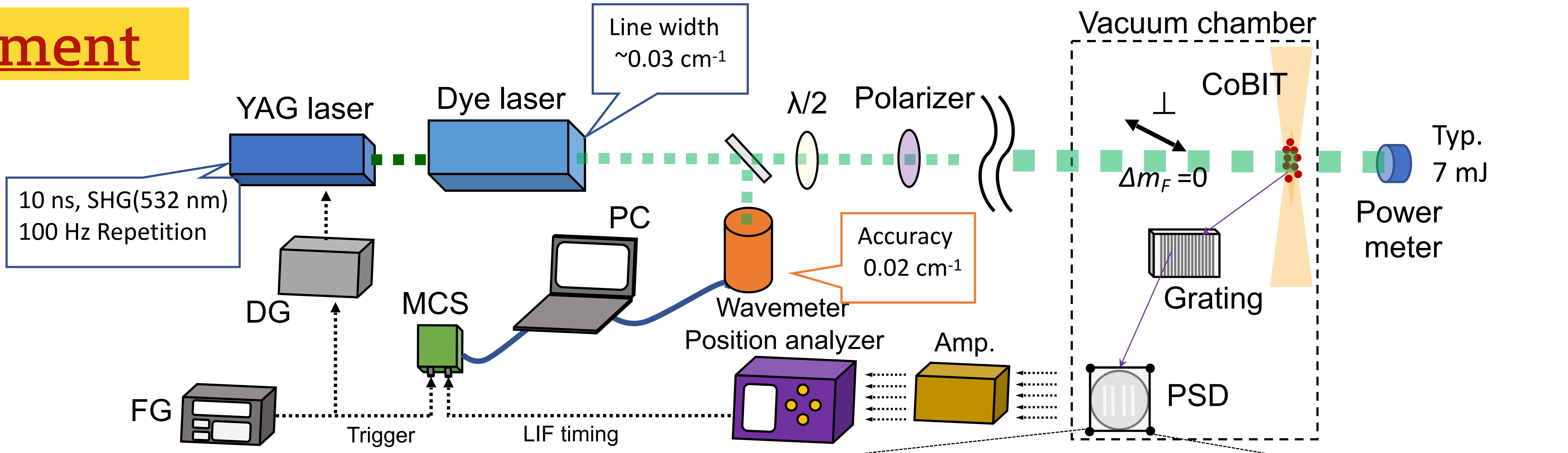
$$\begin{cases} E_e = 105 \text{ eV} \\ I_e = 2 \text{ mA} \\ B = 0.03 \text{ T} \end{cases}$$

Zeeman splitting < 0.05 cm^{-1}

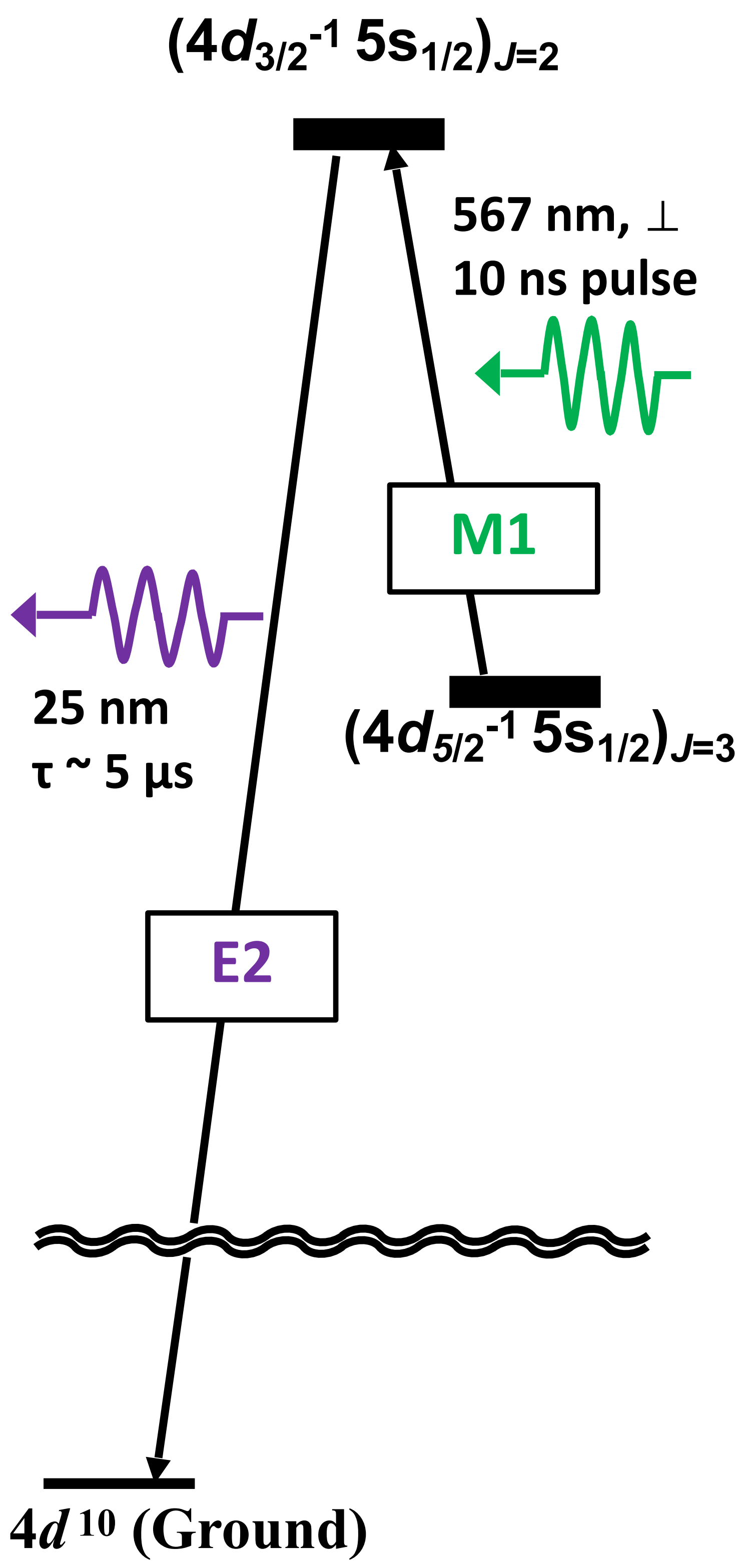


ASOS14, Paris, July 10-13, 2023

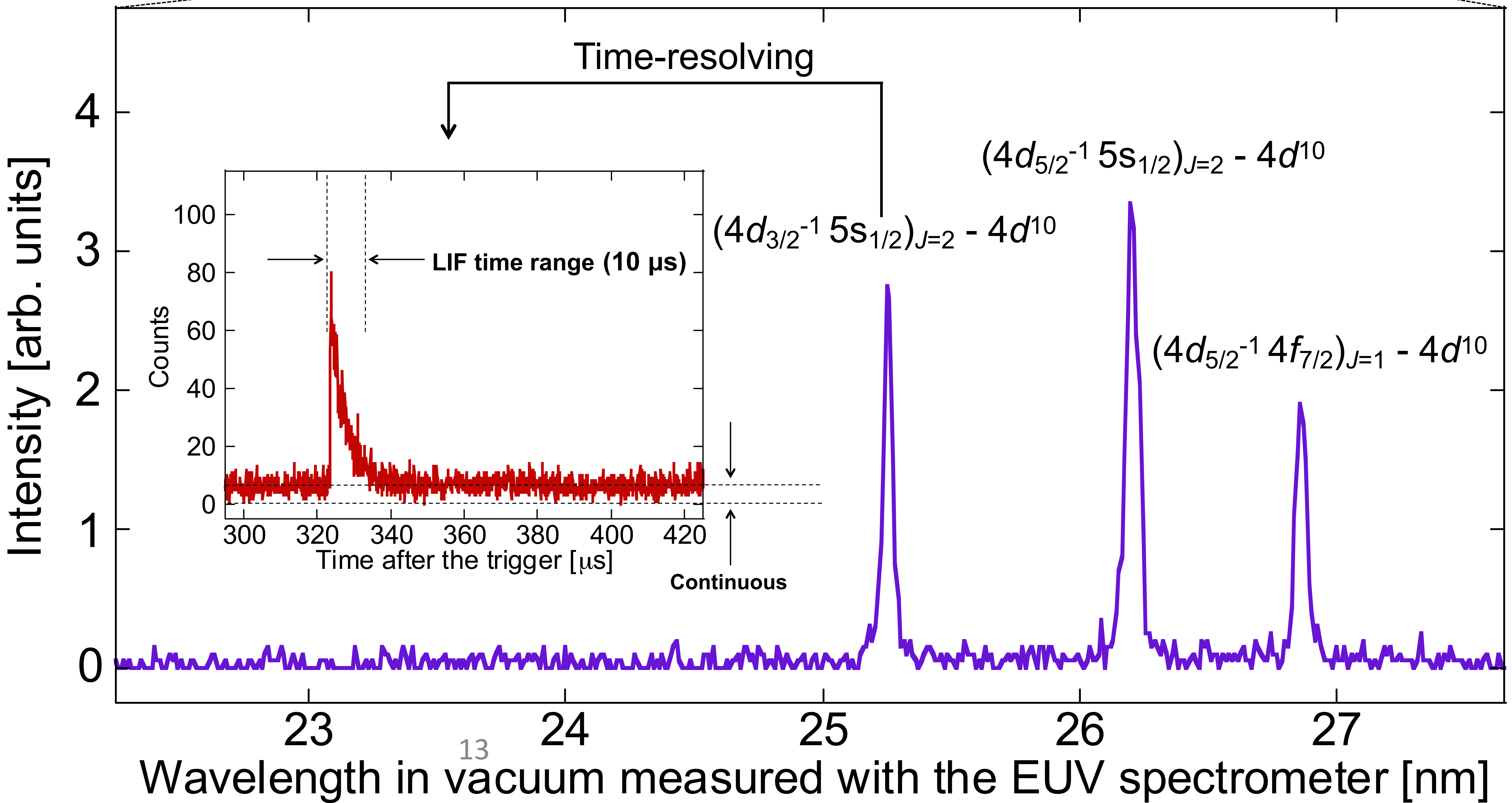
Experiment



YAG laser
10 ns, SHG(532 nm)
100 Hz Repetition
Dye laser
Line width
~0.03 cm-1
λ/2
Polarizer
Vacuum chamber
CoBIT
⊥
Δm_F =0
Typ.
7 mJ
Power
meter
Grating
PSD
PC
Wavemeter
Accuracy
0.02 cm-1
DG
MCS
FG
Trigger
LIF timing
Position analyzer
Amp.



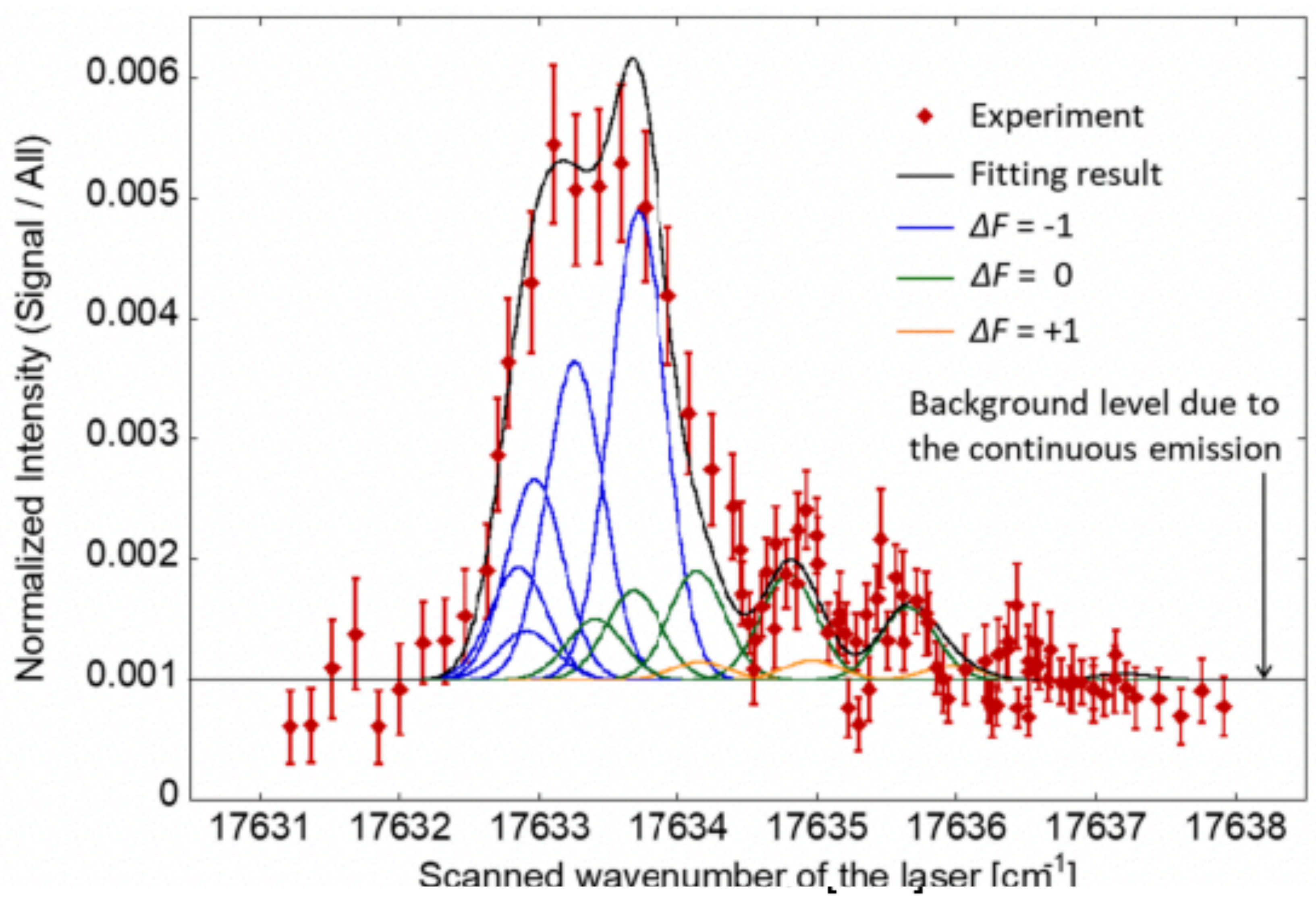
(4d3/2-1 5s1/2)J=2
567 nm, ⊥
10 ns pulse
M1
(4d5/2-1 5s1/2)J=3
25 nm
τ ~ 5 μs
E2
4d 10 (Ground)



Time-resolving
(4d5/2-1 5s1/2)J=2 - 4d10
(4d3/2-1 5s1/2)J=2 - 4d10
(4d5/2-1 4f7/2)J=1 - 4d10
LIF time range (10 μs)
Counts
Time after the trigger [μs]
Continuous
Intensity [arb. units]
Wavelength in vacuum measured with the EUV spectrometer [nm]

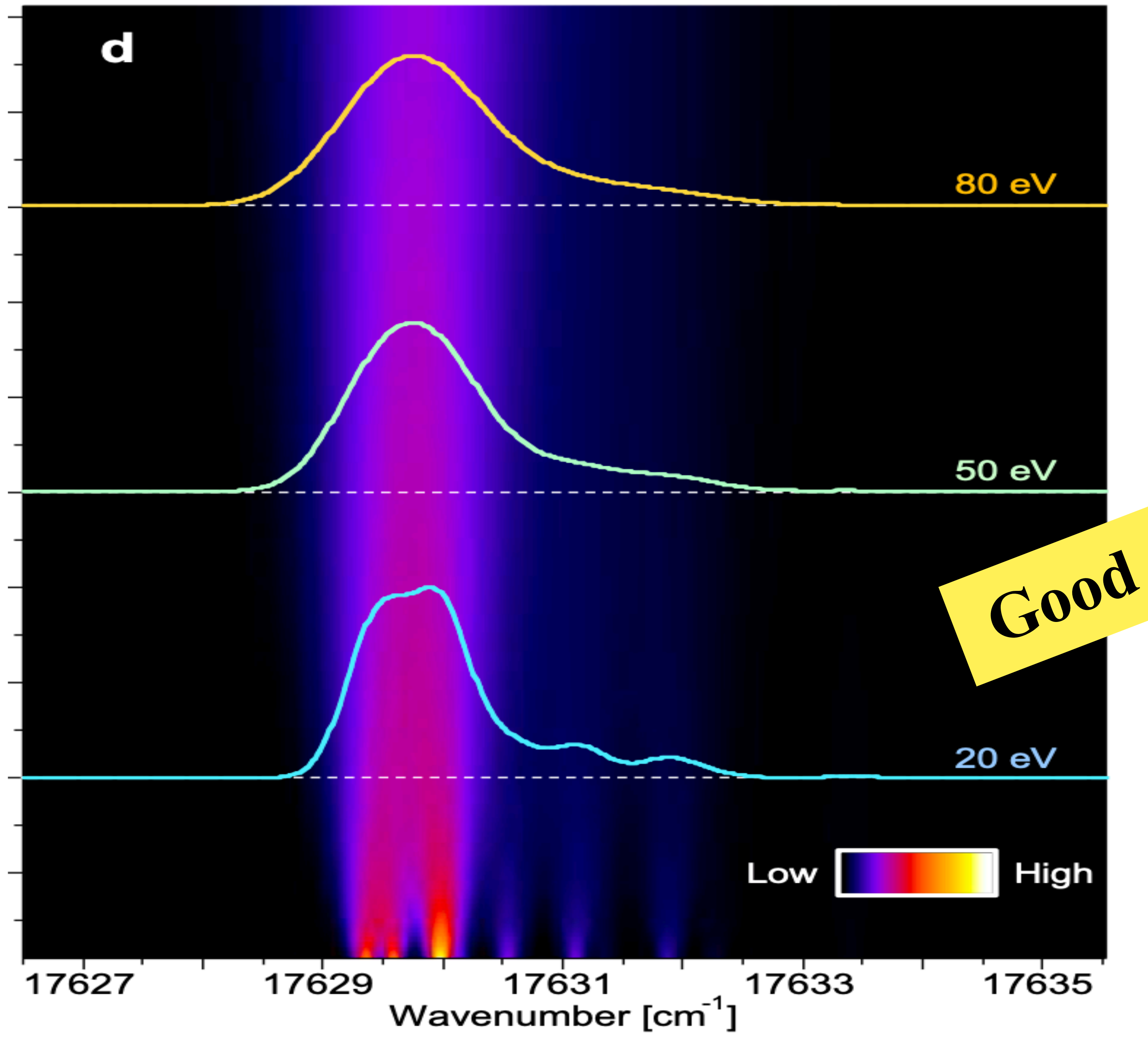
Wavelength spectrum for the LIF signal

N. Kimura, Priti, Y Kono et. al. COMMUNICATIONS PHYSICS | (2023)6:8



symmetric P ile!!!
s it due to hy

	Th. (GRASP)	Exp.
$k_{J=3\rightarrow J=2}$	17616 cm^{-1}	17633.67 (±0.05) cm^{-1}
A_{hfs} (J=3)	10.39 GHz	10.3 (±0.6) GHz
B_{hfs} (J=3)	2.32 GHz	2.9 (±2.1) GHz
A_{hfs} (J=2)	15.33 GHz	15.8 (±0.6) GHz
B_{hfs} (J=2)	2.02 GHz	1.5 (±1.6) GHz



Good Agreement!

$$f(k) = I_0 \sum_{|F'-F|\leq 1} gA_{F'F} \exp\left(\frac{4\ln 2(k-(k_0+k_{F'F}))}{k_D^2}\right).$$

$$k_{F'F} = k_{F'} - k_F.$$

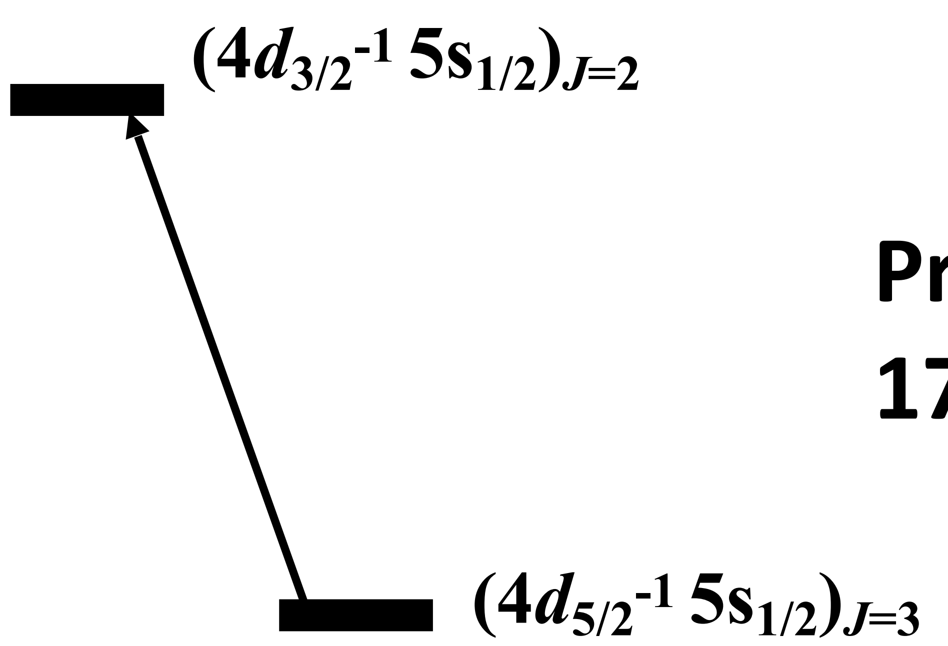
$$k_F = A\frac{K}{2} + B\frac{3K(K+1)-4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)},$$

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

1. C. Froese Fischer, G. Gaigalas, P. J¨onsson, J. Biero´nd, Computer Phys. Comm. 237, 184(2019).
2. 2. W. Li, J. Grumer, T. Brage, P. J¨onsson, Computer Phys. Comm. 253, 107211(2020)

Where is the resonance wavelength ??

I^{7+}



Present Experiment
17633.67 (±0.05) cm^{-1}

0.1 %

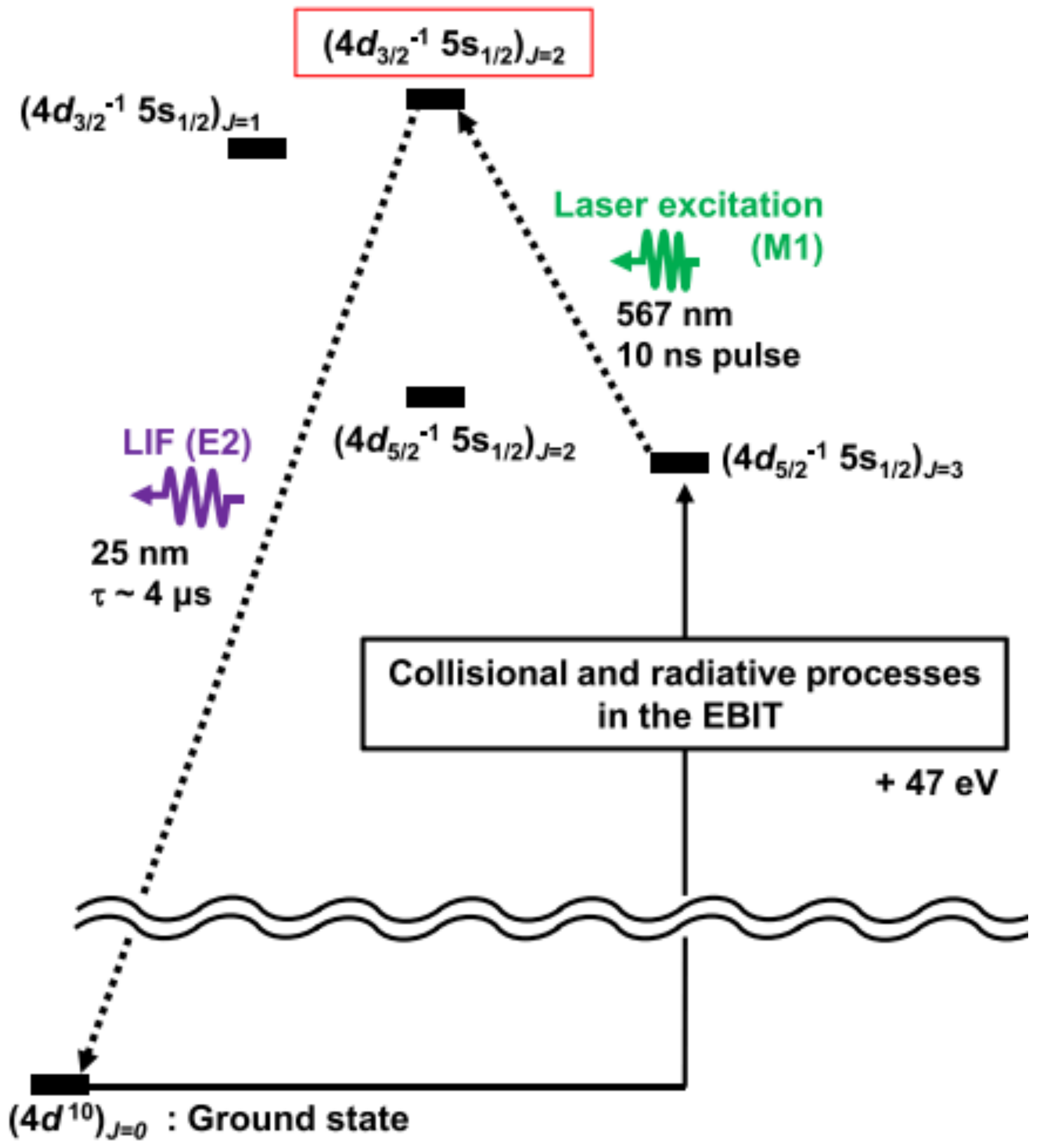
Grasp calculation

Dirac-Fock (DF)	18241.15
Valence-valence correlation (VV)	−481.30
Core-valence correlation (CV)	326.82
Core-core correlation (CC)	−70.62
Breit interaction (Breit)	−418.24
self-energy(SE)	17.34
vacuum polarization (VP)	0.80
Total transition energy	17616.03 $\pm 22 cm^{-1}$

Electric-quadrupole transition-rate measurement

We also measured the microsecond-order lifetime of $(4d^9 5s^1)_{J=2}$ in Pd-like I^{7+} using pulsed laser excitation from a metastable state.

While the experimental lifetime of this state has the potential to be a benchmark for developing reliable atomic structure calculations of relativistic many-electron systems with *d* electrons, it is generally difficult to measure such short lifetimes.



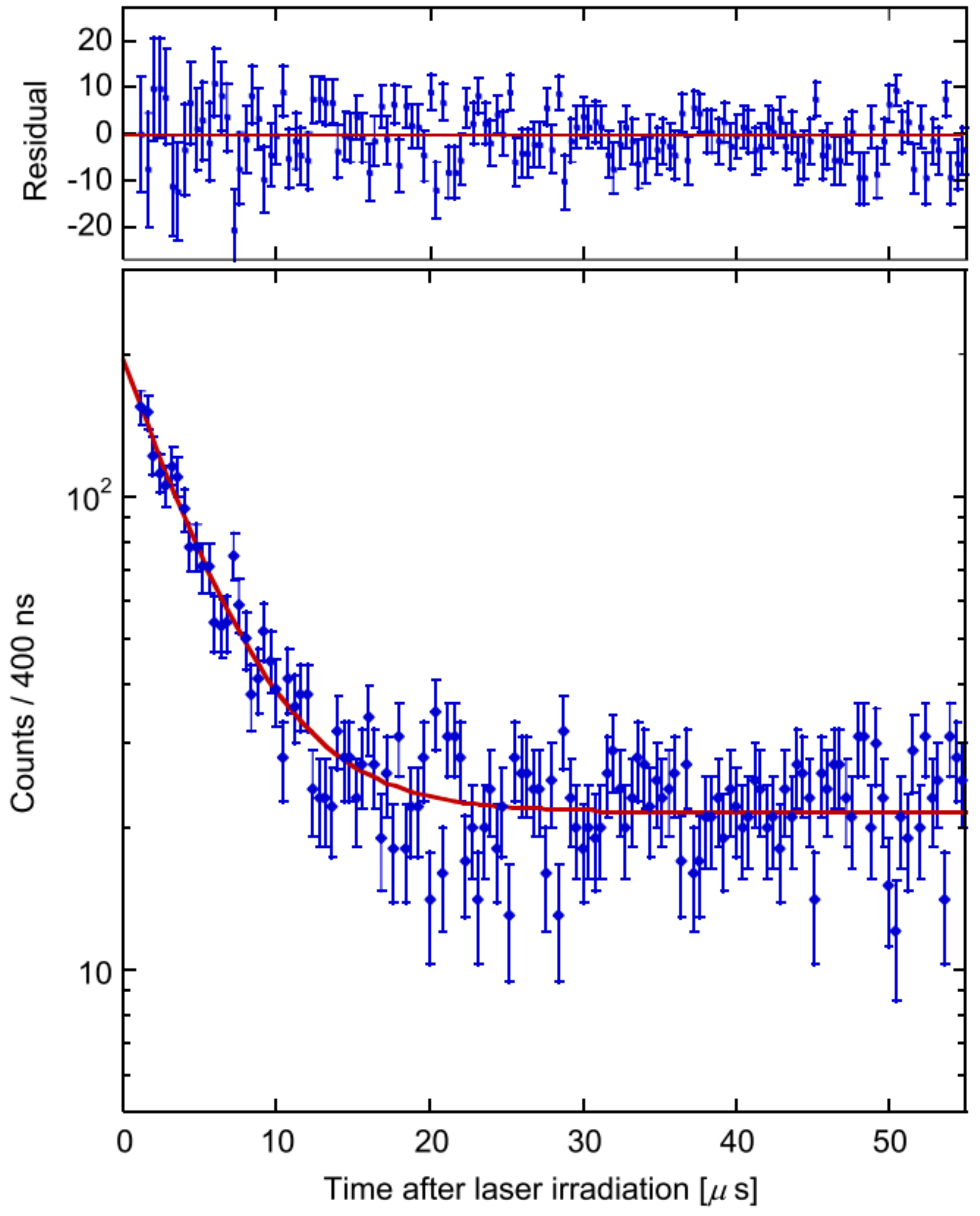
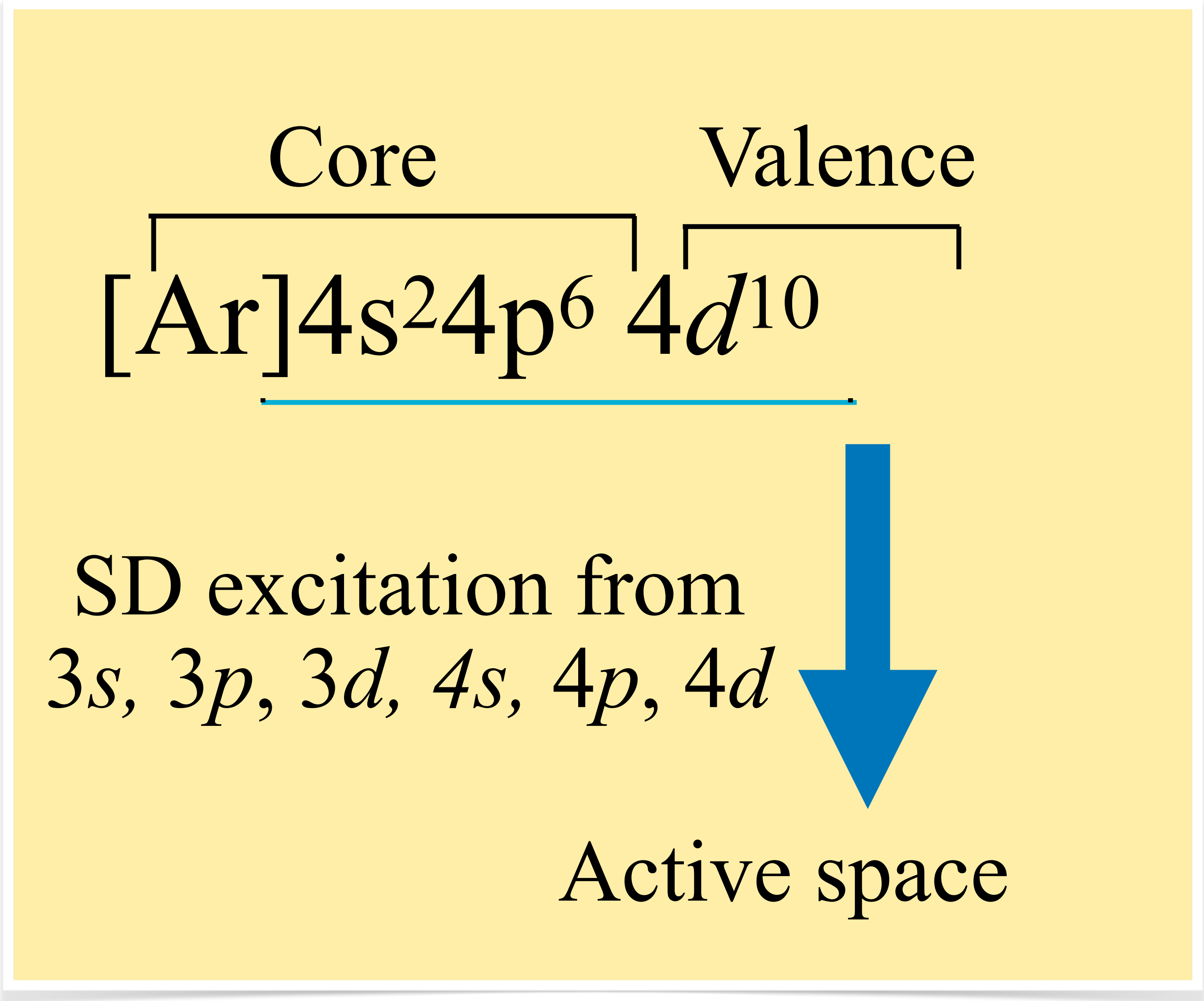


FIG. 3. Bottom: Experimentally observed LIF decay profile. The red line represents the fitting result. Top: Residuals of the experimental plots from the fitting line. Error bars reflect Poisson counting statistics.

TABLE I. Summary of the experimental and theoretical lifetime τ with calculated individual transition probabilities. The theoretical values were calculated by employing the active space set AS4 and include the RCI correction.

			Theory	
	Decay channel	Experiment	Coulomb gauge	Babushkin gauge
A_{E2} (s^{-1})	$(4d^{10})_{J=0}$		2.32×10^5	2.19×10^5
$A_{M1,J=3}$ (s^{-1})	$(4d_{5/2}^{-1}5s)_{J=3}$		4.95×10^1	
$A_{M1,J=2}$ (s^{-1})	$(4d_{5/2}^{-1}5s)_{J=2}$		3.06×10^0	
$A_{M1,J=1}$ (s^{-1})	$(4d_{3/2}^{-1}5s)_{J=1}$		3.52×10^{-1}	
A_{total} (s^{-1})		$2.32(\pm 0.07_{stat} \pm 0.01_{sys}) \times 10^5$	2.32×10^5	2.19×10^5
τ (μs)		$4.31(\pm 0.14_{stat} \pm 0.02_{sys})$	4.31	4.57

Theoretical transition probability using GRASP2018*



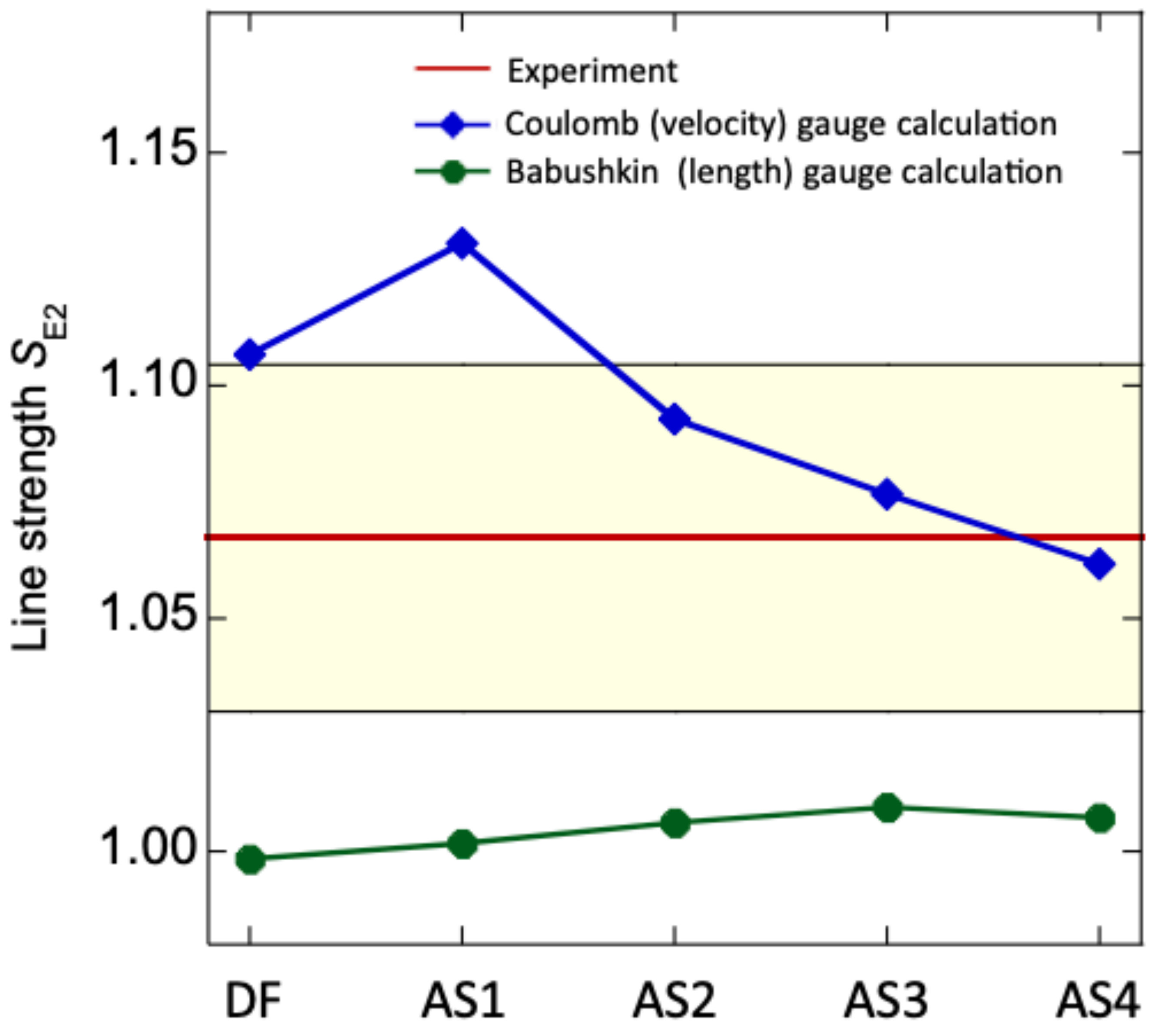
$\mathrm{DF} = \{3s^2\,3p^6\,4s^2\,4p^6\,4d^{10},\ 3s^2\,3p^6\,4s^2\,4p^6\,4d^9\,5s^1\}$,

$\mathrm{AS1} = \mathrm{DF} + \{5p, 5d, 5f, 5g\}$,

$\mathrm{AS2} = \mathrm{AS1} + \{6s, 6p, 6d, 6f, 6g, 6h\}$,

$\mathrm{AS3} = \mathrm{AS2} + \{7s, 7p, 7d, 7f, 7g, 7h\}$,

$\mathrm{AS4} = \mathrm{AS3} + \{8s, 8p, 8d, 8f, 8g, 8h\}$.



Active space set dependence of the E2 transition line strength (in atomic units) in the MCDF calculation without the RCI correction. The thin black lines represent the experimental uncertainty (1σ).

*C. Froese Fischer, *et. al.*, Computer Physics Communications 2019, 237, 184

Summary

- We have demonstrated laser spectroscopy of forbidden transitions between metastable states of HCIs stored in an EBIT by employing Pd-like $^{127}I^{7+}$.
- The laser excitation spectrum of the HCIs in a quasi- Zeeman-free low magnetic field revealed distinct hyperfine structures.
- Even though the transition observed in this study is not a proposed HCI clock candidate, the building of a benchmark to understand hyperfine structures in many-electron HCIs.

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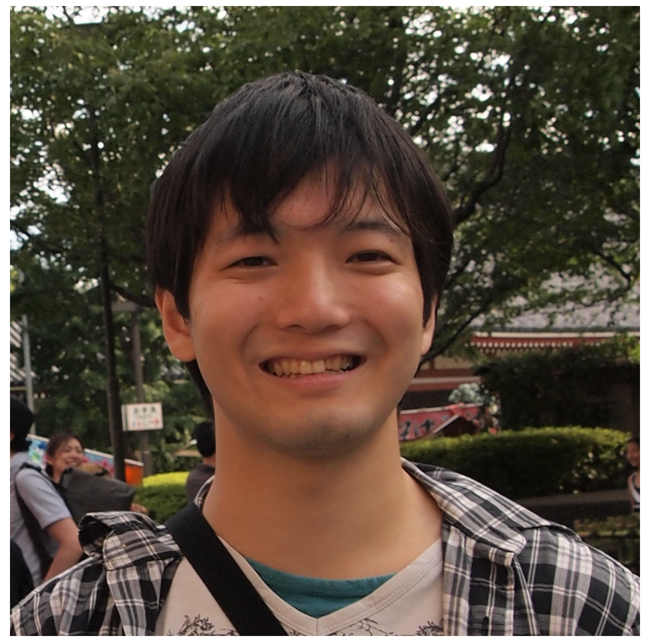

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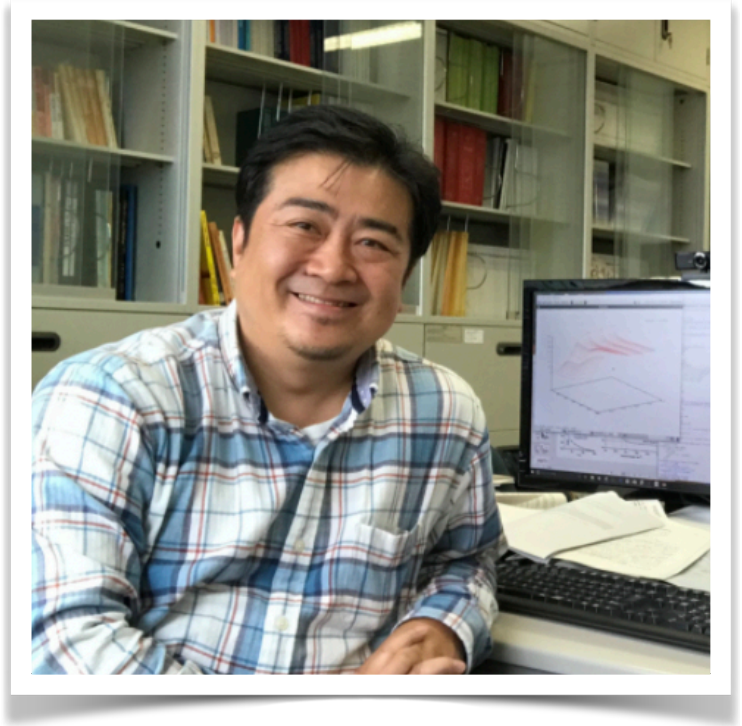
Dr. Kuma

Prof. Azuma

AMO physics RIKEN



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