Toward a measurement of nuclear Magnetic Quadrupole Moment (nMQM) using quantum logically controlled molecular ions

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University of Nevada, Las Vegas
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UNLV and Zhou lab

Molecules – quantum control and spectroscopy

- Molecular ions – eEDM & nMQM
- Rydberg molecules – BaF and RaF
- OFC spectroscopy
- Ion-radical collisions

Students

- Rodrigo Fernandez
- Jose Mosquera Ojeda
- Govinda Bhandari
- Bernardo Gutierrez
- Trevor Taylor
- Stephanie Letourneau
- Xuanyi Wu

Collaborators

- Ion storage group, NIST, Boulder
- Prof. Garcia-Ruiz and Prof. Field at MIT
- Prof. McGuire at MIT and Prof. Liu at UofL

Working at JILA

PIs

- Eric Cornell
- Jun Ye

Students & Postdoc

- Kia Boon Ng
- Will Cairncross
- Tanya Roussy
- Tanner Grogen
- Yuval Shagam
- Matt Grau
- Kevin Cossel
- Dan Gresh

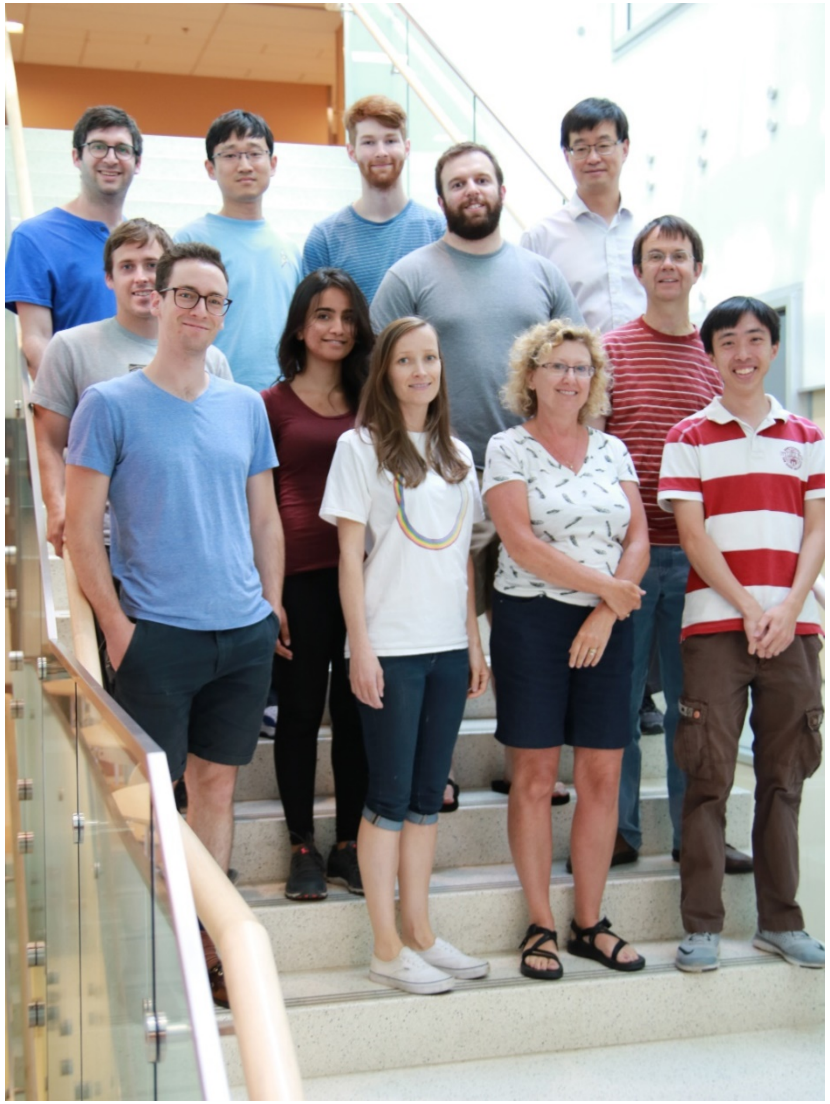
Collaborators

- Robert Field
- Lan Cheng
- Tanya Zelevinsky
- Victor Flambaum

Funding

Marisco Foundation

JILA eEDM team (2017)



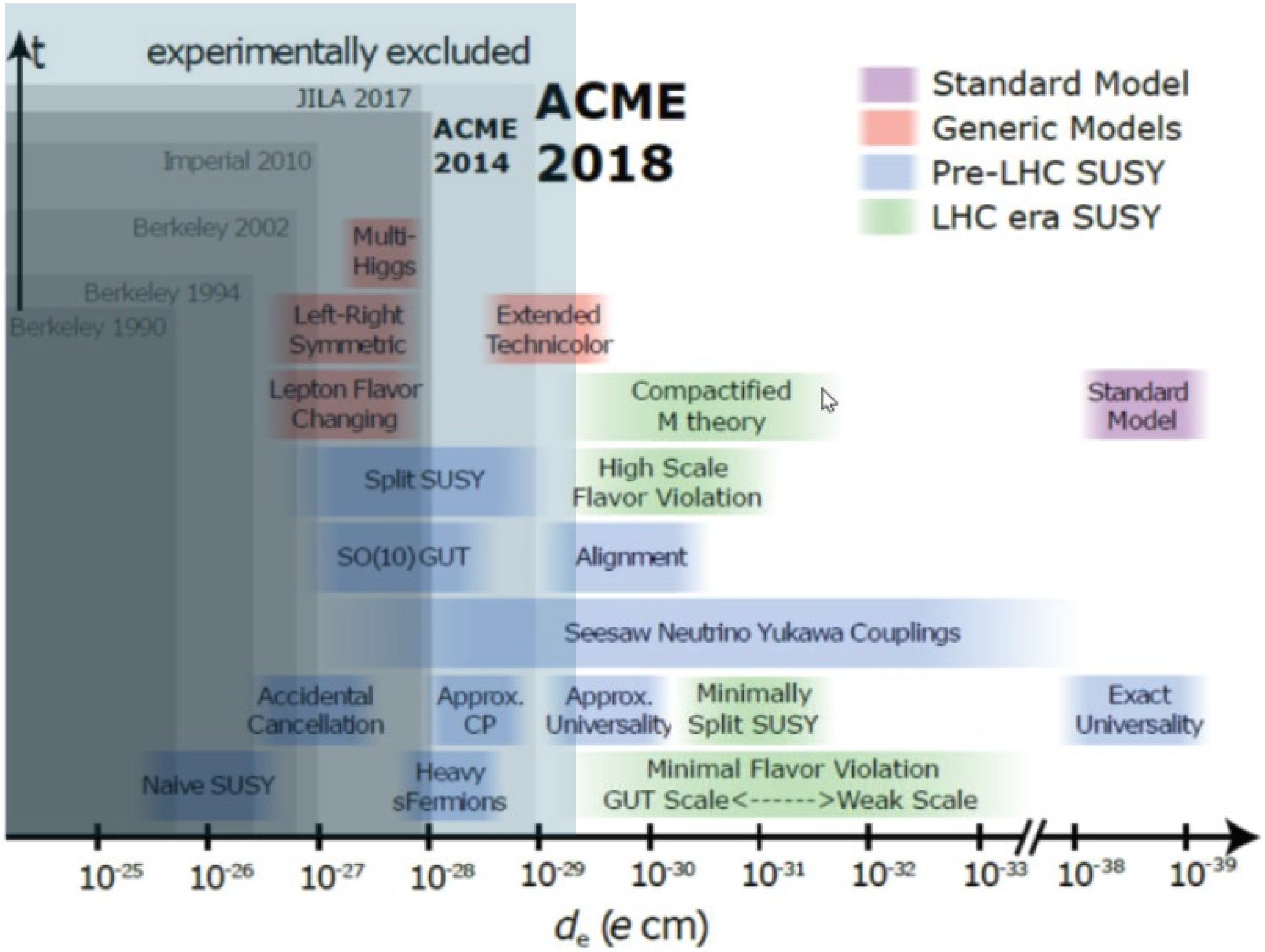
Outline

- eEDM measurements
- Quantum logic spectroscopy
- New method in a ring trap
- From eEDM to nMQM

eEDM roadmap

- In the past decade
  - 250 times improvement
  - YbF, ThO, HfF^+
  - 10 TeV energy scale

JILA 2023



ACME collaboration

eEDM roadmap

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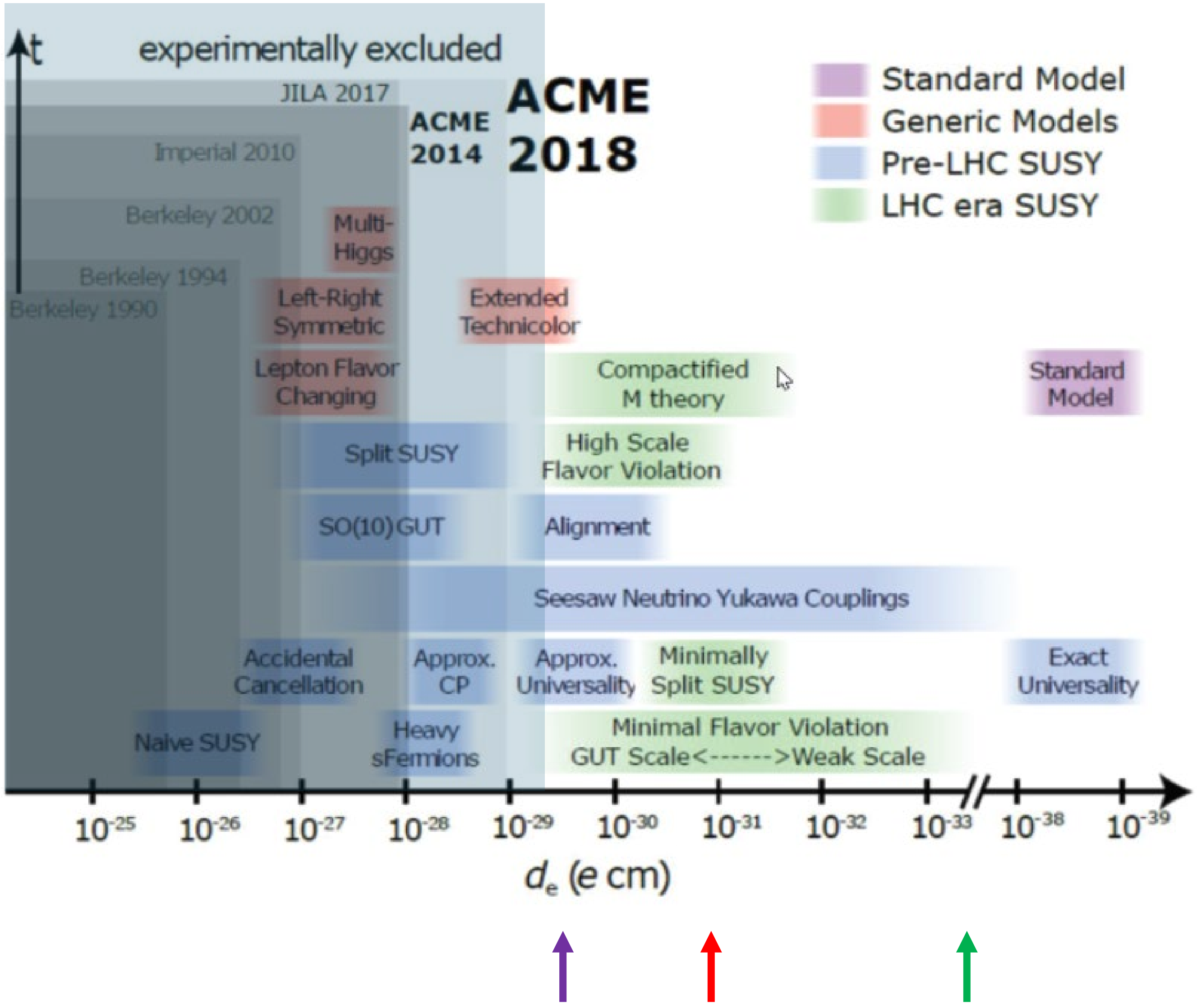
- In the next decade
  - Another 2-order of magnitude
  - Toward PeV energy scale
  - Far beyond LHC energy
  - Cross-verifications
    - Species
    - Platforms

JILA 2023



NL-eEDM YbF | ACME III JILA III | EDM^3

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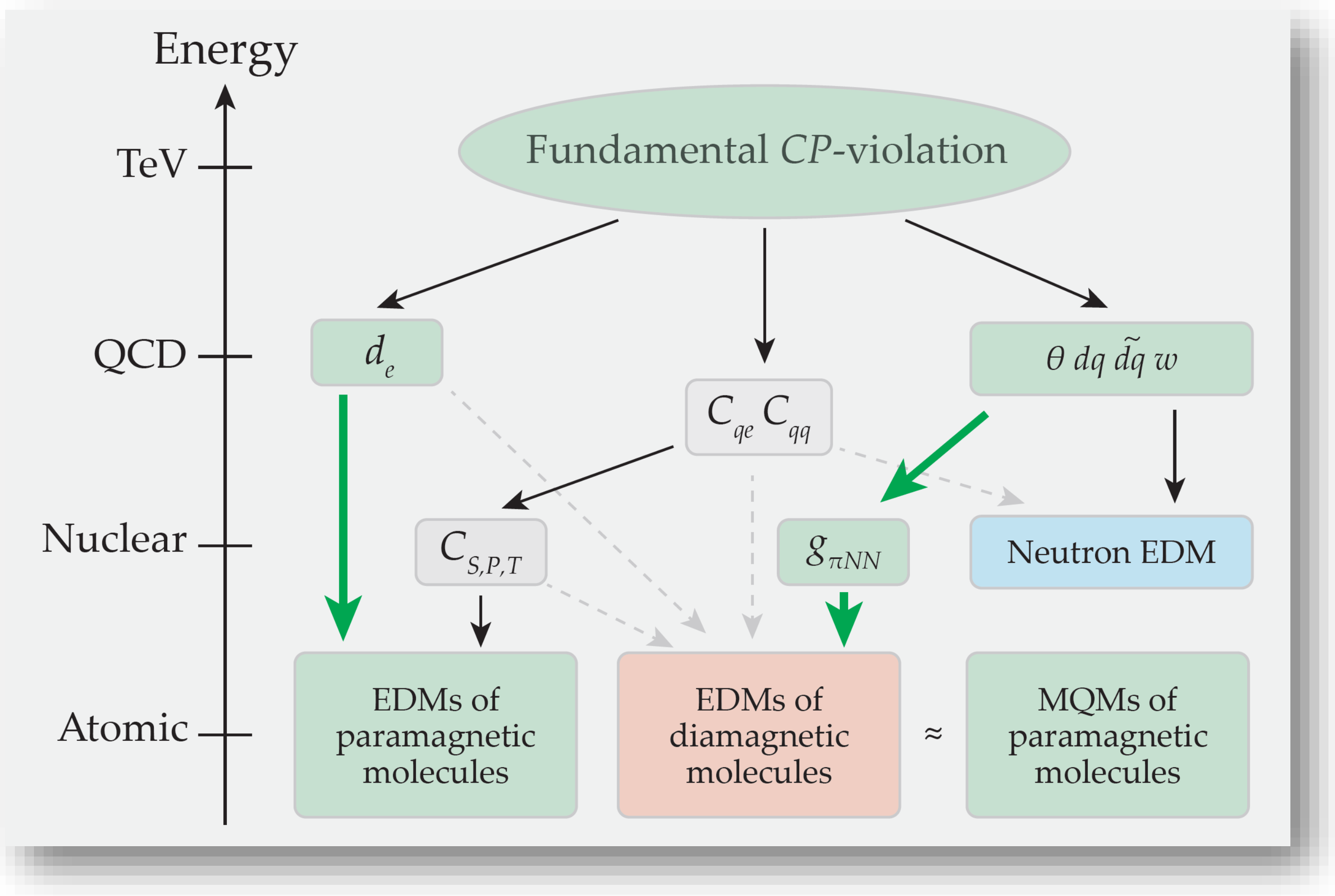
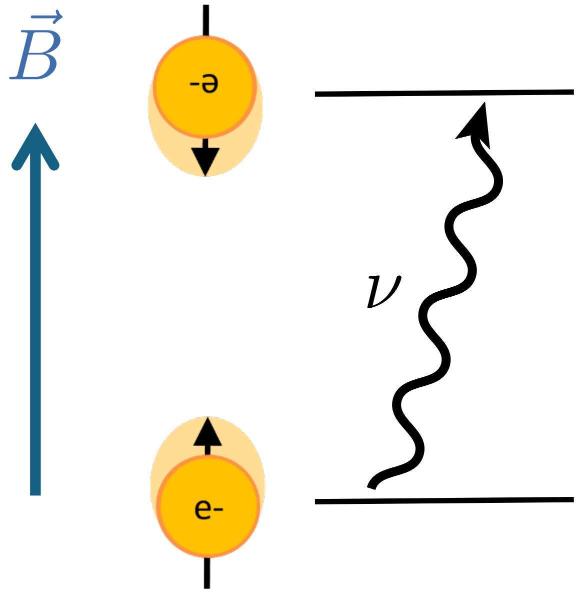
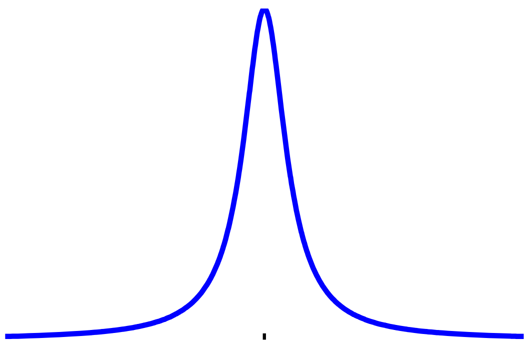


How to measure the eEDM



$$\Delta E = \mu_B B$$



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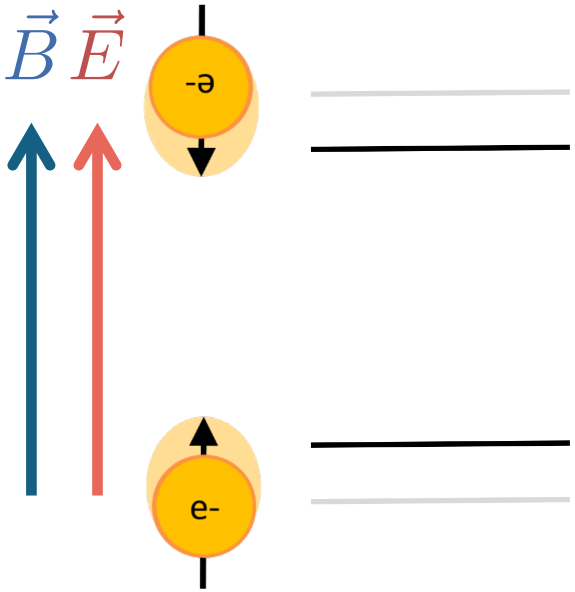

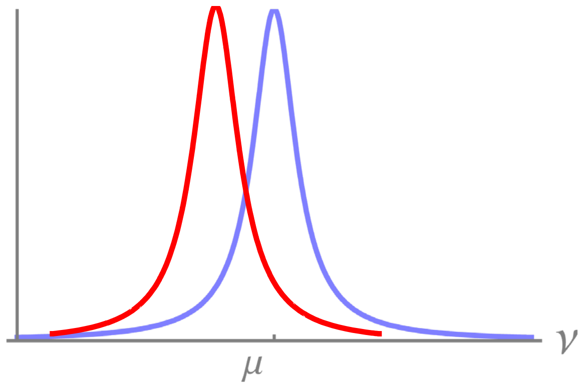

$$\Delta E = \mu_B B - d_e E$$

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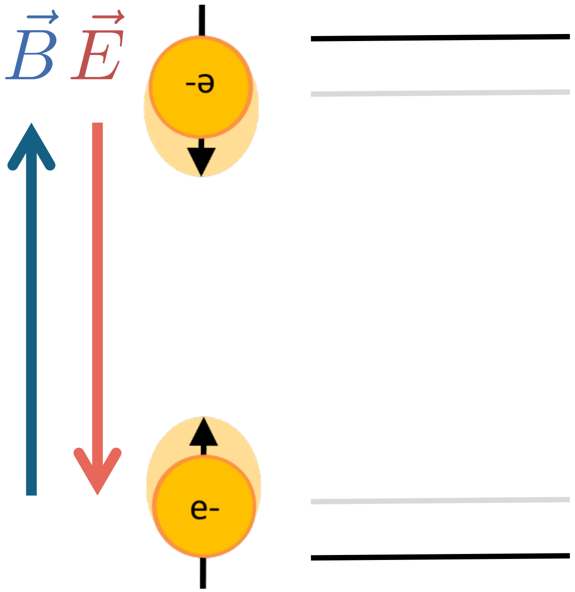

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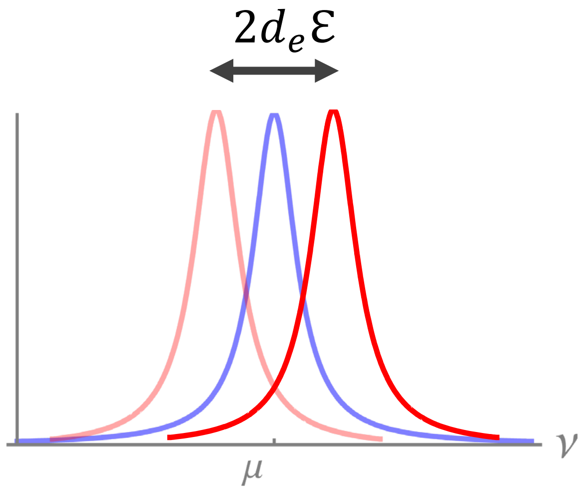

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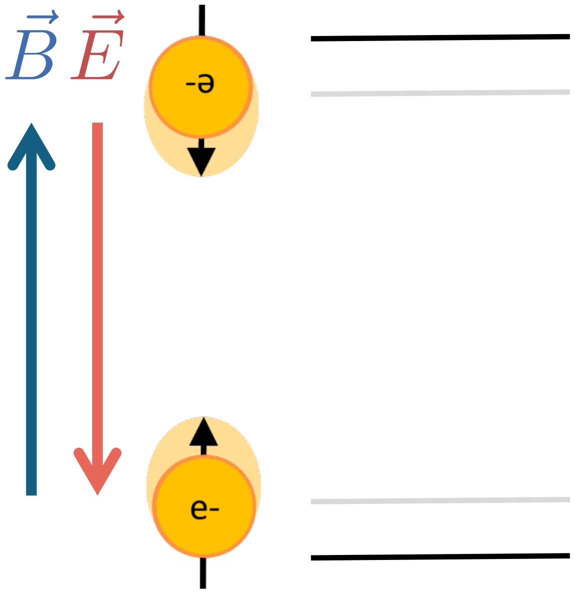

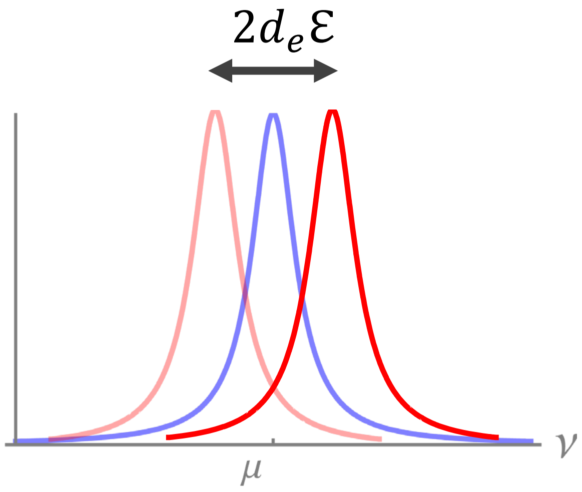

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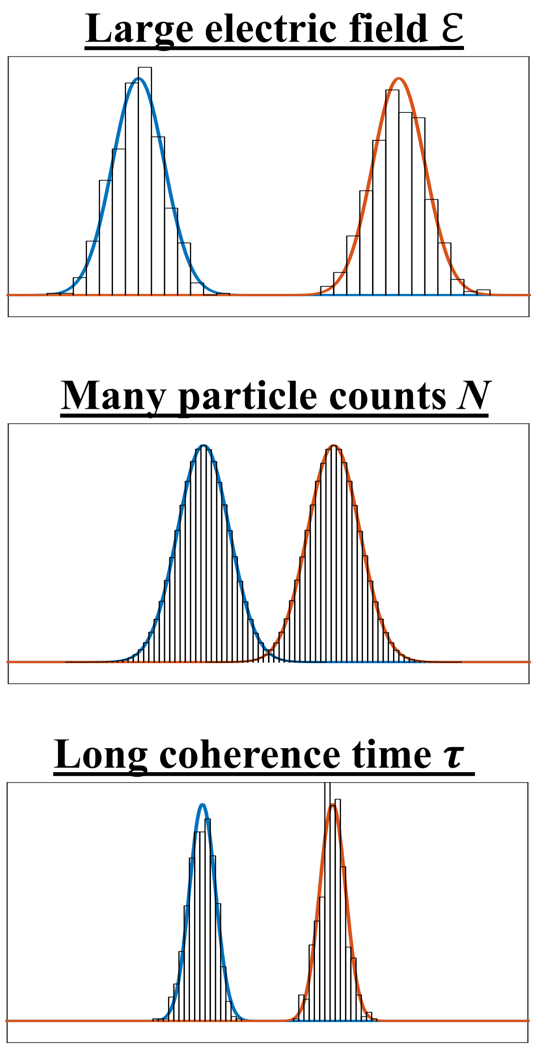

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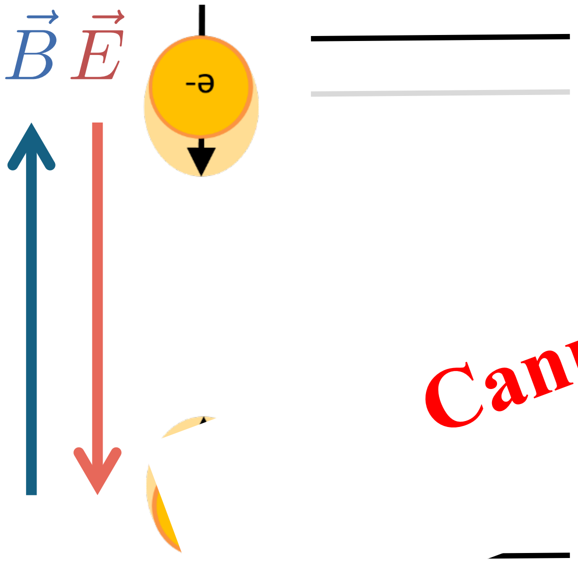

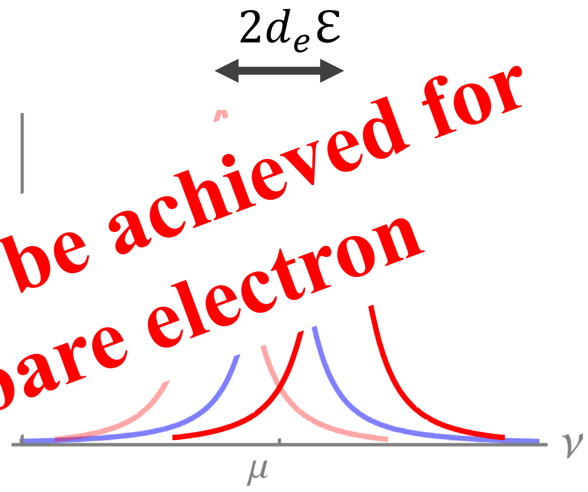

Cannot be achieved for a bare electron

$$\Delta E = \mu_B B + d_e E$$

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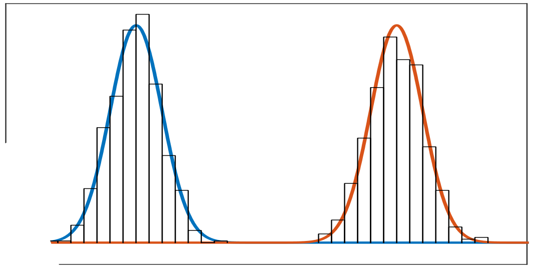
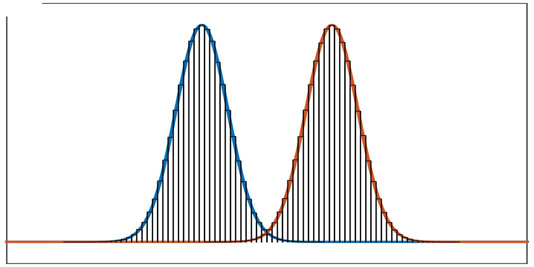
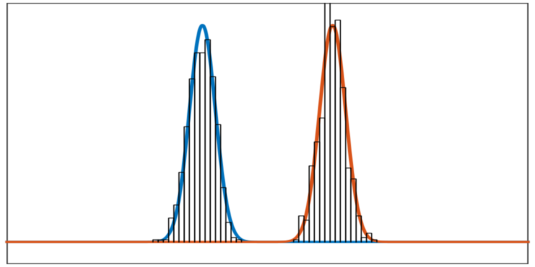
Large electric field $\mathcal{E}$



Many particle counts N

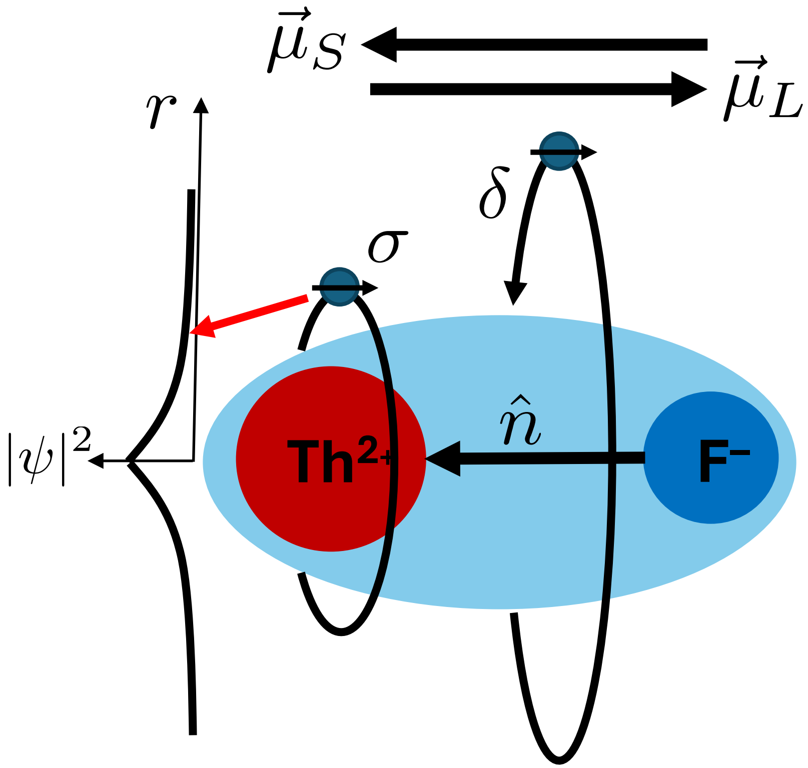


Long coherence time τ



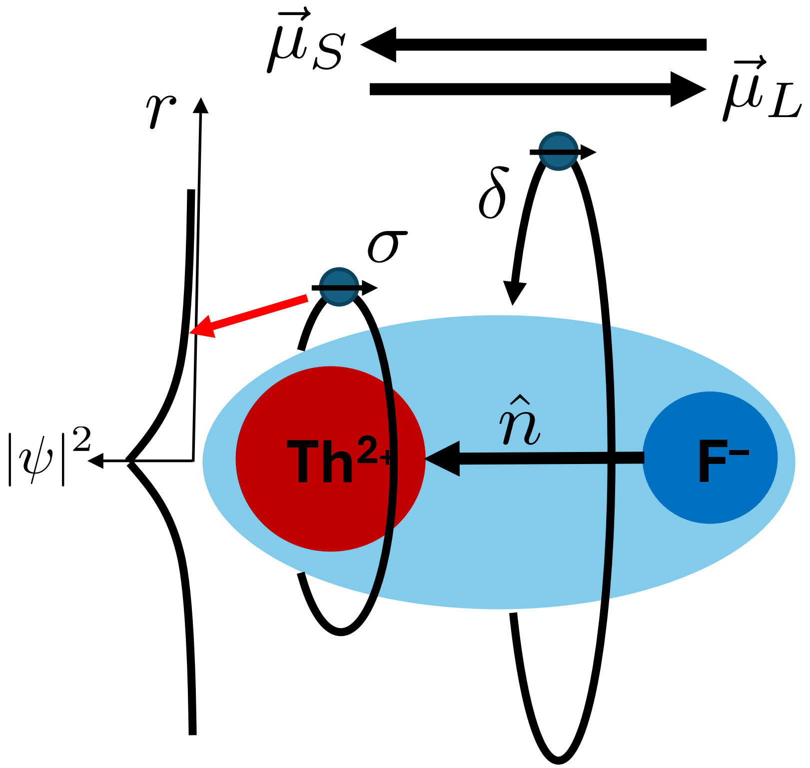
Polar molecules, $^3\Delta_1$ state

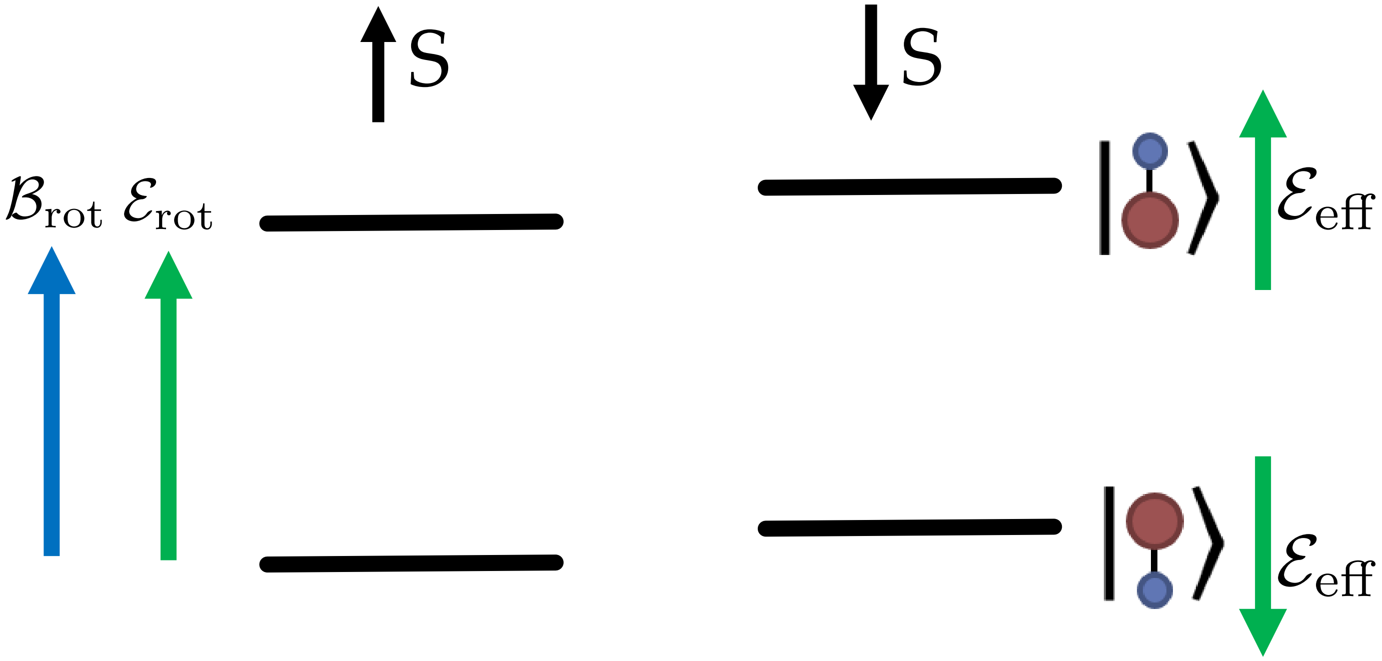
- δ electron orientates molecules
- σ electron senses a large electric field
- $\mu_S \sim -\mu_L$, small magnetic g-factor



Polar molecules, $^3\Delta_1$ state

- Electric field orientates molecules
- Magnetic field orientates electron spin





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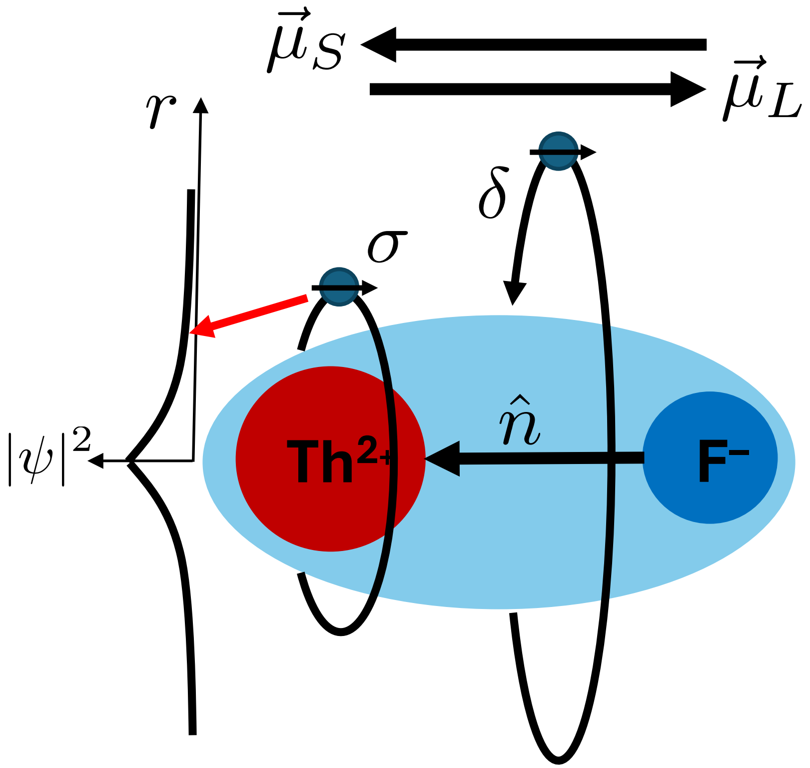

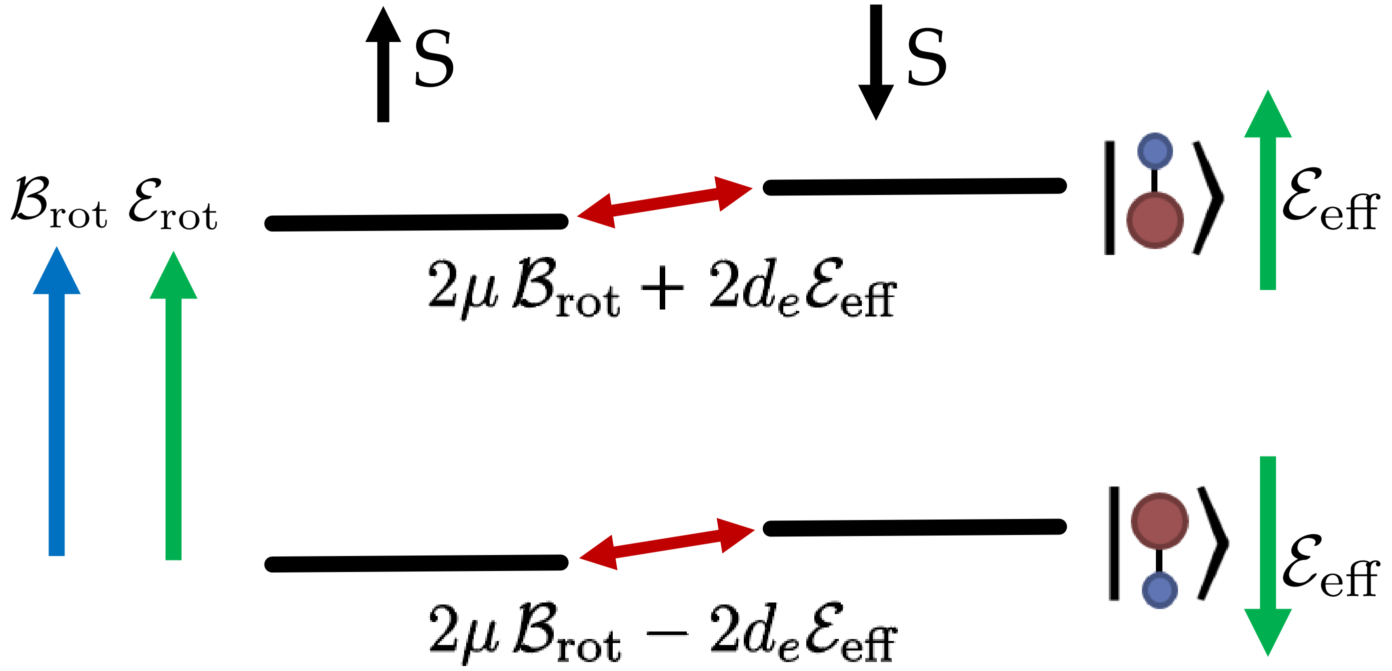

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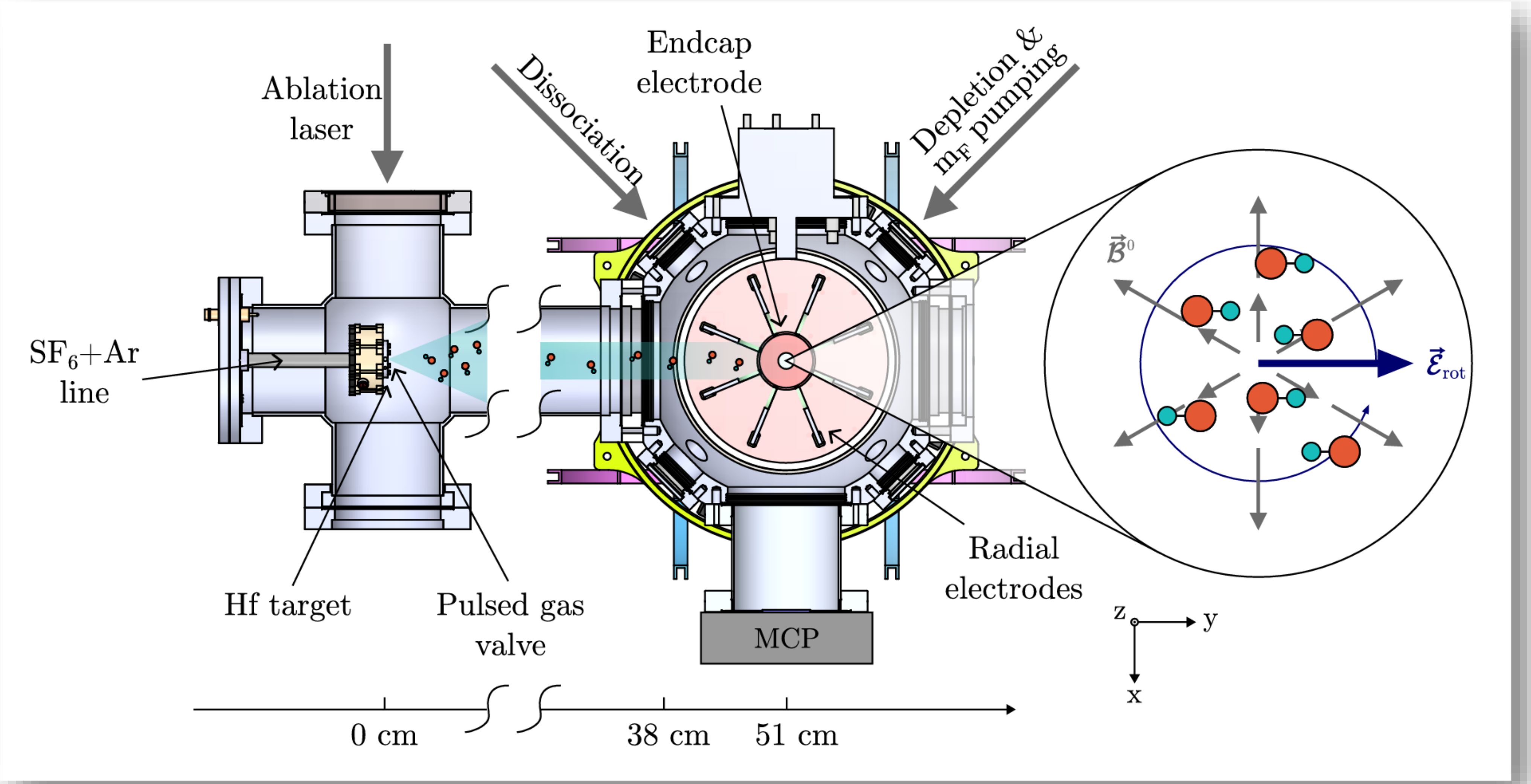
JILA eEDM measurements



Science, **381**, 46 (2023)

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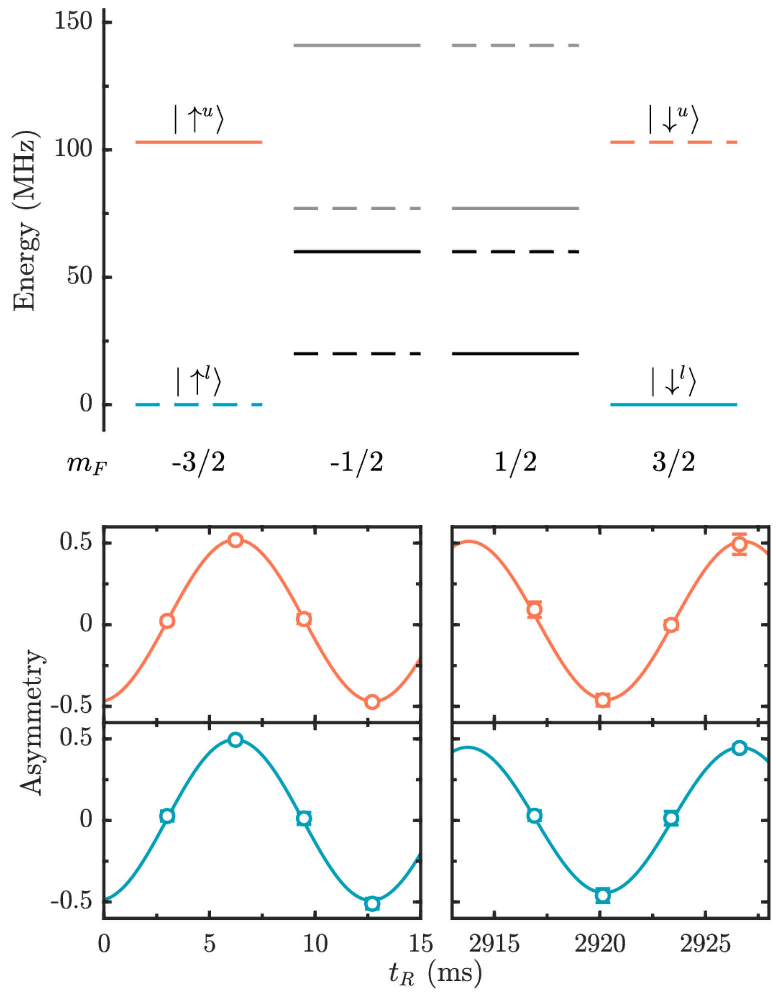

- 3 s coherence time
- 23 GV/cm effective electric field
- N ~ 120 ions/shot
- 620 hours data

- f = -14.6 ± 22.8$_{stat}$ ± 6.9$_{syst}$ μHz
- d_e = (-1.3 ± 2.0$_{stat}$ ± 0.6$_{syst}$)×10^{-30} e.cm
- $|d_e|$ < 4.1×10^{-30} e.cm (90% confidence)

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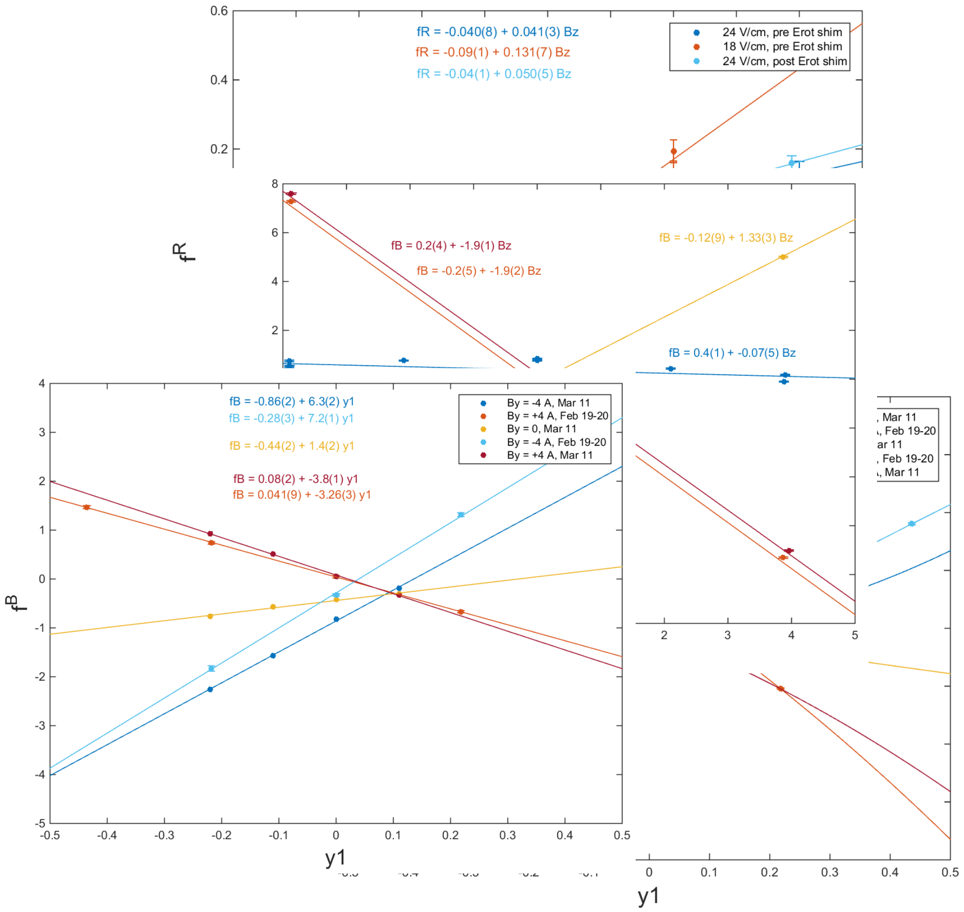
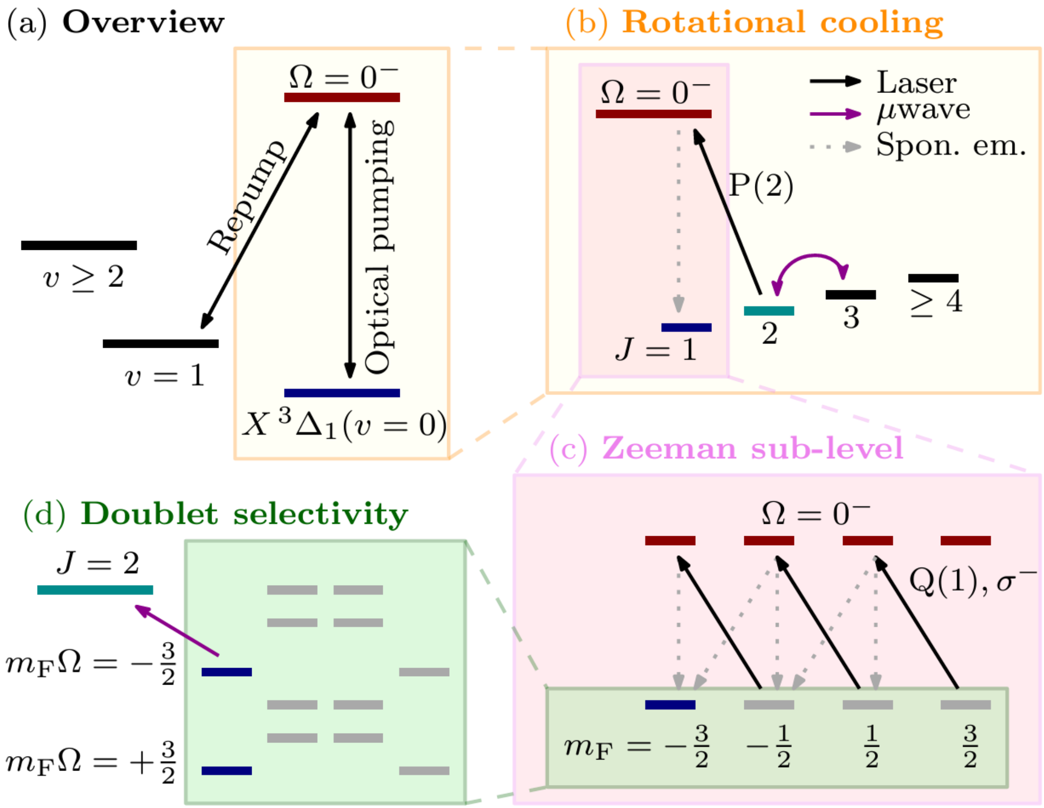
What I have learnt – JILA eEDM I

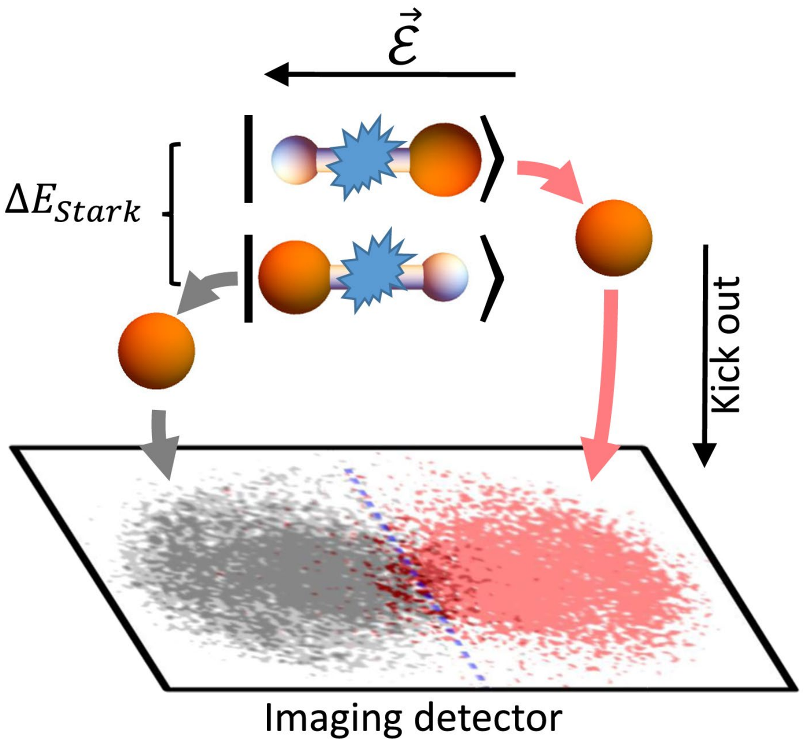
- ❑ Deliberately “bad” measurement
    - o Ion position in the trap
    - o Ion slosh
    - o External magnetic fields
    - o Electric field magnitude
    - o Rotation frequency
    - o Ion density
    - o $\pi/2$ pulse duration
    - o ….
- ❑ Perturbation method
- ❑ Numerical modeling



What I have learnt – JILA eEDM II

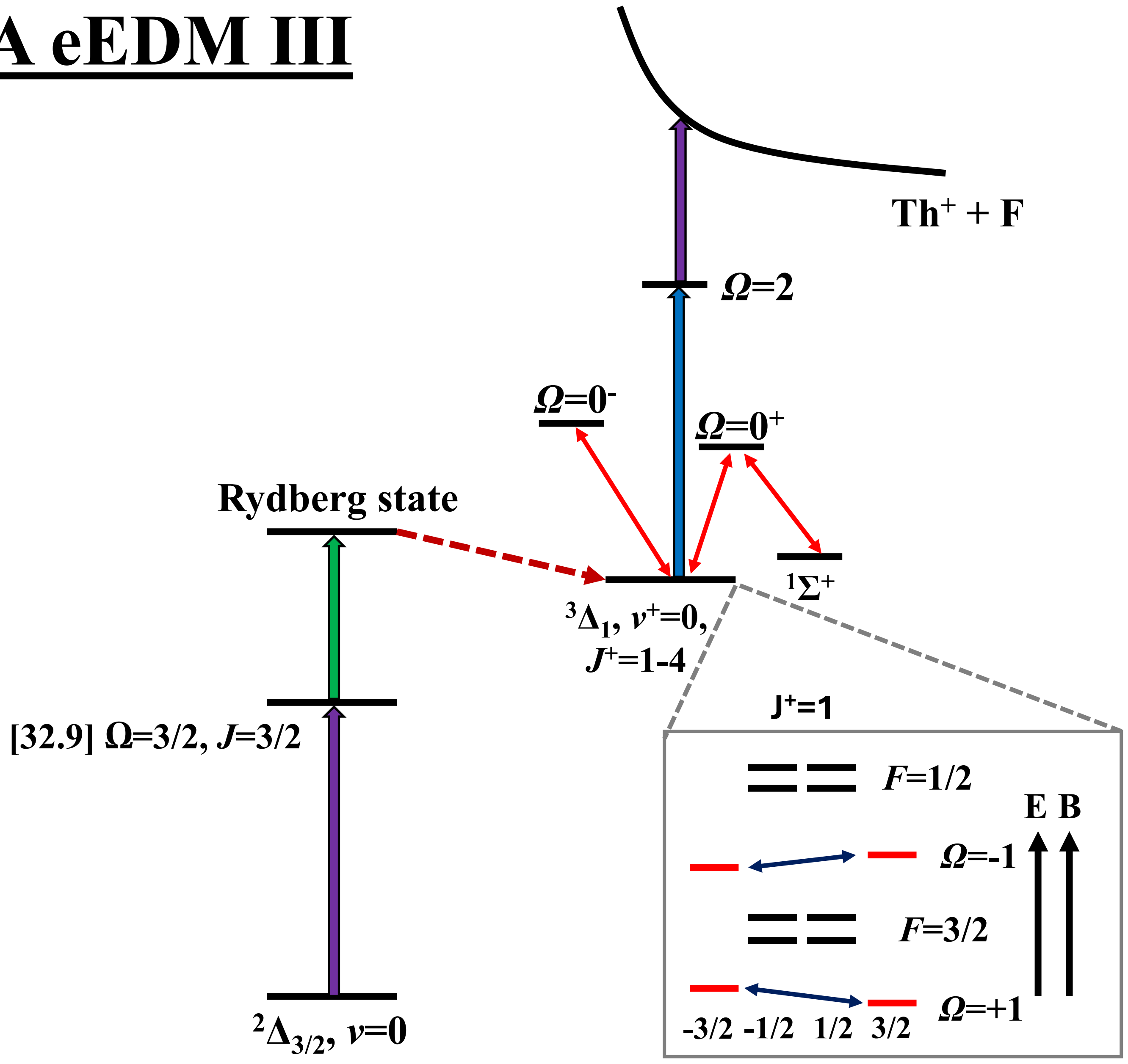
- ❑ Quantum control and readout





What I have learnt – JILA eEDM III

- Spectroscopy of ThF and ThF^+



What I have learnt – JILA eEDM III

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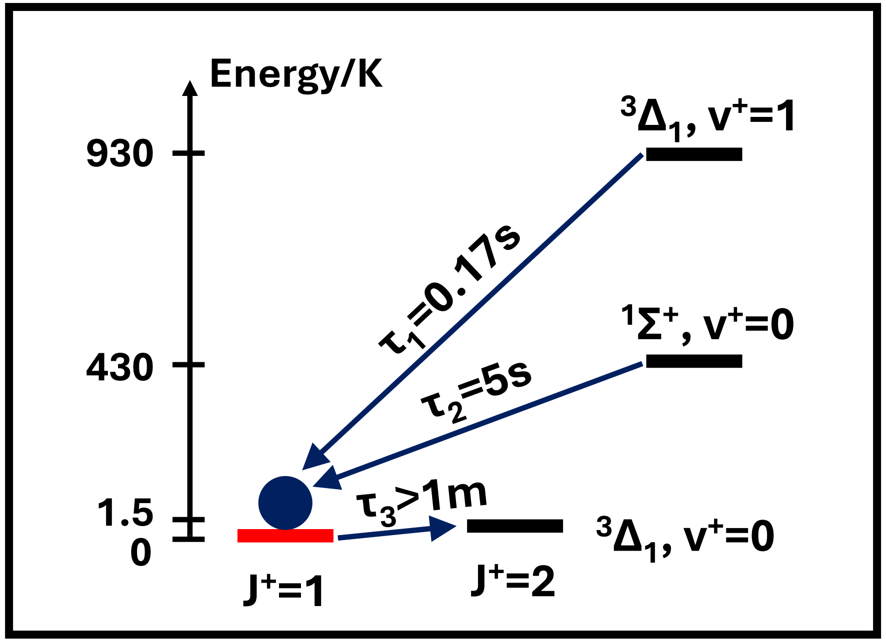
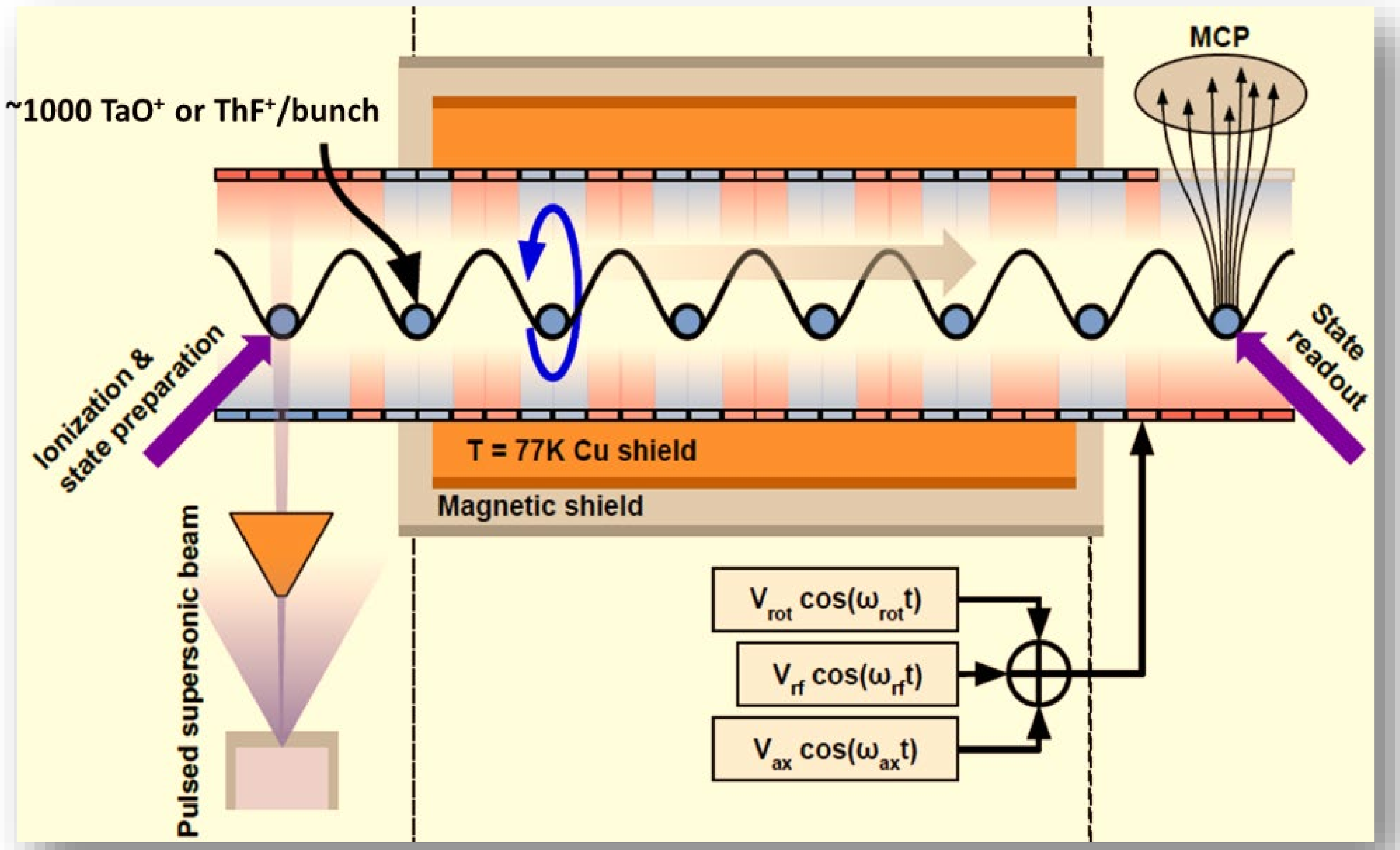


$$\tau_{exc} = \frac{\tau_{decay}}{n_{black}}$$

	300 K	200 K
BBR vibration	4 s	20 s
BBR $^1\Sigma^+$	20 s	45 s
BBR rotation	190 s	280 s

What I have learnt – JILA eEDM III

- ❑ Spectroscopy of ThF and ThF^+
- ❑ Infinitely long lifetime of $^3\Delta_1$
- ❑ Multiplex measurements



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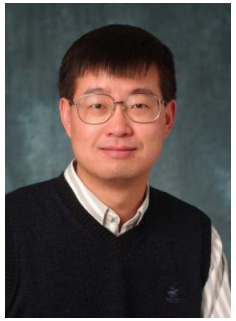
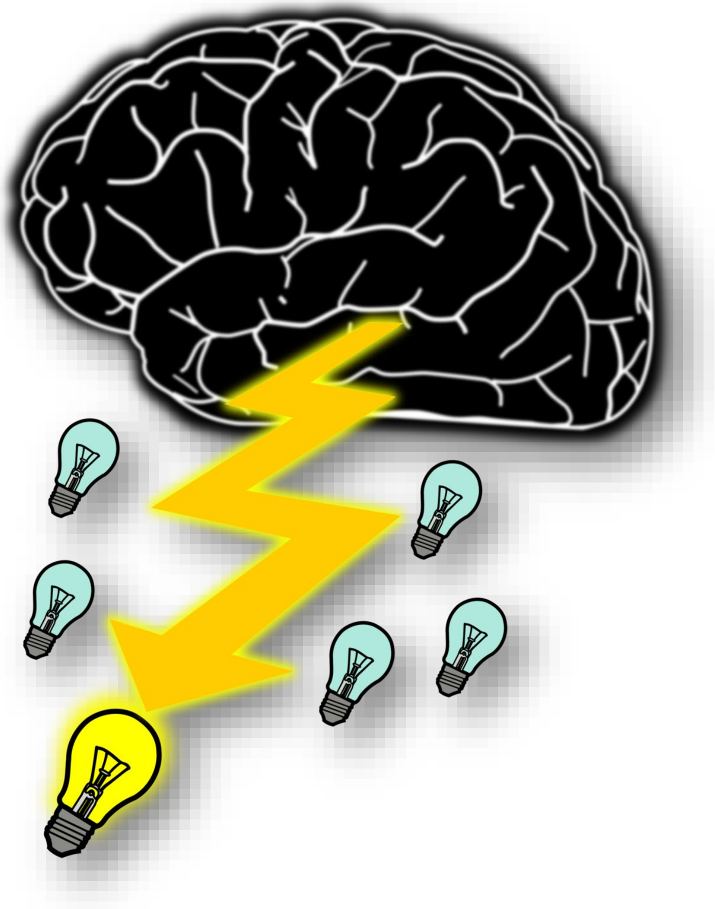
A new experimental platform

- ❑ Precision metrology
- ❑ Quantum control/readout
- ❑ Multiplexing measurements

- ❑ QLS at NIST

- ❑ Molecular spectroscopy

- ❑ Heavy elements

- ❑ AMO – Standard Model

What is next?

- JILA – larger ion trap
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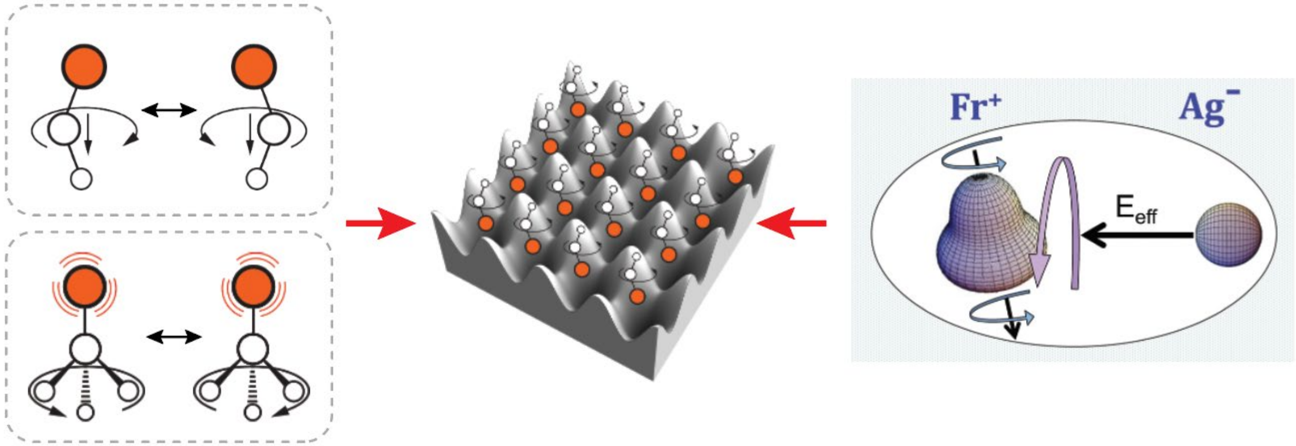
  - Large sample consumption (expensive with Th-229 or others)
- Laser cooling and trapping
  - Very exciting prospective



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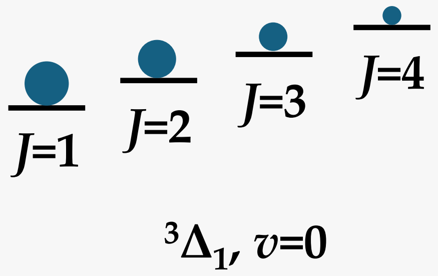
- Minimum systematics – inherit reference, quantum sensors

State preparation and detection

$^{232}ThF^+$



State preparation and detection

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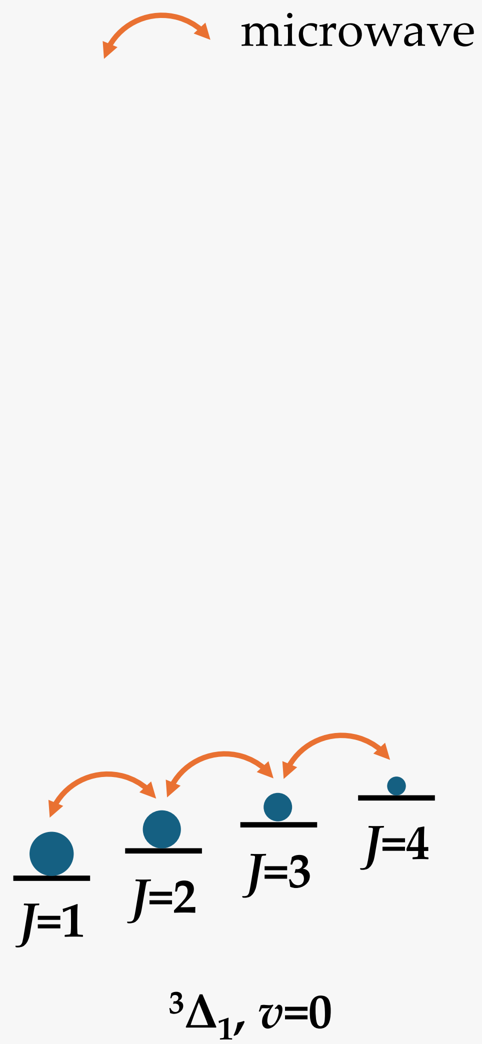

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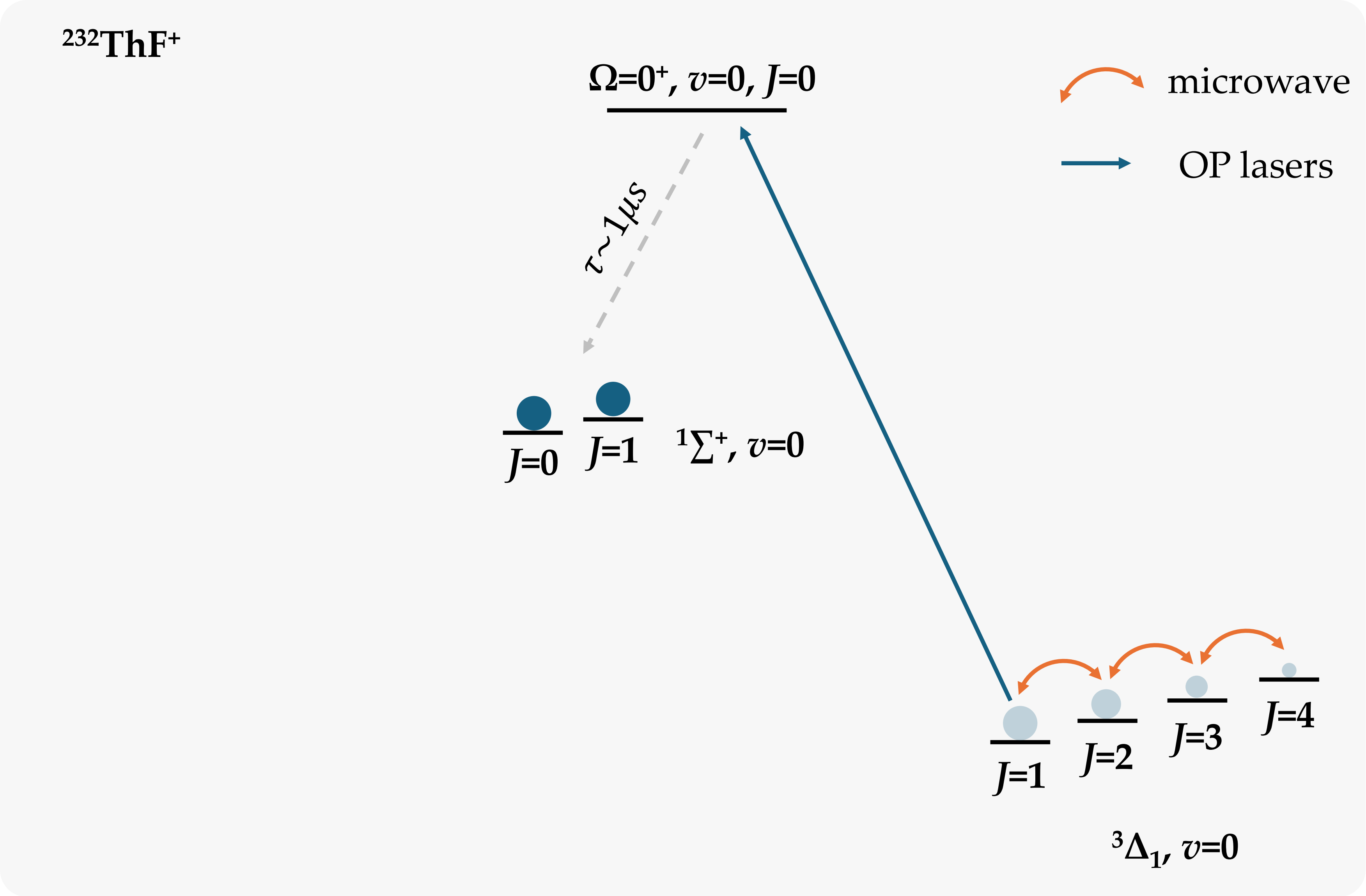

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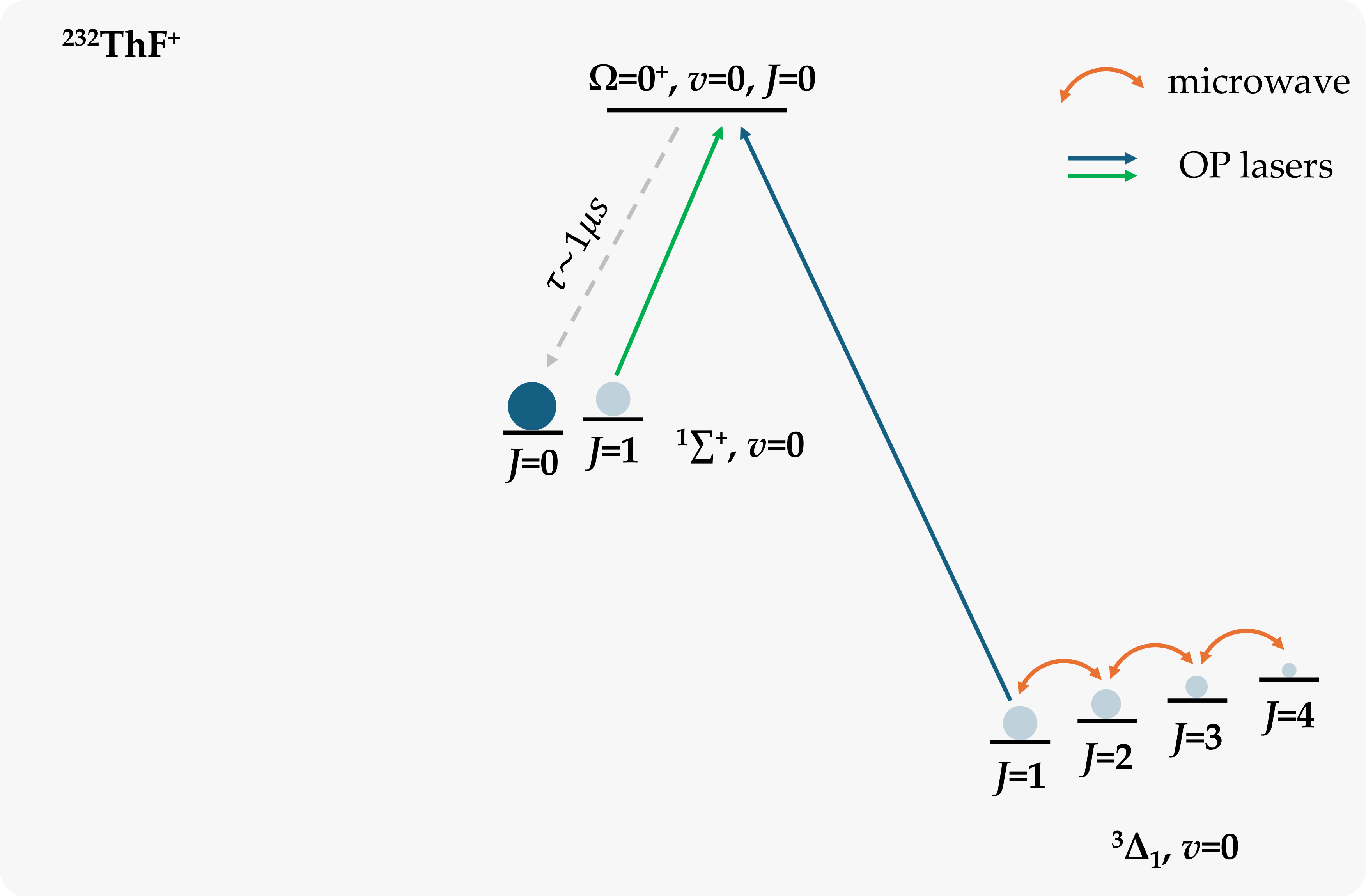

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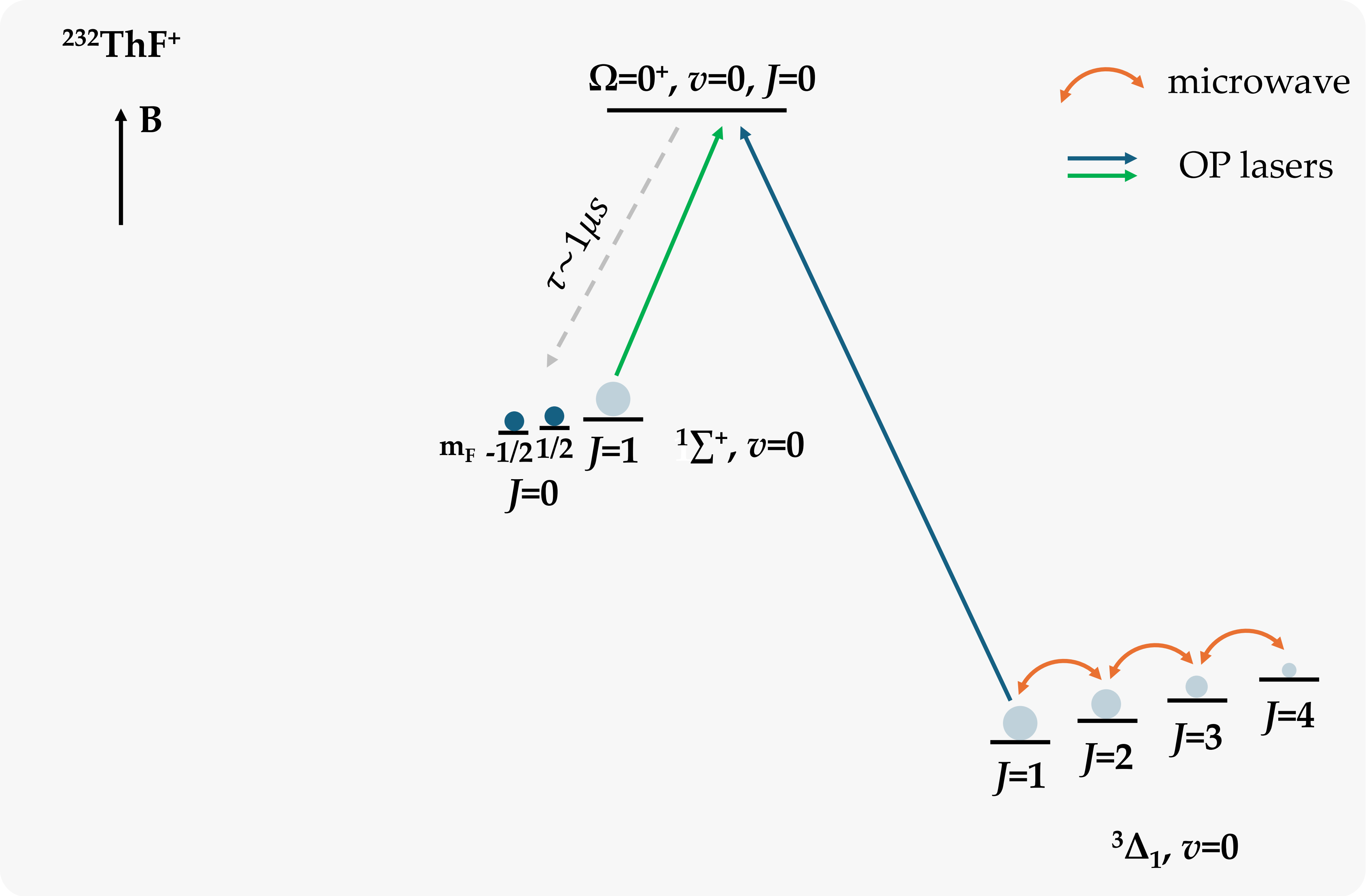

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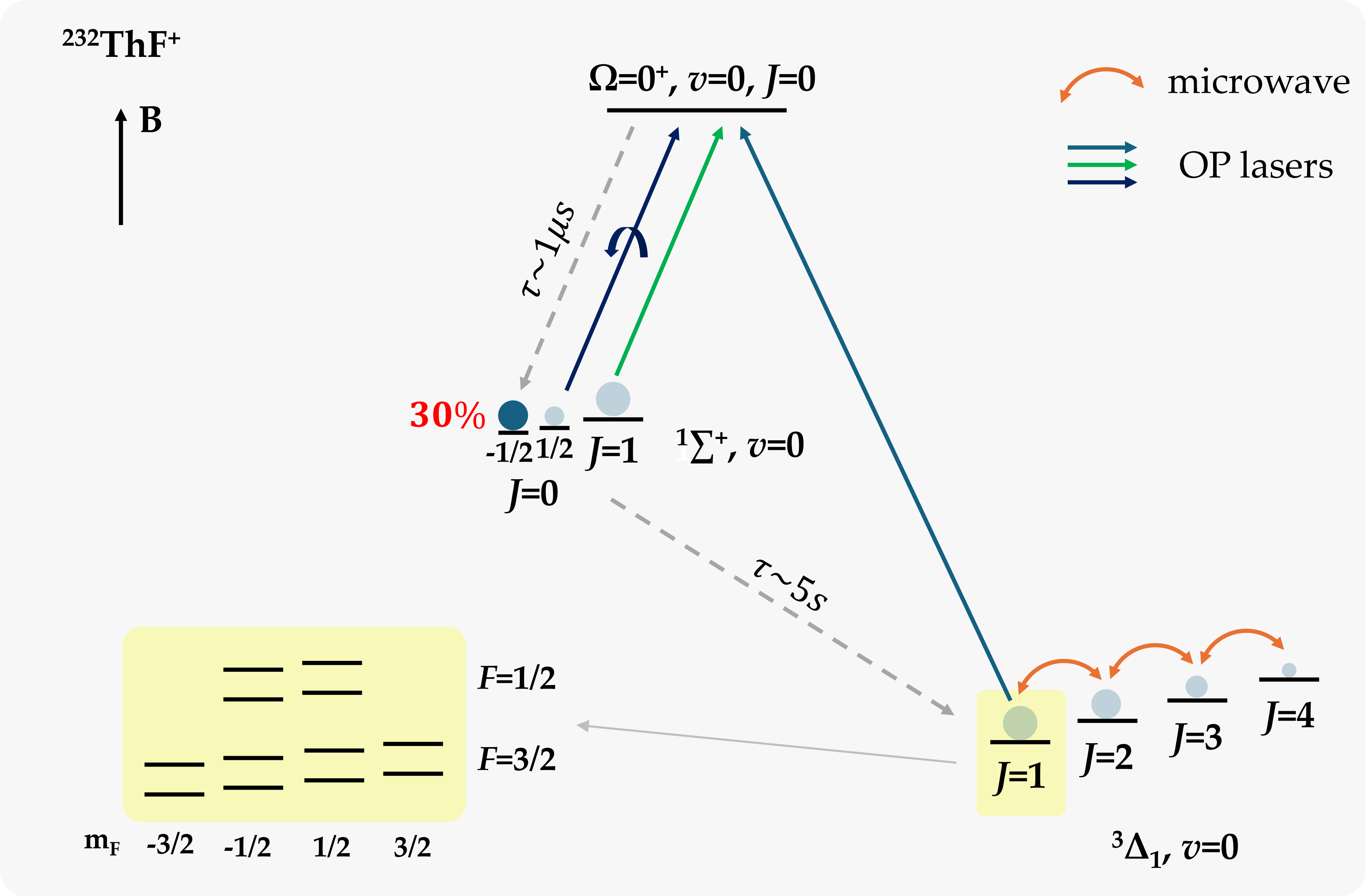

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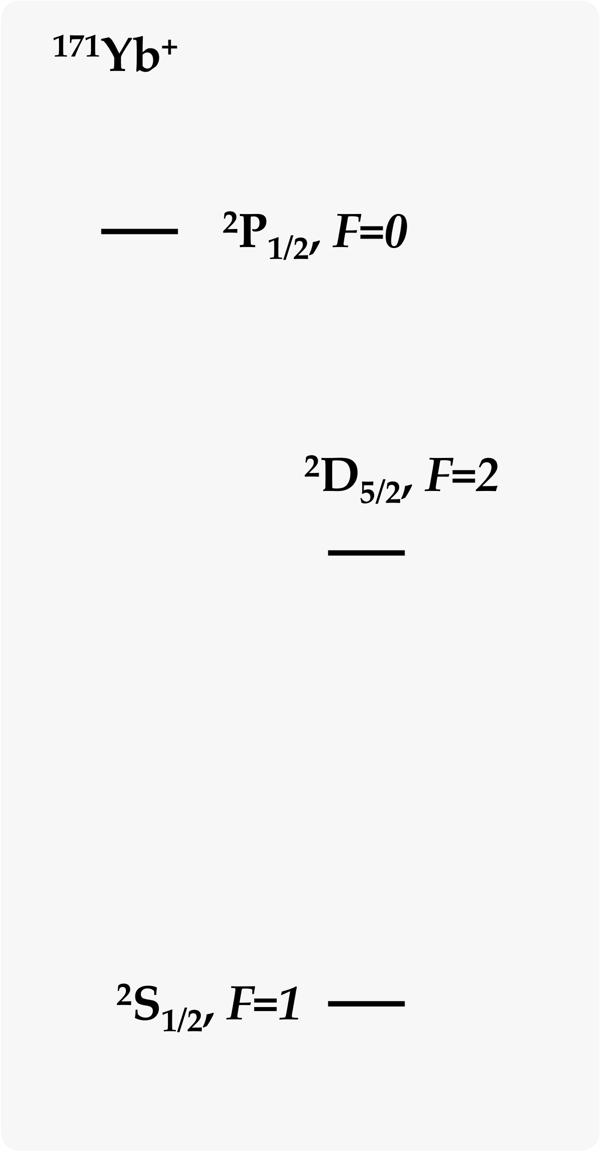

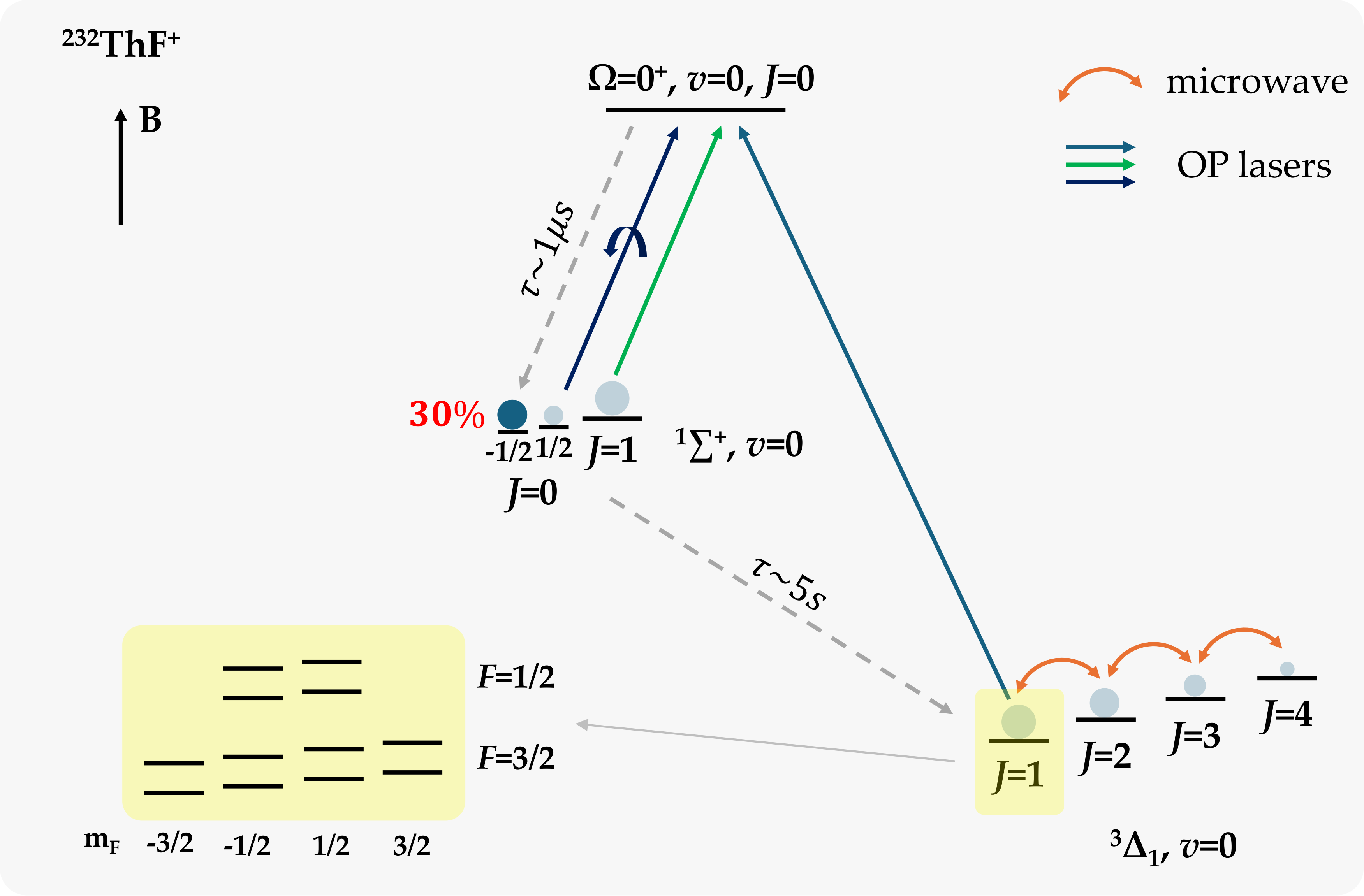

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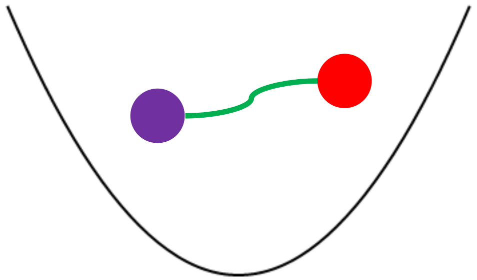
- We have a harmonic ion trap
- Load one **Yb^+** and one **ThF^+** in the trap
- Two ion species are linked by the Coulomb force



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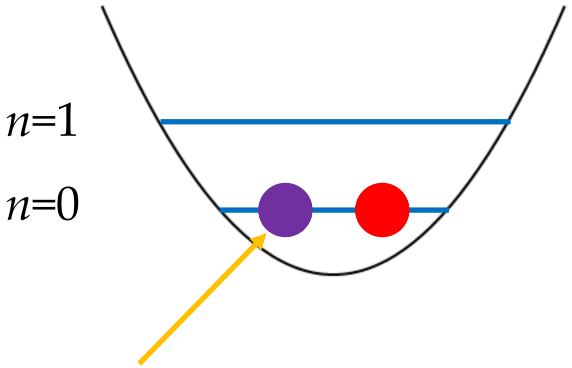

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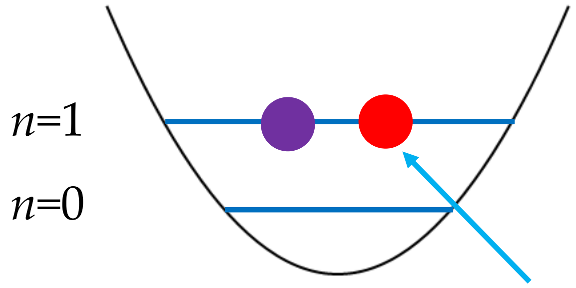

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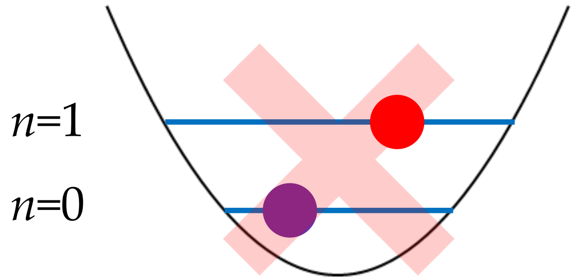

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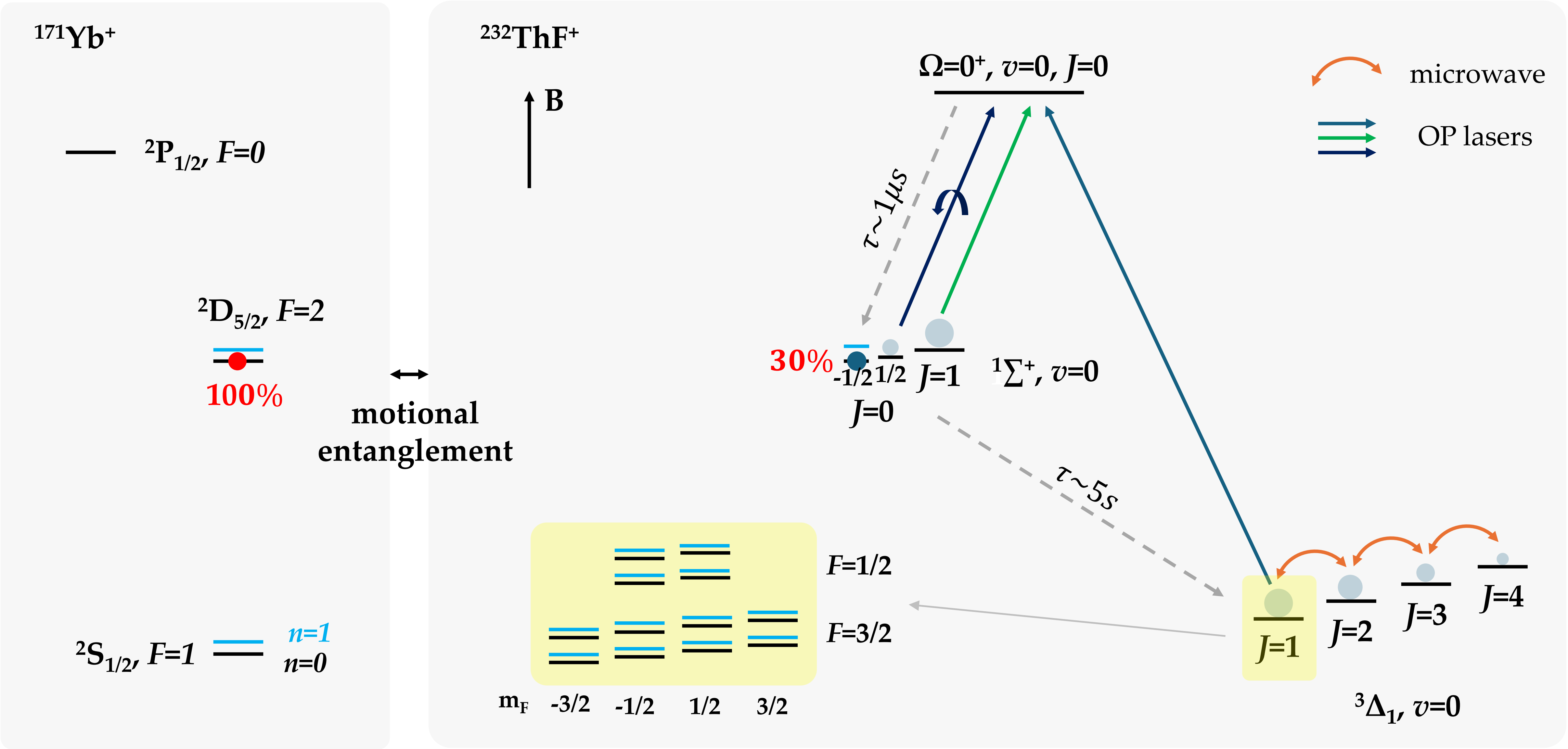
- If **ThF^+** is excited to the motional excited state, **Yb^+** is in the motional excited state as well
- This state does not exist

State preparation and detection



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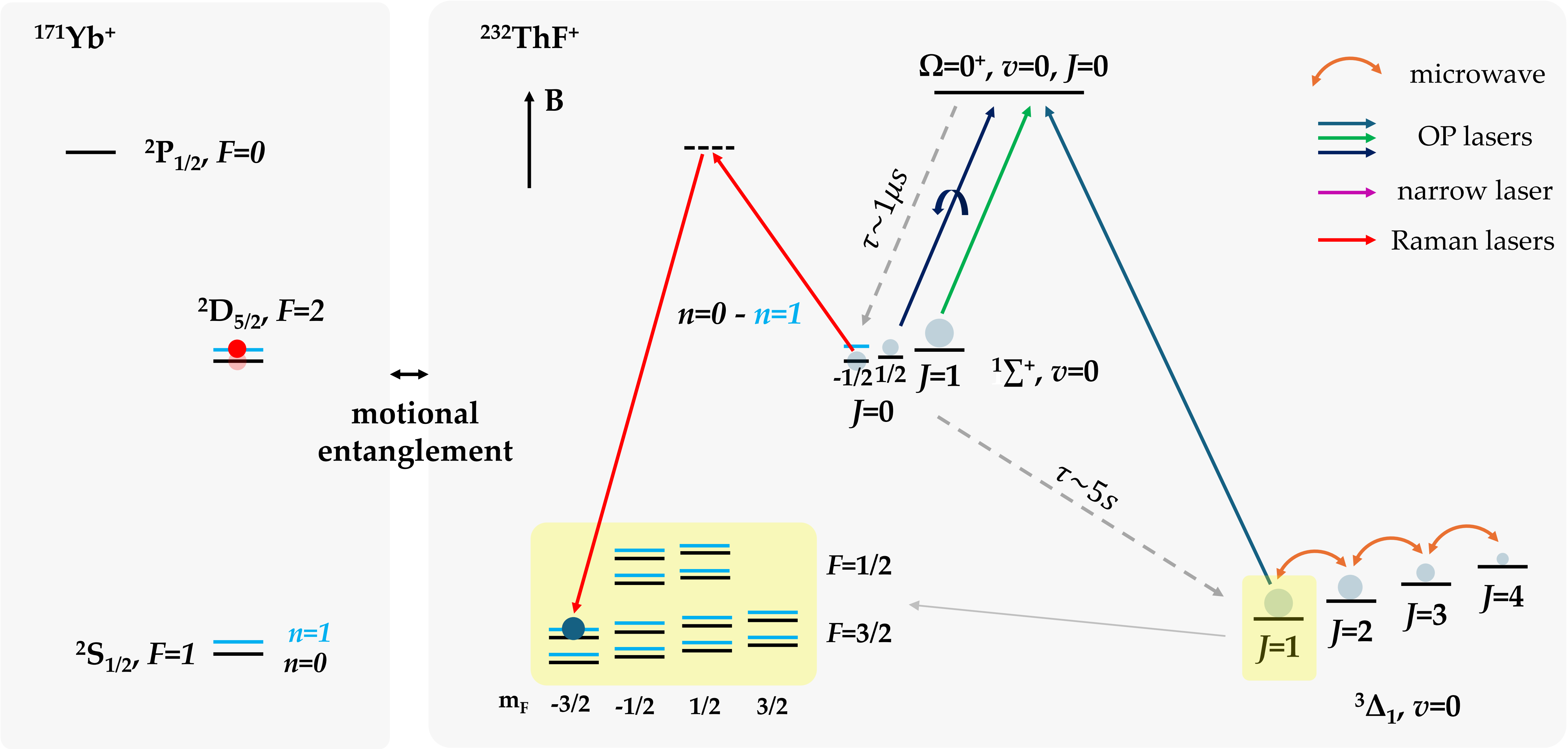

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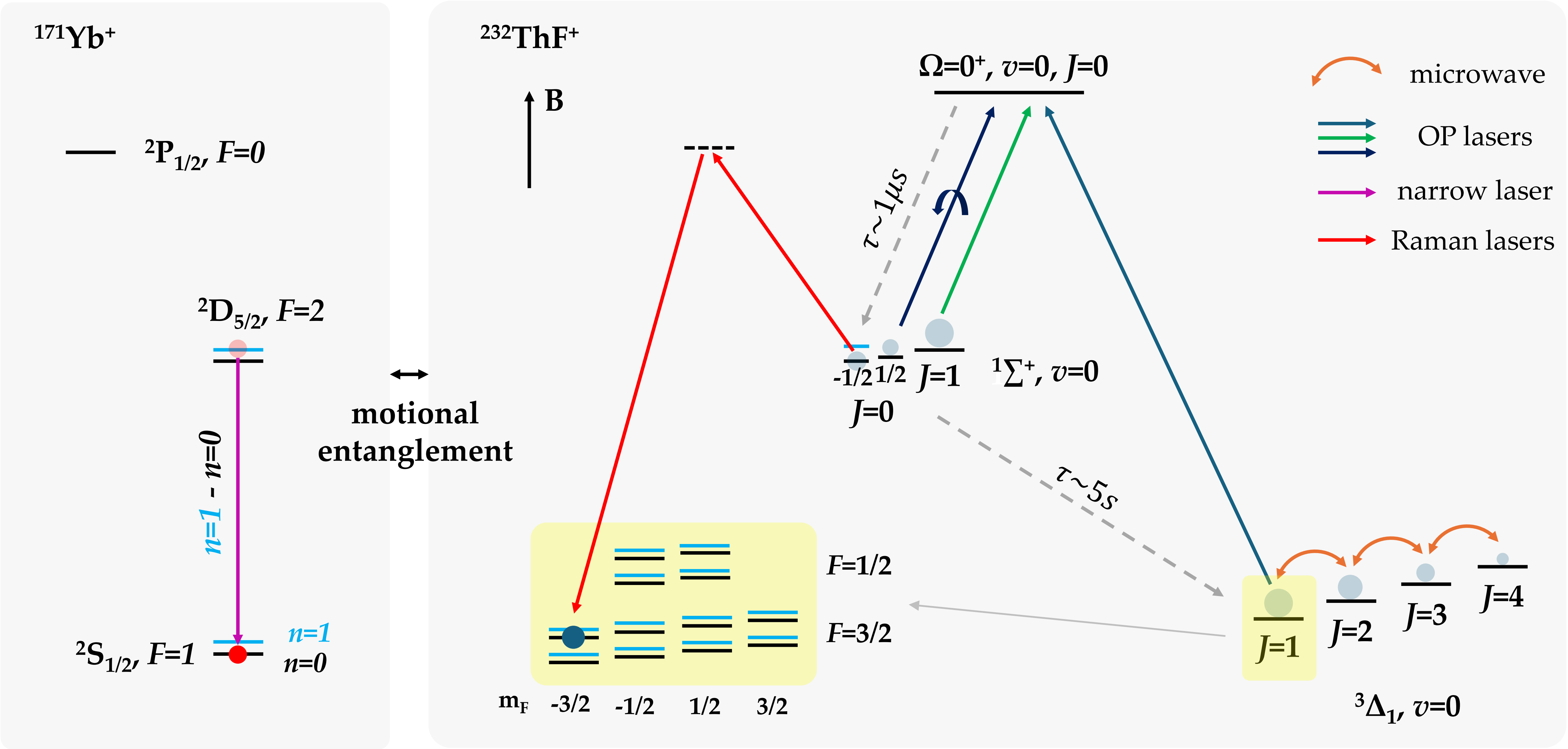

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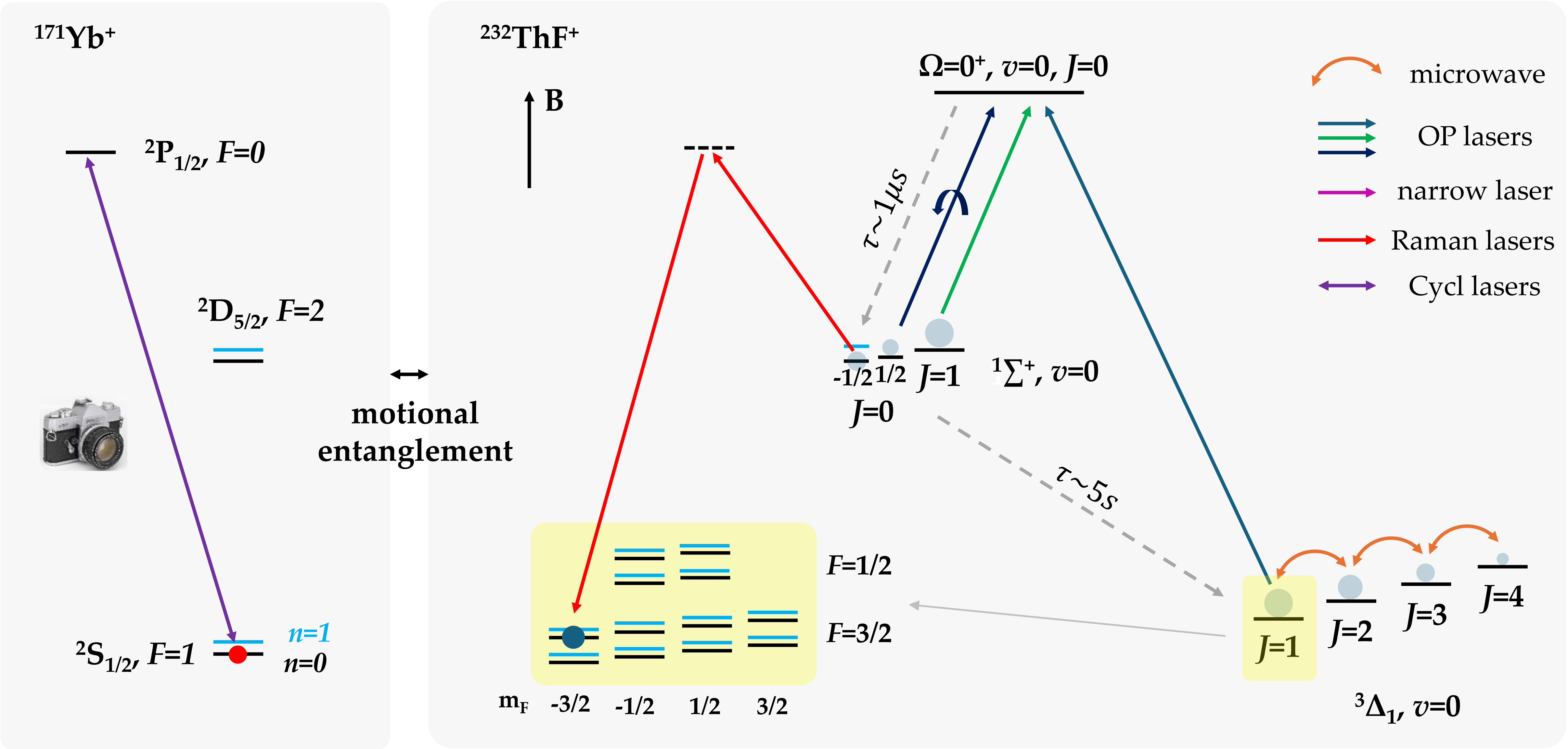

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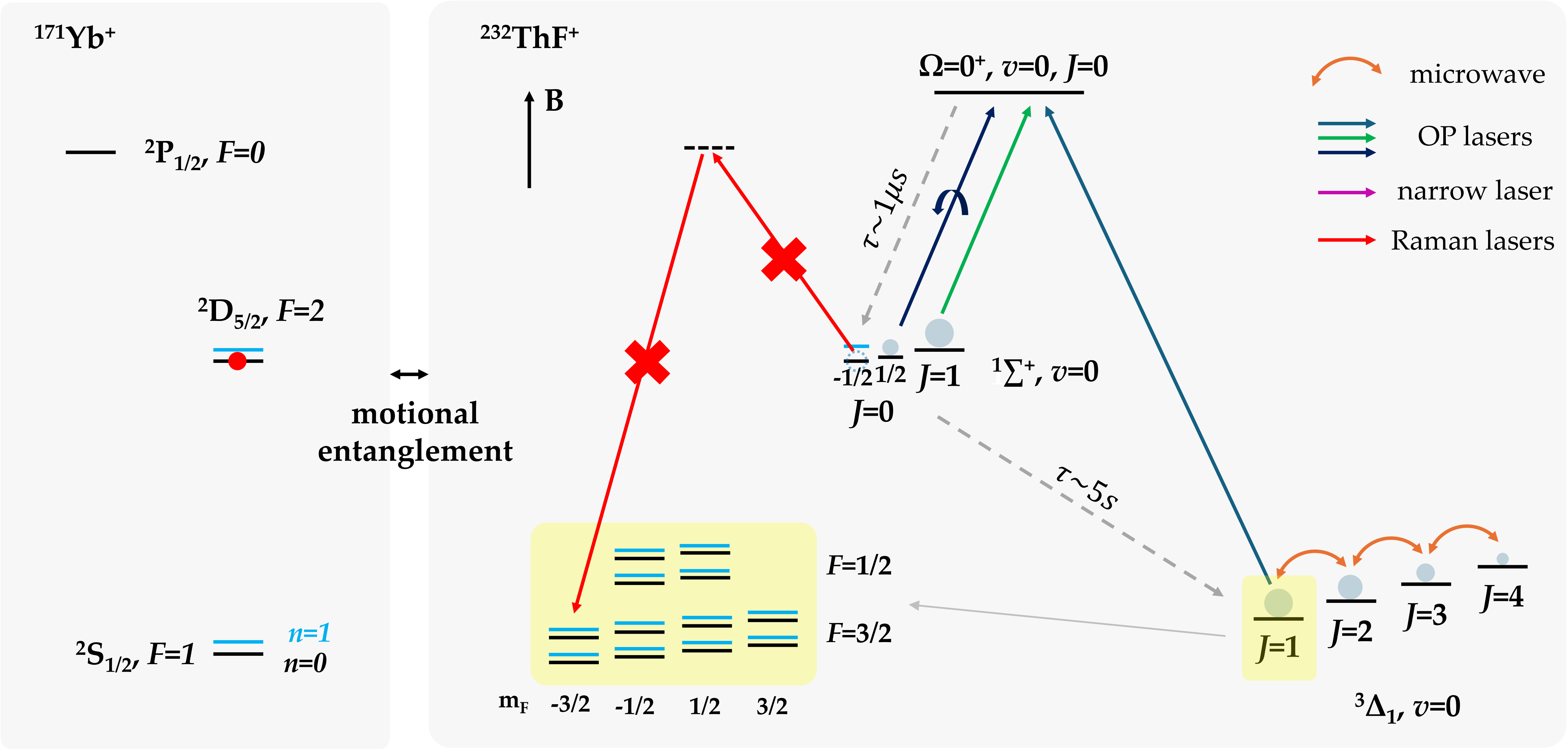

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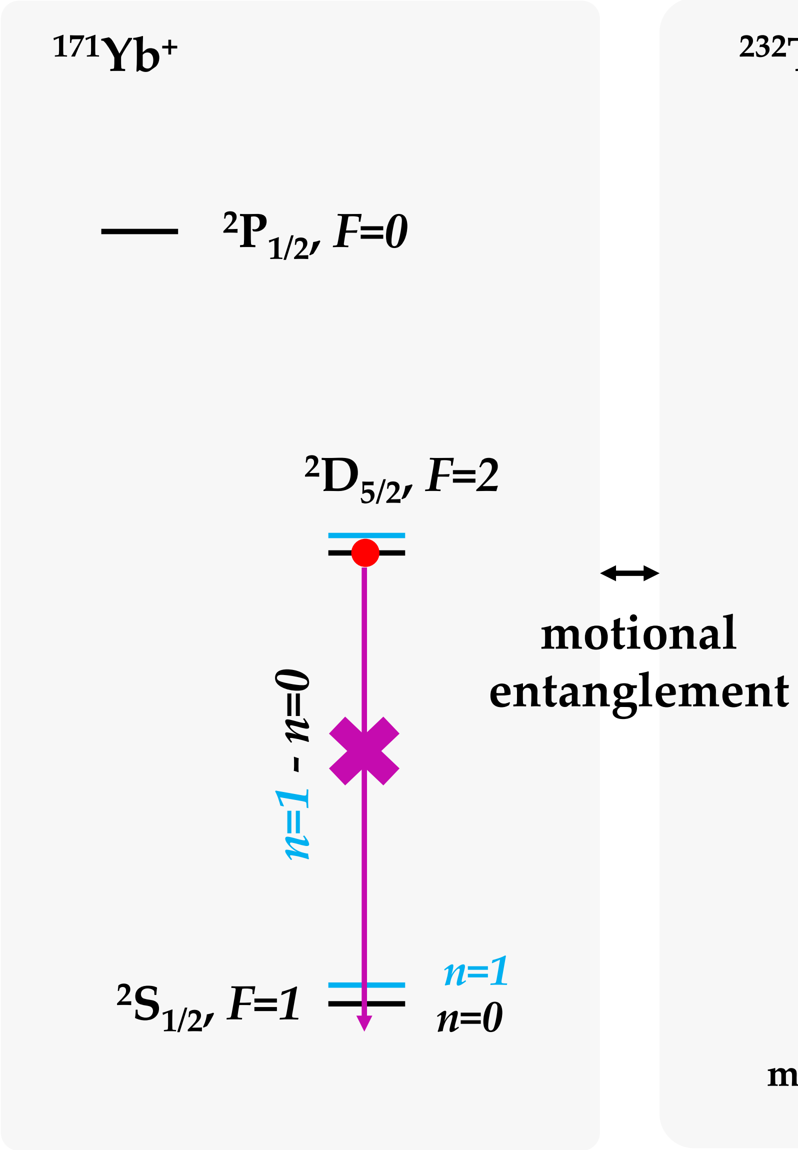
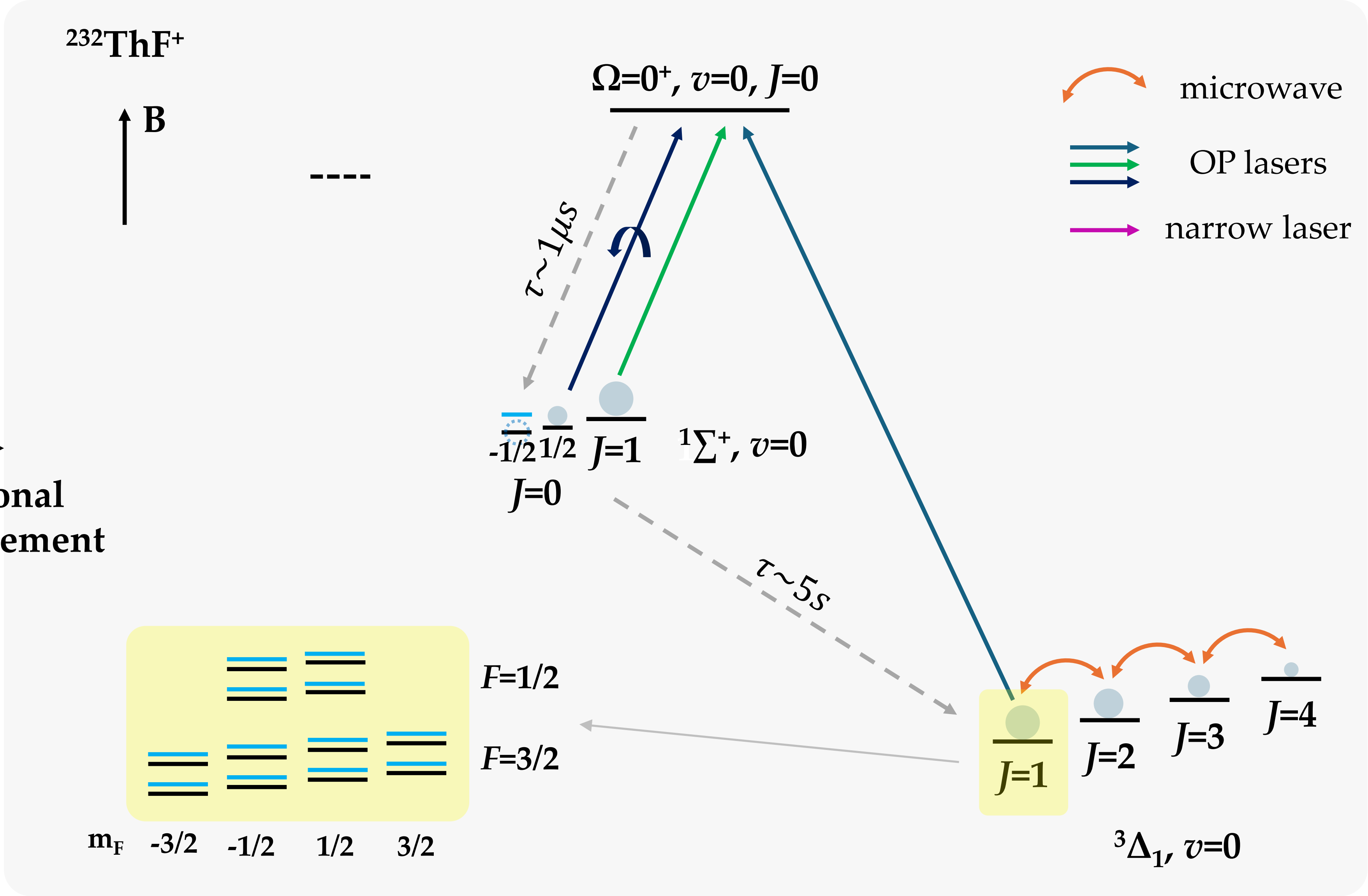
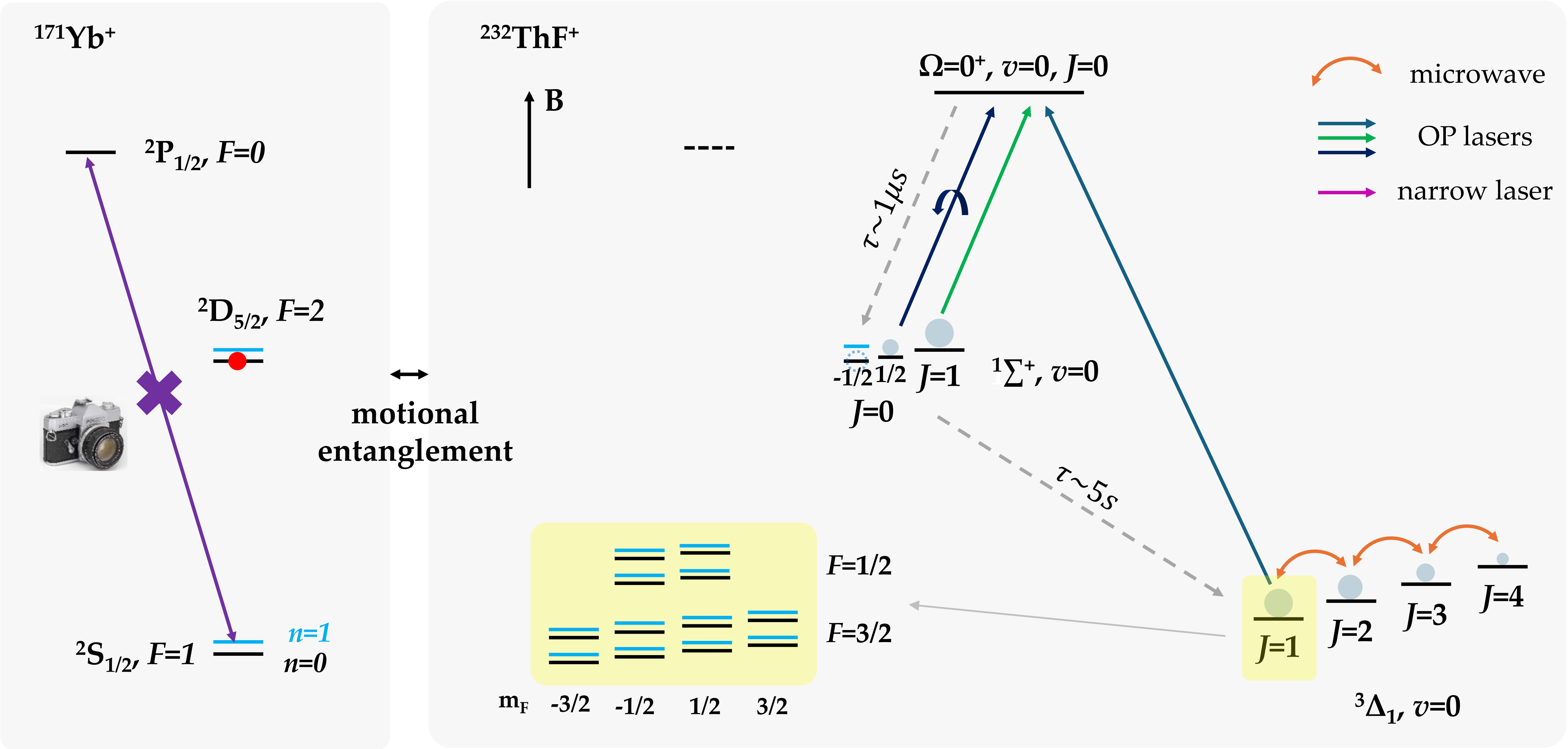




State preparation and detection



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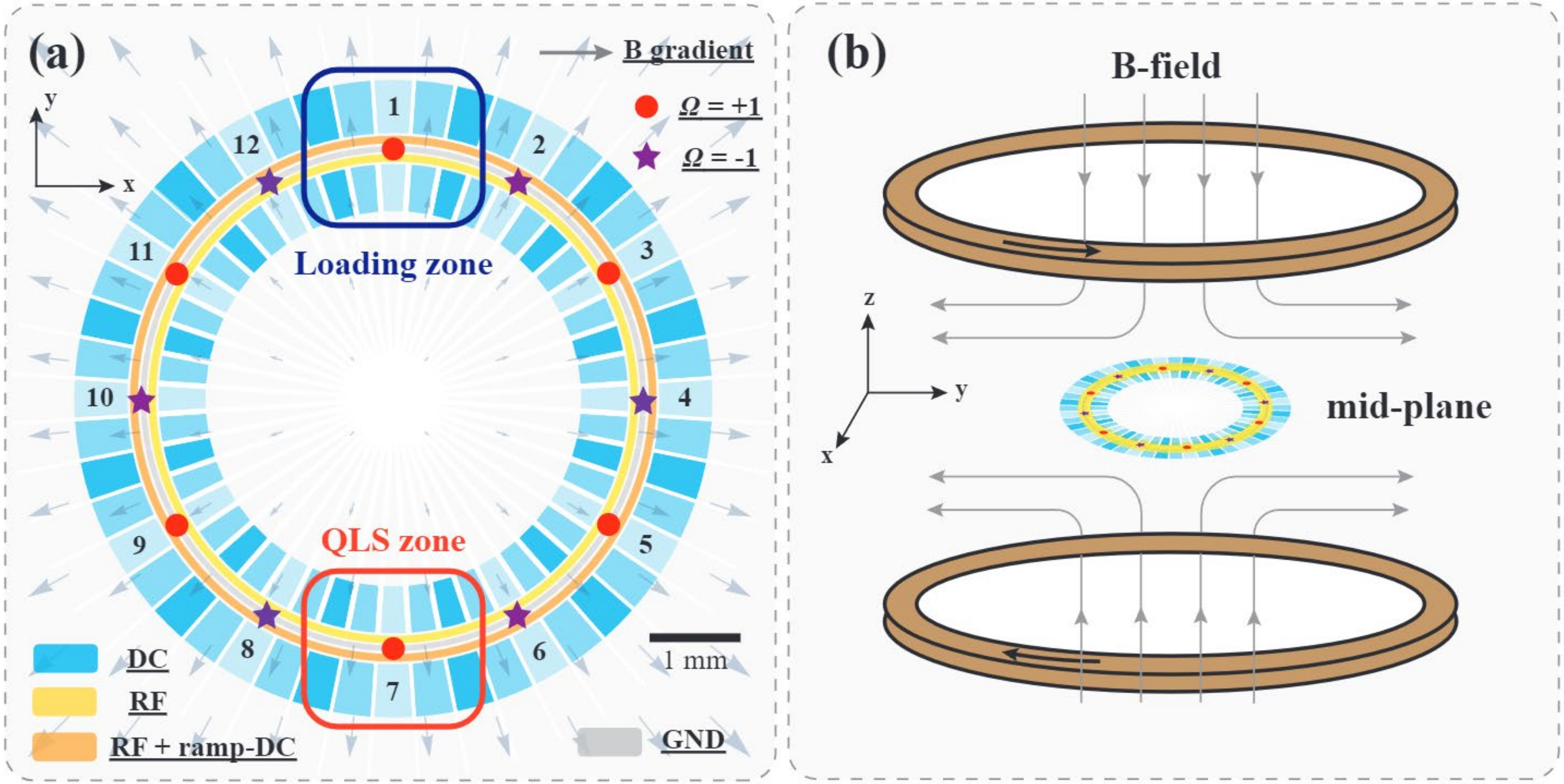
- Solution
  - **Separate QLS (static frame) and spin-precession (rotating frame)**
  - A smooth transition between these frames

Ring ion trap



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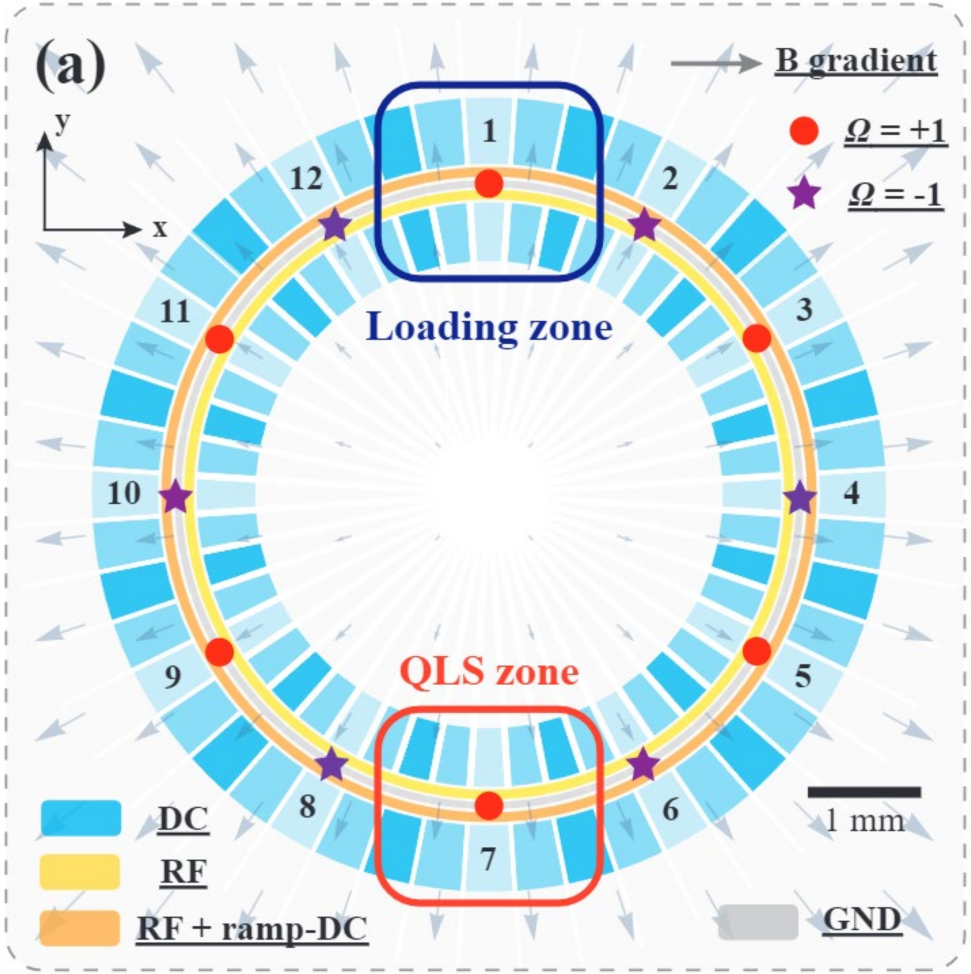
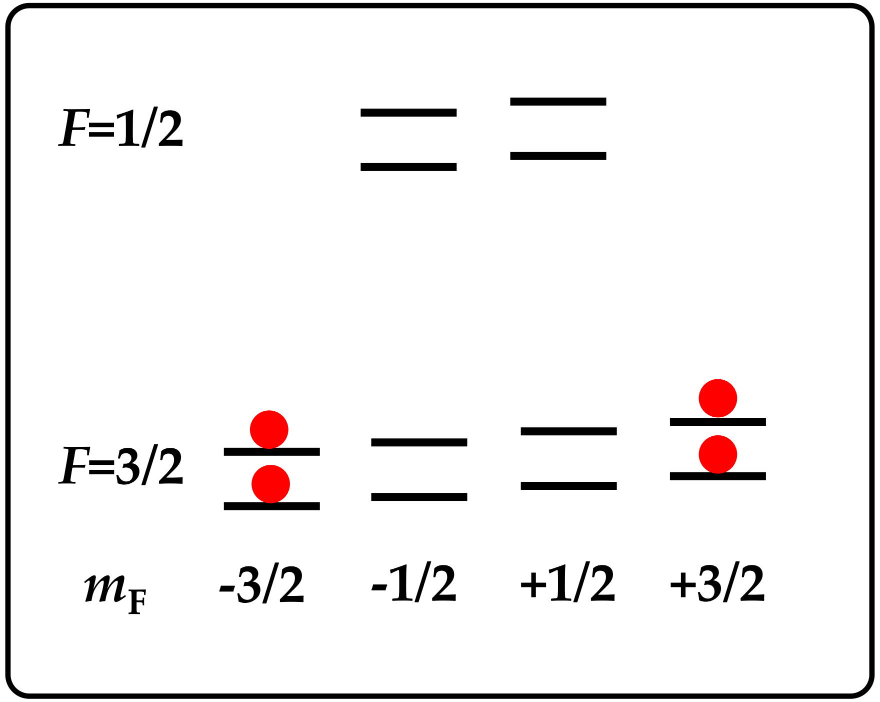


Property	Value
Radial Freq	2.5 MHz
Axial Freq	1 MHz
Rotation Freq	0-100 kHz
Rotation radius	3 mm
E-field	0-32 V/cm

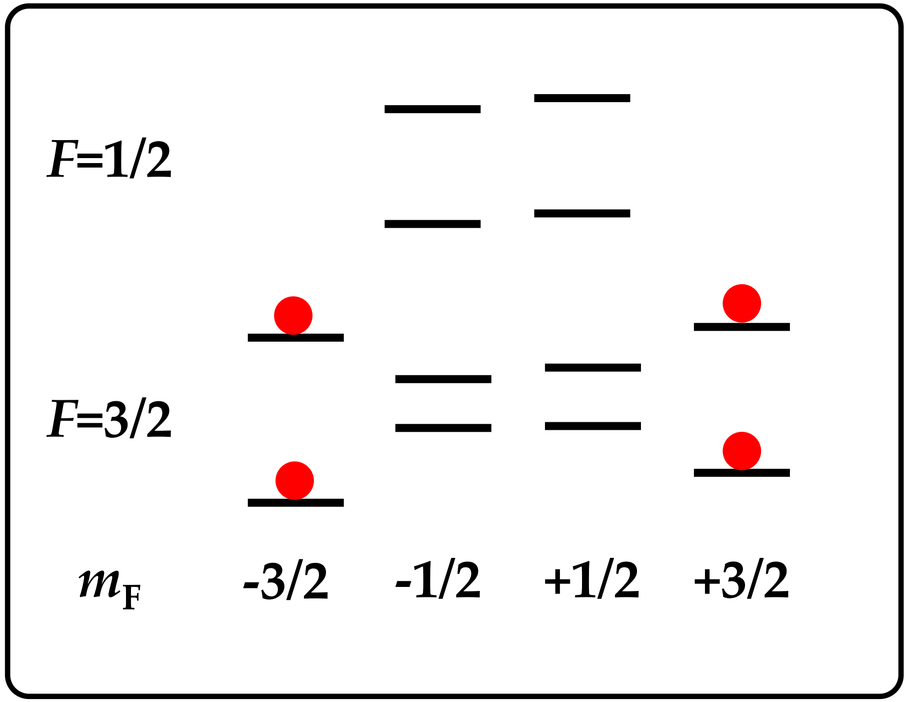
- QLS in the static frame
- Precision measurement in the rotating frame

Transition from static to rotating frames

static frame

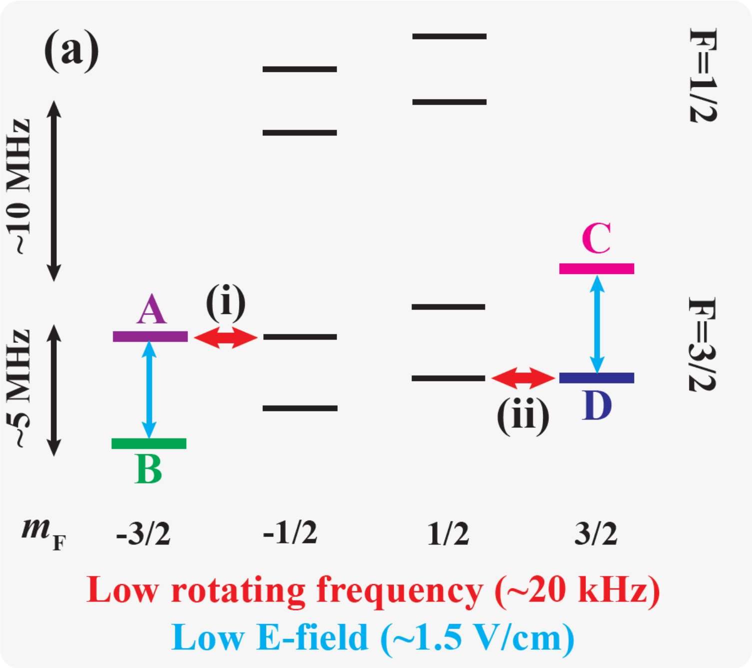


rotating frame



Transition from static to rotating frames

- What happens when the ions are rotating faster and faster?
  - Rotating E-field repel A and B, C and D
  - Rotating coupling interacts $\Delta m_F = \pm 1$
  - Rotating B-field is constant – Zeeman shifts do not change



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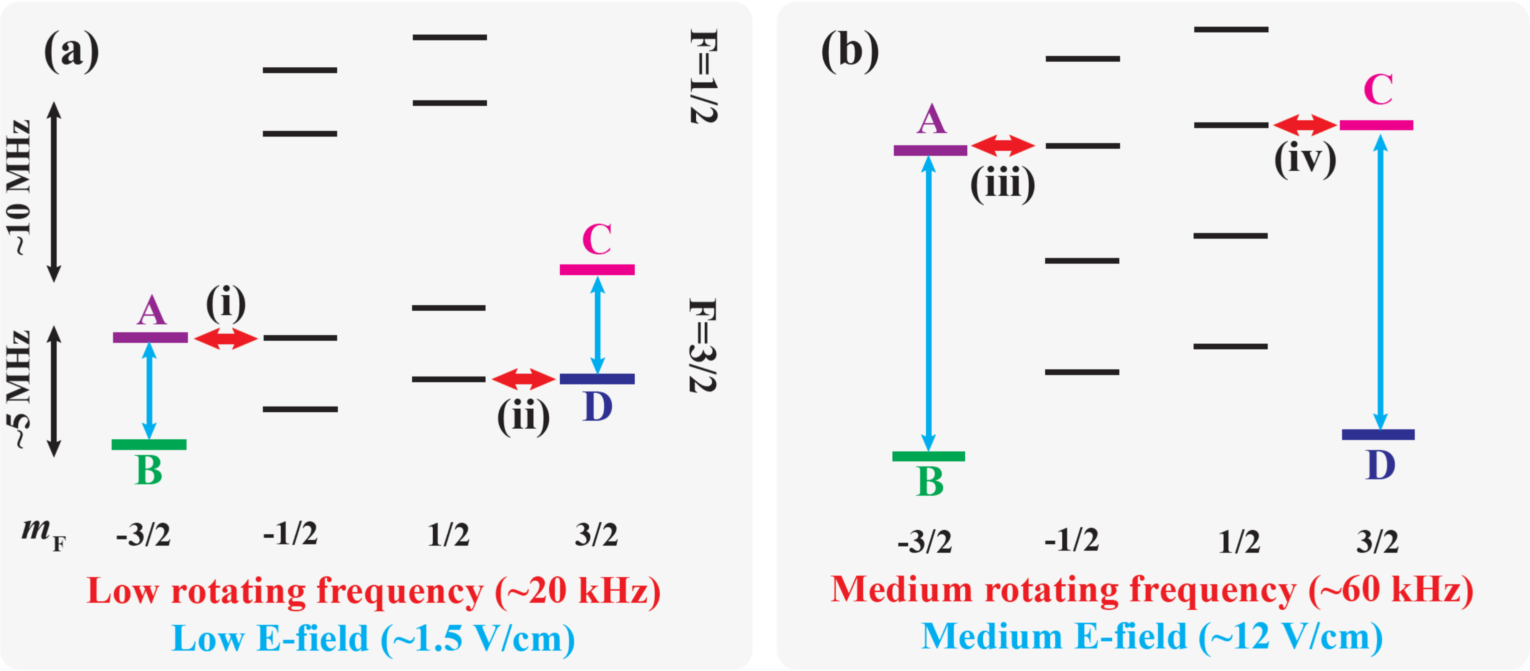

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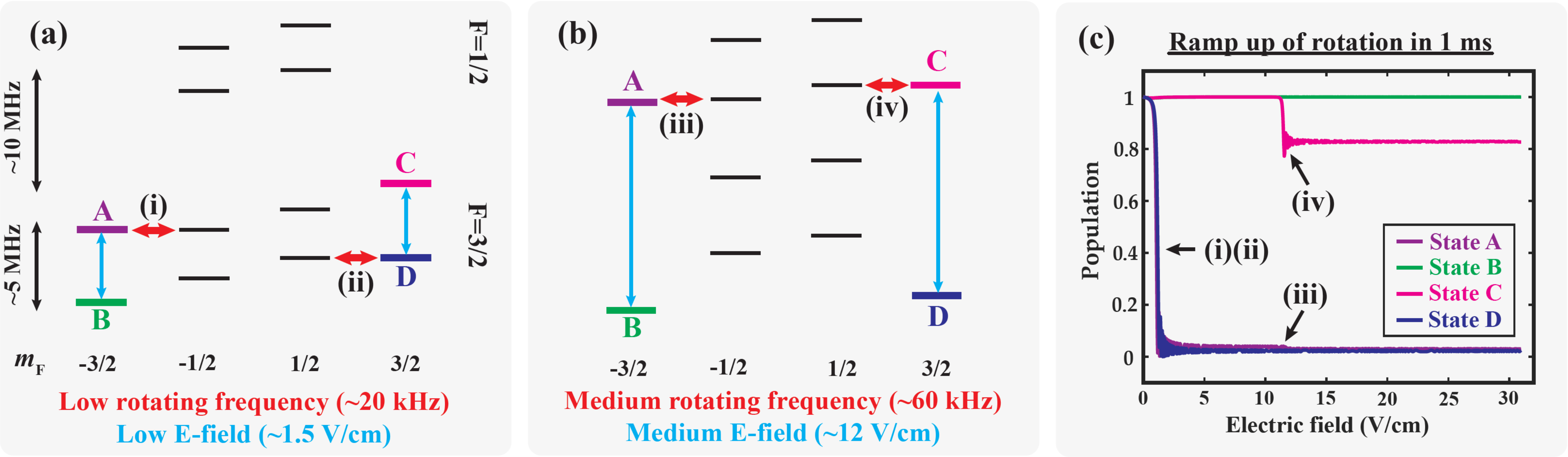
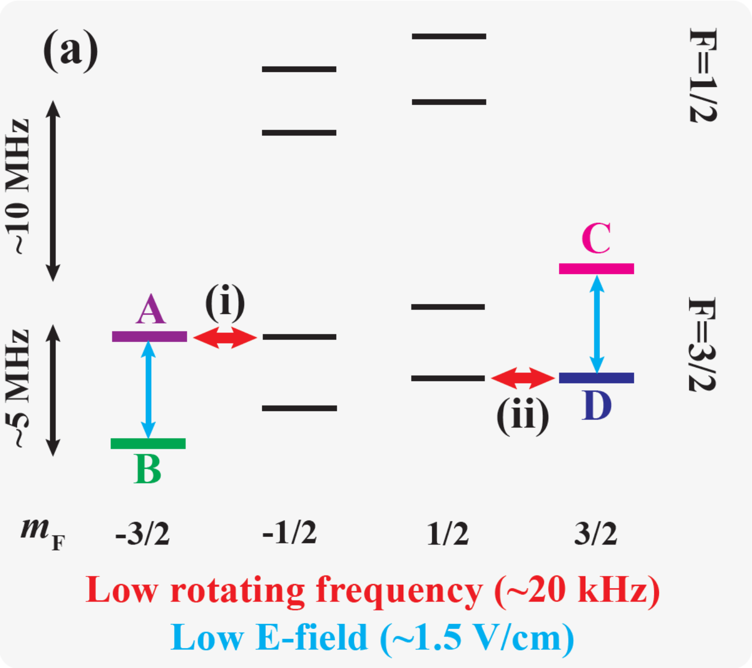
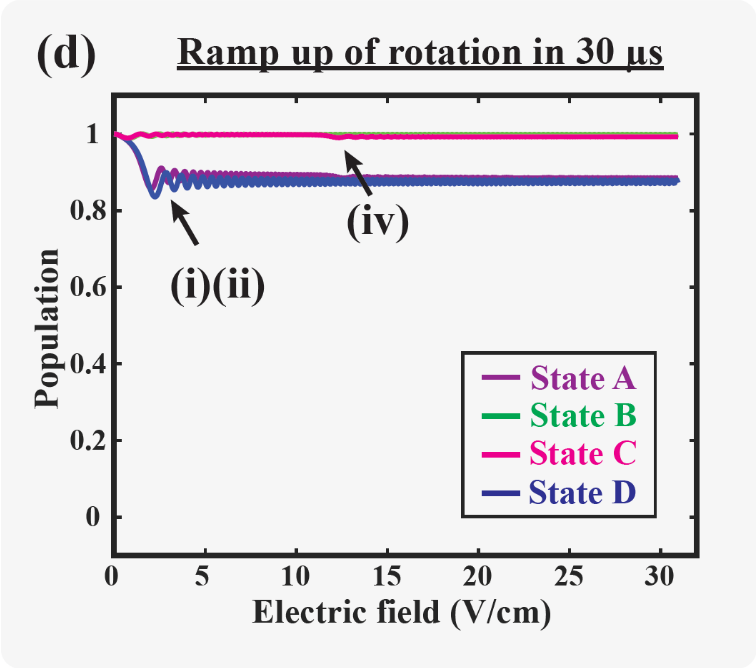


Transition from static to rotating frames

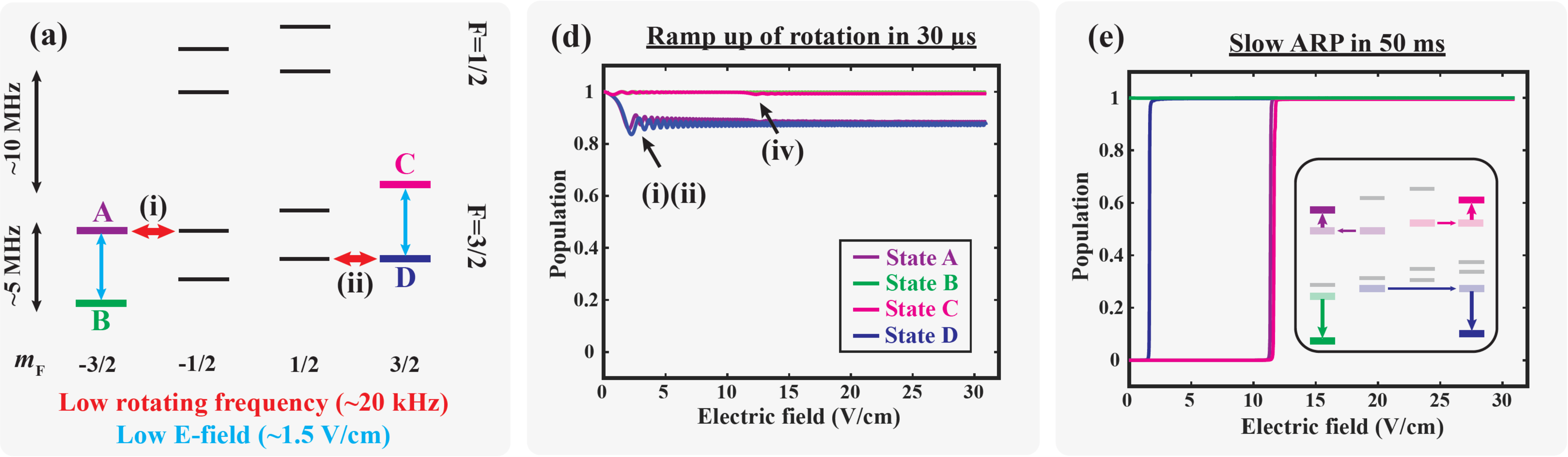
- ❑ Solution 1: increase the ramp rate



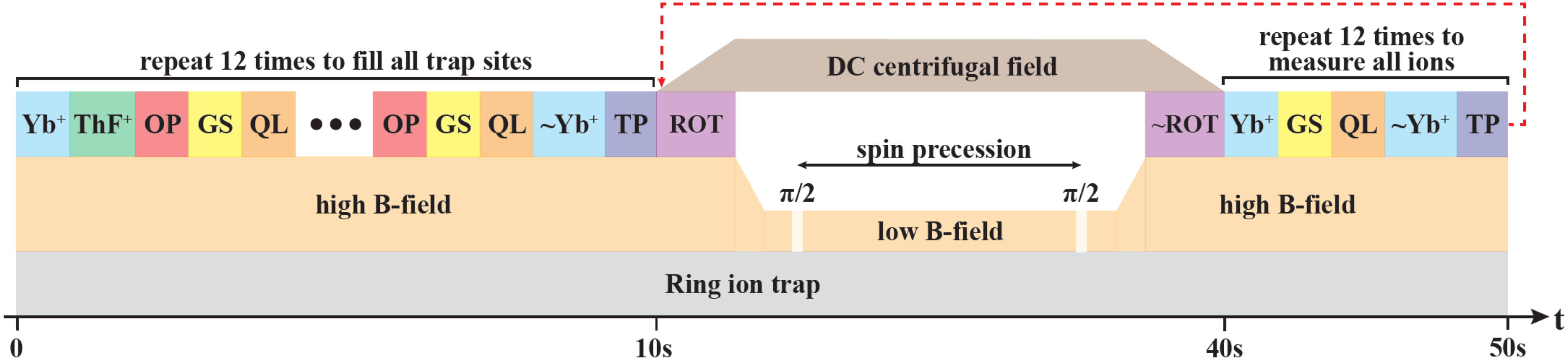


Transition from static to rotating frames

- ❑ Solution 1: increase the ramp rate
- ❑ Solution 2: adiabatic population transfer

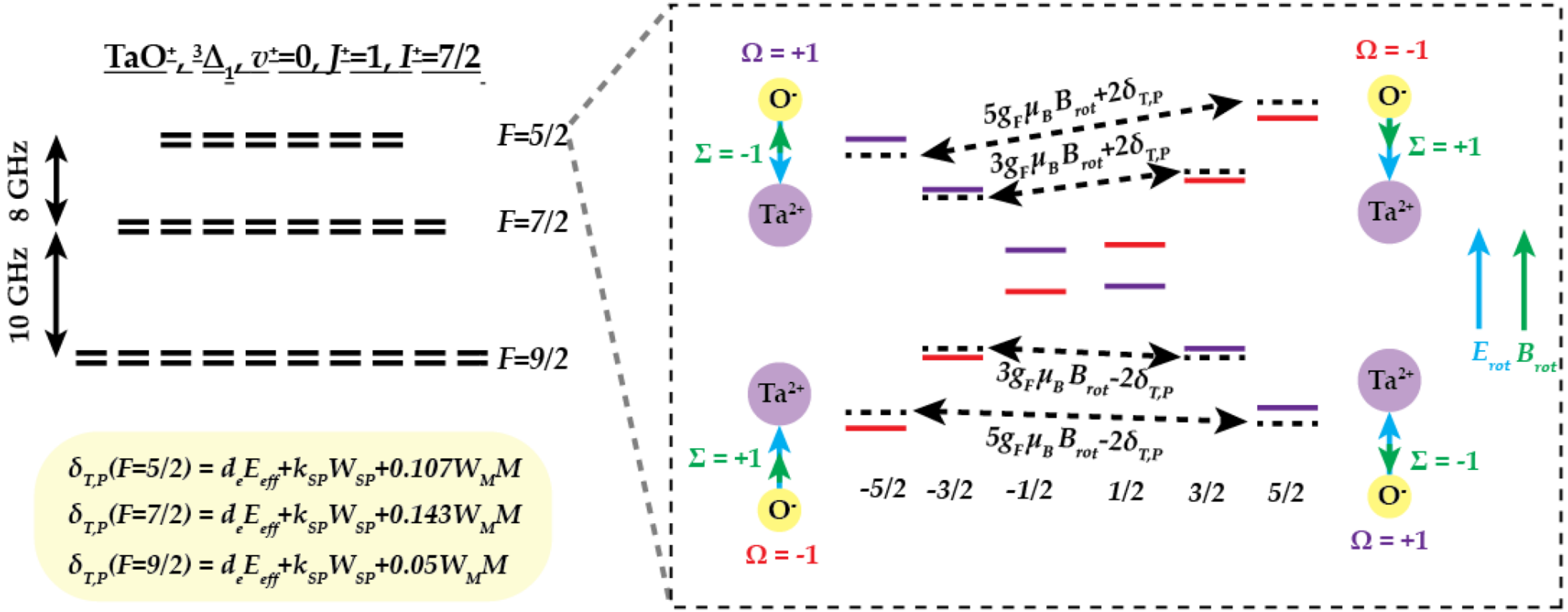


Experimental sequence



- ❑ State preparation and detection is performed for each ions one-by-one
- ❑ Spin-precession is for all ions
- ❑ State readout of one measurement is the state preparation of the next measurement

nuclear MQM



$\delta_{T,P}(F=5/2) = d_e E_{eff} + k_{SP} W_{SP} + 0.107 W_M M$

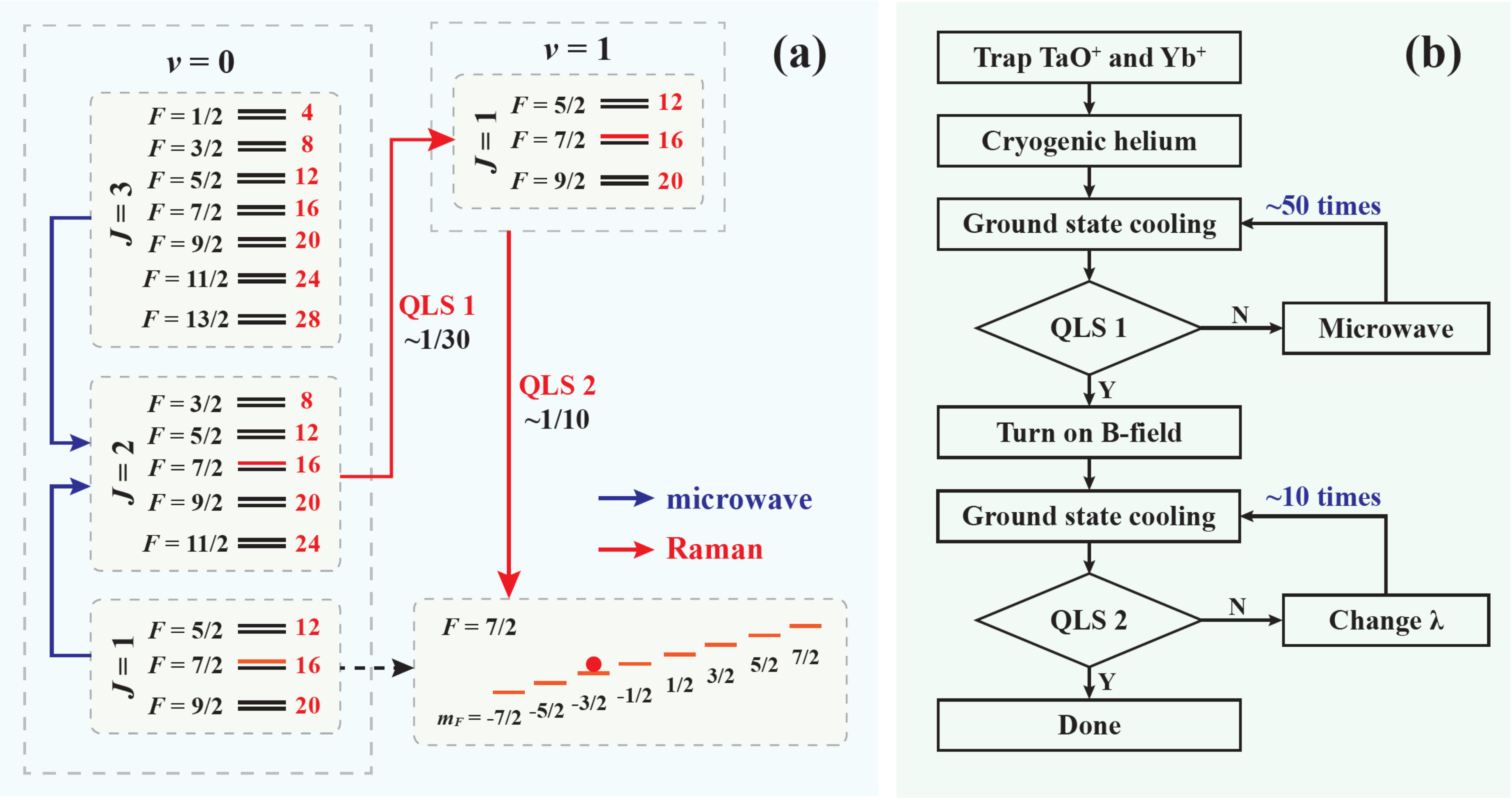
$\delta_{T,P}(F=7/2) = d_e E_{eff} + k_{SP} W_{SP} + 0.143 W_M M$

$\delta_{T,P}(F=9/2) = d_e E_{eff} + k_{SP} W_{SP} + 0.05 W_M M$

- ❑ More hyperfine states
- ❑ Rotation-induced couplings are more complicated

nuclear MQM

- ❑ Degenerate QLS



Current status

- ❑ QLS and degenerate QLS for heavy molecular ions
- ❑ High-precision simulations
- ❑ Ring trap fabrication and tests
  - 3D trap using the laser cutting method
  - Surface trap using microfabrication method

Thank you!