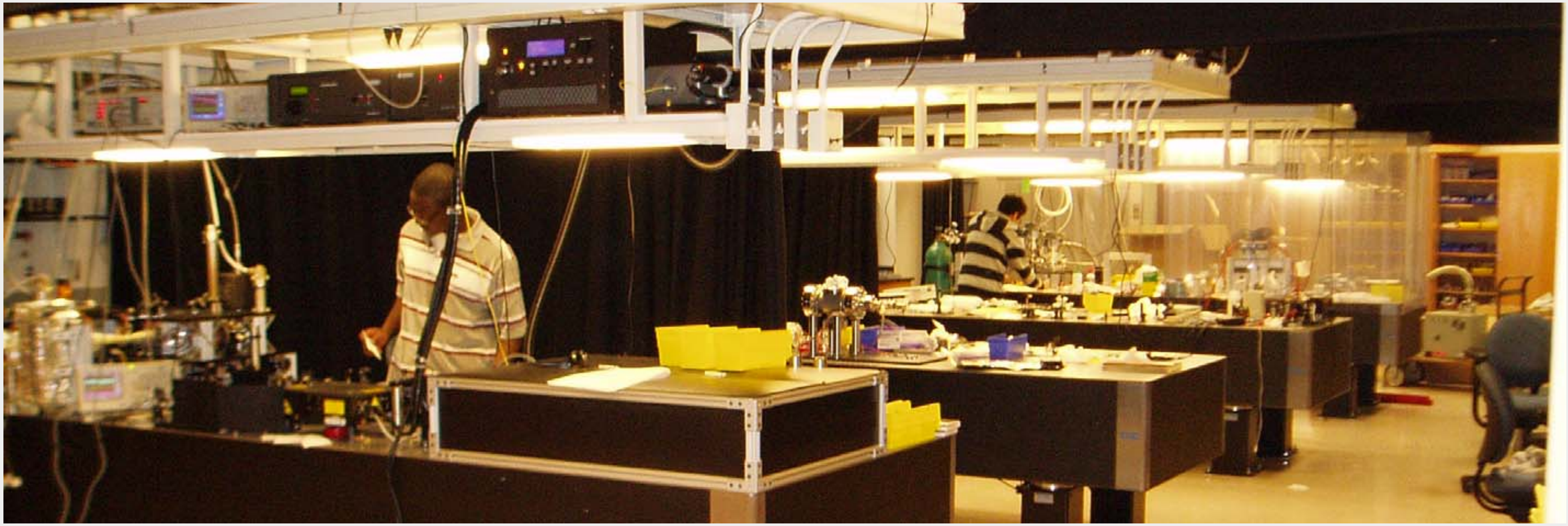
Testing Supersymmetry without the LHC



Aaron E. Leanhardt

October 31, 2008

DEPARTMENT OF PHYSICS UNIVERSITY OF MICHIGAN

High Energy Particle Physics

Particle Physics “Hit List”, from *Symmetry* Magazine, December 2006

High Energy Particle Physics

Particle Physics “Hit List”, from *Symmetry* Magazine, December 2006

Fundamental Symmetries

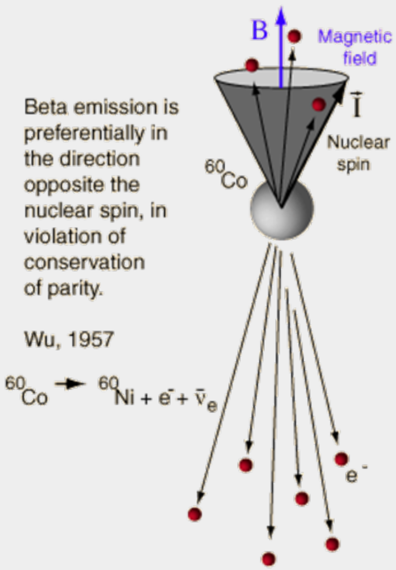
- C [charge conjugation]: particle ↔ antiparticle
- P [parity]: {+x,+y,+z} ↔ {-x,-y,-z}
- T [time-reversal]: +t ↔ -t

Fundamental Symmetries

- C [charge conjugation]: particle ↔ antiparticle
- P [parity]: {+x,+y,+z} ↔ {-x,-y,-z}
- T [time-reversal]: +t ↔ -t

P-Violation

$$^{60}Co \longrightarrow {}^{60}Ni + e^{-} + \overline{\nu}_e$$

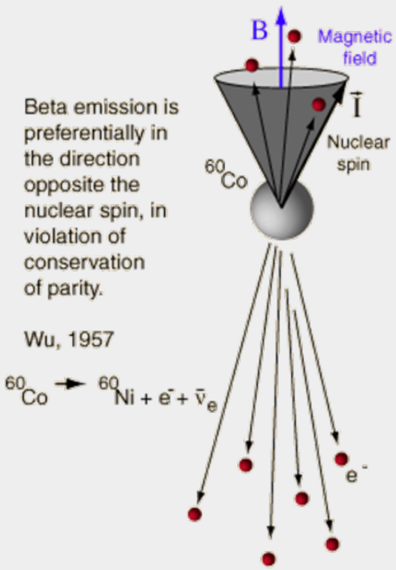


Fundamental Symmetries

- C [charge conjugation]: particle ↔ antiparticle
- P [parity]: {+x,+y,+z} ↔ {-x,-y,-z}
- T [time-reversal]: +t ↔ -t

P-Violation

$$^{60}Co \longrightarrow {}^{60}Ni + e^{-} + \bar{\nu}_e$$



CP-Violation

K and B meson decays

$$K_L \xrightarrow{49.9\%} \pi^{+} + e^{-} + \bar{\nu}_e$$

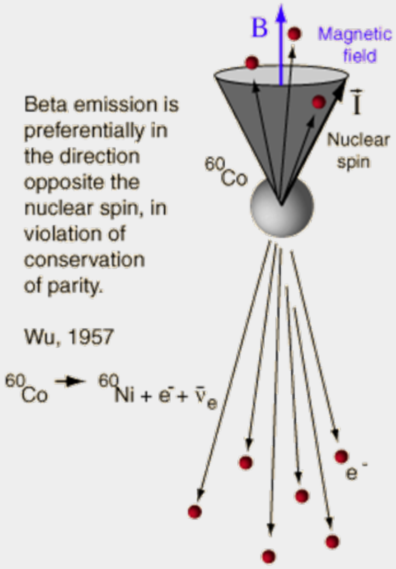
$$K_L \xrightarrow{50.1\%} \pi^{-} + e^{+} + \nu_e$$

Fundamental Symmetries

- C [charge conjugation]: particle ↔ antiparticle
- P [parity]: {+x,+y,+z} ↔ {-x,-y,-z}
- T [time-reversal]: +t ↔ -t

P-Violation

$$^{60}Co \longrightarrow {}^{60}Ni + e^{-} + \overline{\nu}_e$$



CP-Violation

K and B meson decays

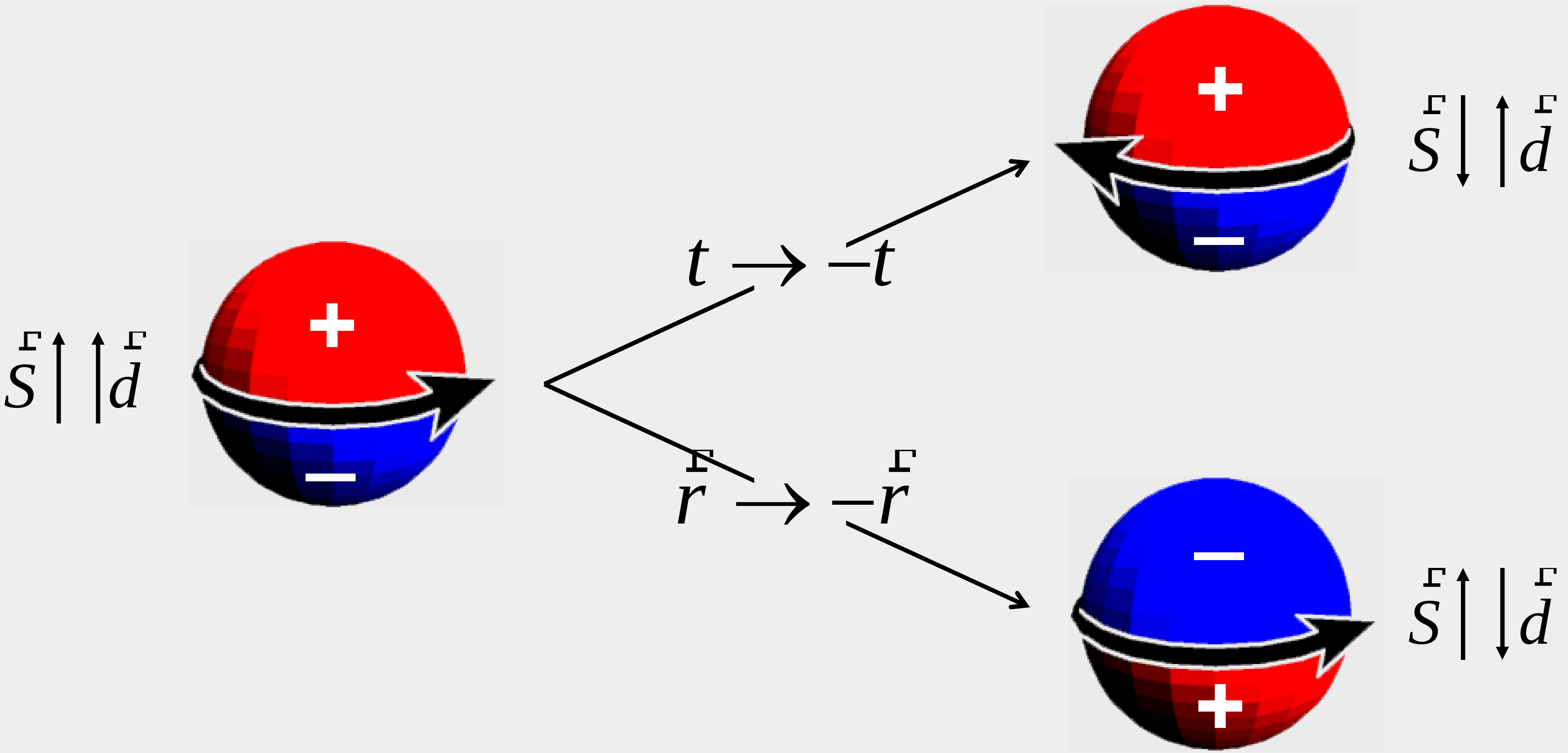
$$K_L \xrightarrow{49.9\%} \pi^{+} + e^{-} + \overline{\nu}_e$$

$$K_L \xrightarrow{50.1\%} \pi^{-} + e^{+} + \nu_e$$

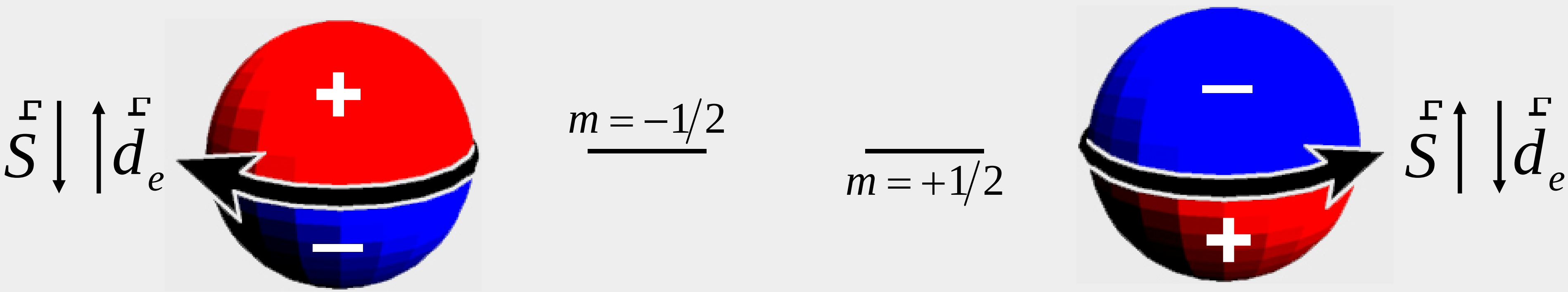
- From the CPT Theorm: CP-violation is equivalent to T-violation.

P & T Applied to the Electron

- Electron has a spin, S.
- Assume electron has an electric dipole moment (EDM), d_e.
- d_e is NOT independent of S!

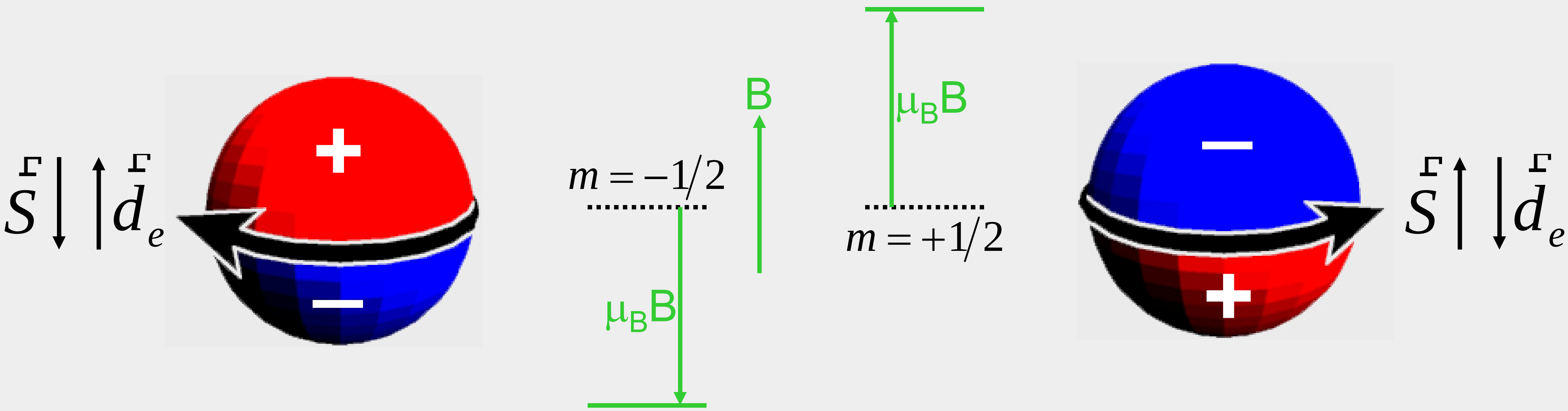


e^- Energy Levels



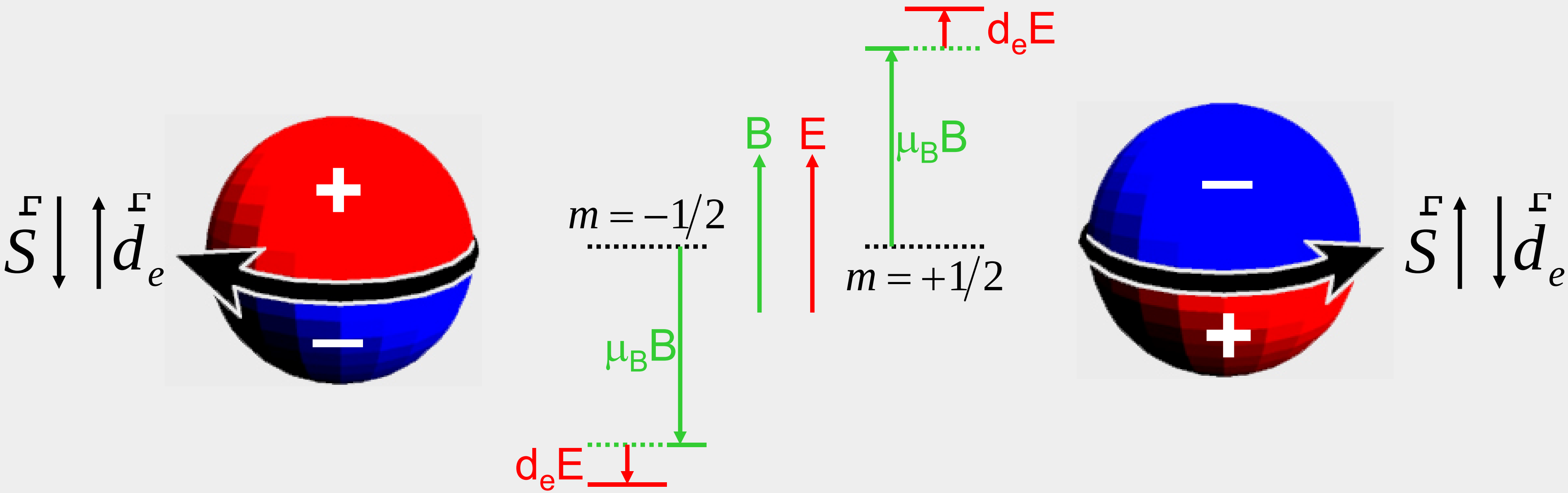
e^- Energy Levels

$$\underbrace{H_B \propto \vec{S} \cdot \vec{B}}_{\text{P-even, T-even}}$$



e^- Energy Levels

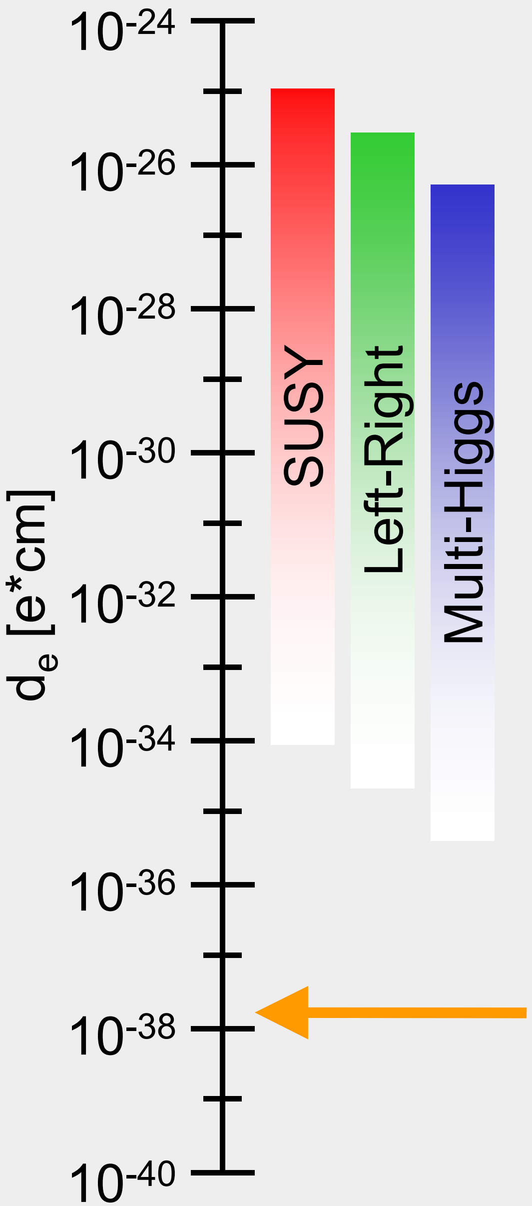
$$\underbrace{H_B \propto \vec{S} \cdot \vec{B}}_{\text{P-even, T-even}} \qquad \underbrace{H_E \propto \vec{S} \cdot \vec{E}}_{\text{P-odd, T-odd}}$$



Frequency Shift: $\Delta\nu = \dfrac{2d_e E_{eff}}{h}$

Frequency Resolution: $\Delta\nu = \dfrac{1}{2\pi\sqrt{N\tau}}$

Extensions to the Standard Model



Extra CP-violation predicts e^- EDM significantly larger than in Standard Model.

Supersymmetry: $|d_e| \approx \varepsilon_e \left(1\times10^{-25}\, e*cm\right)$

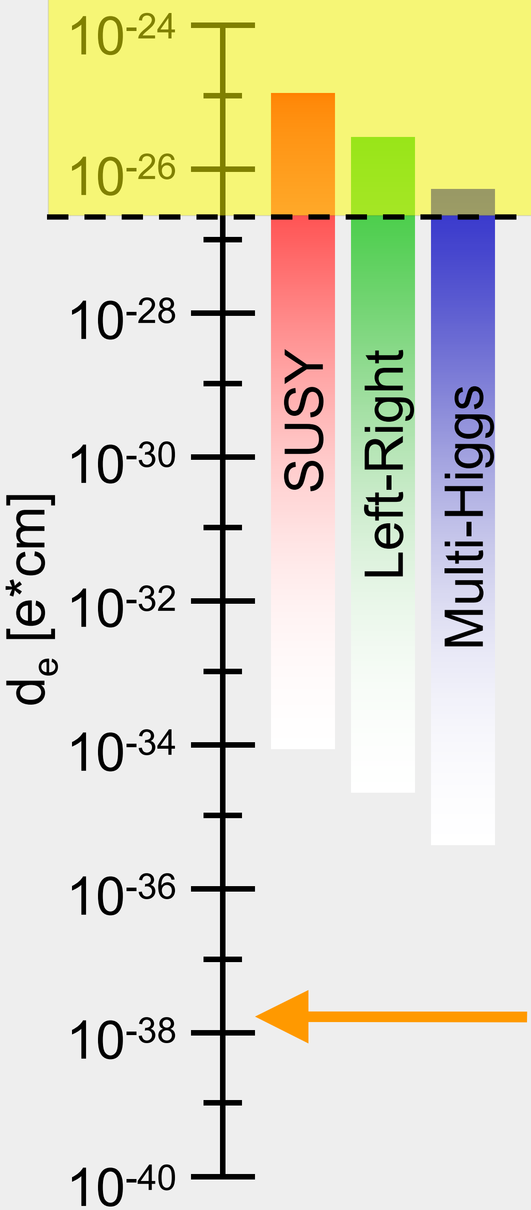
Left-Right: $|d_e| \approx \chi_B \left(3\times10^{-26}\, e*cm\right)$

Multi-Higgs: $|d_e| \approx \varepsilon_H \tan\beta \left(1-k\right)\left(5\times10^{-27}\, e*cm\right)$

Standard Model: $|d_e| \approx 1\times10^{-38}\, e*cm$

S.M. Barr, Int. J. Mod. Phys. A **8**, 209 (1993).

Extensions to the Standard Model



$|d_e| < 1.6 \times 10^{-27}$ e*cm [~10^{-18} Debye]
E.D. Commins Tl Exp. Limit [PRL **88**, 071805 (2002)]

Supersymmetry: $\left|d_e\right| \approx \varepsilon_e\left(1\times10^{-25}\,e*cm\right)$

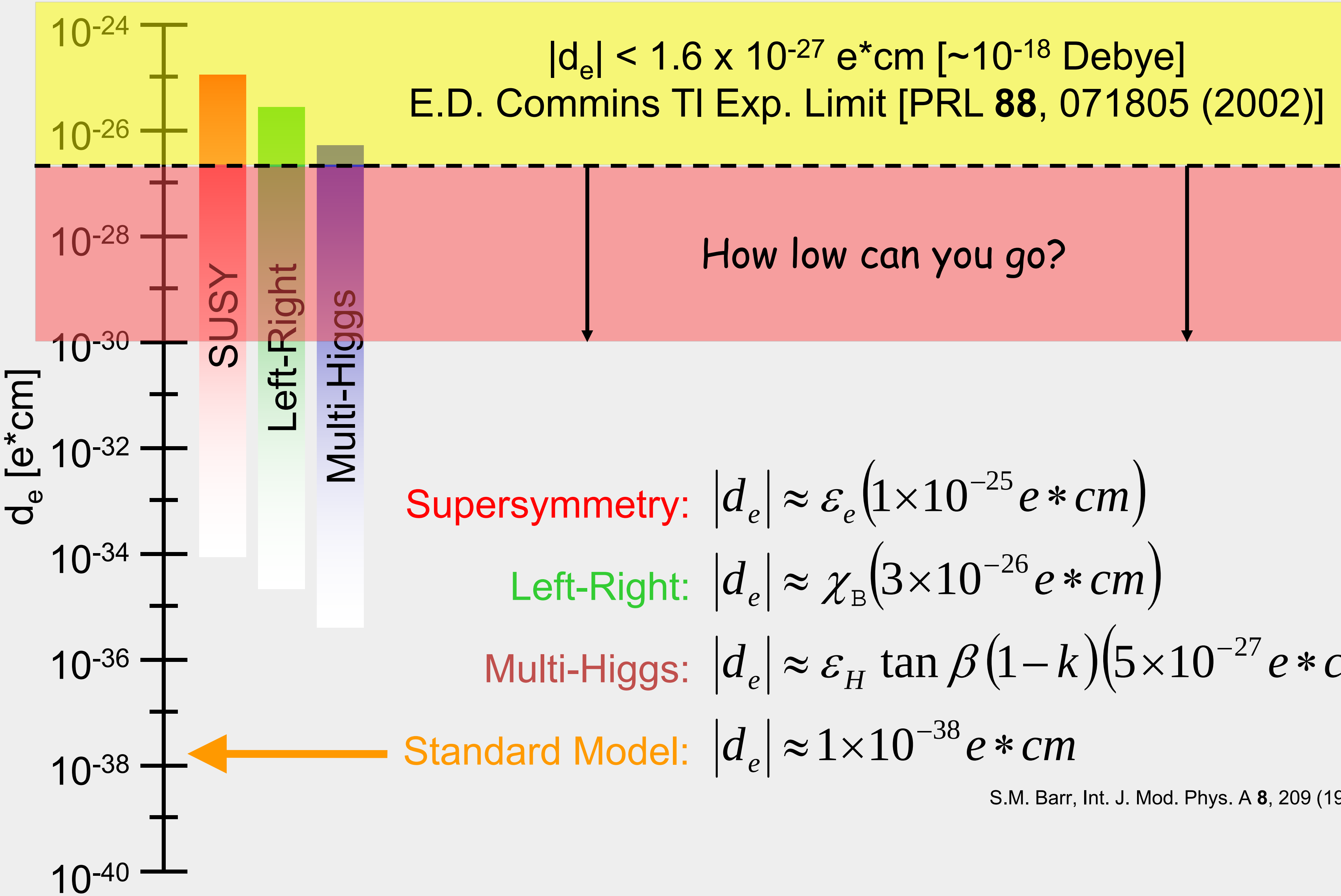
Left-Right: $\left|d_e\right| \approx \chi_B\left(3\times10^{-26}\,e*cm\right)$

Multi-Higgs: $\left|d_e\right| \approx \varepsilon_H \tan\beta\left(1-k\right)\left(5\times10^{-27}\,e*cm\right)$

Standard Model: $\left|d_e\right| \approx 1\times10^{-38}\,e*cm$

S.M. Barr, Int. J. Mod. Phys. A **8**, 209 (1993).

Extensions to the Standard Model



Supersymmetry: $|d_e| \approx \varepsilon_e \left(1 \times 10^{-25} e * cm\right)$

Left-Right: $|d_e| \approx \chi_B \left(3 \times 10^{-26} e * cm\right)$

Multi-Higgs: $|d_e| \approx \varepsilon_H \tan\beta \left(1 - k\right)\left(5 \times 10^{-27} e * cm\right)$

Standard Model: $|d_e| \approx 1 \times 10^{-38} e * cm$

S.M. Barr, Int. J. Mod. Phys. A **8**, 209 (1993).

General Considerations

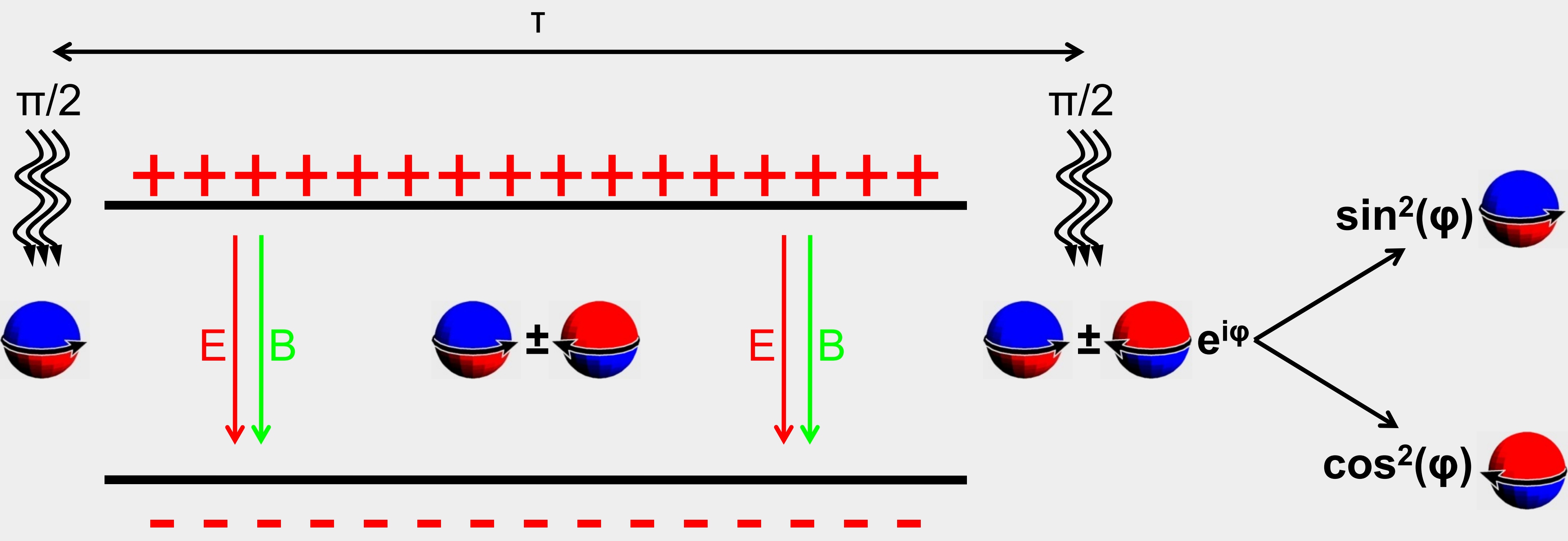
Resolution: $\Delta\nu = \frac{1}{2\pi\sqrt{N\tau}}$ Hz/√Hz

EDM Shift: $\Delta\nu = \frac{2d_e E_{eff}}{h}$ ~30 mHz [d_e ~ 10^{-27} e*cm, E_{eff} ~ 60 GV/cm]

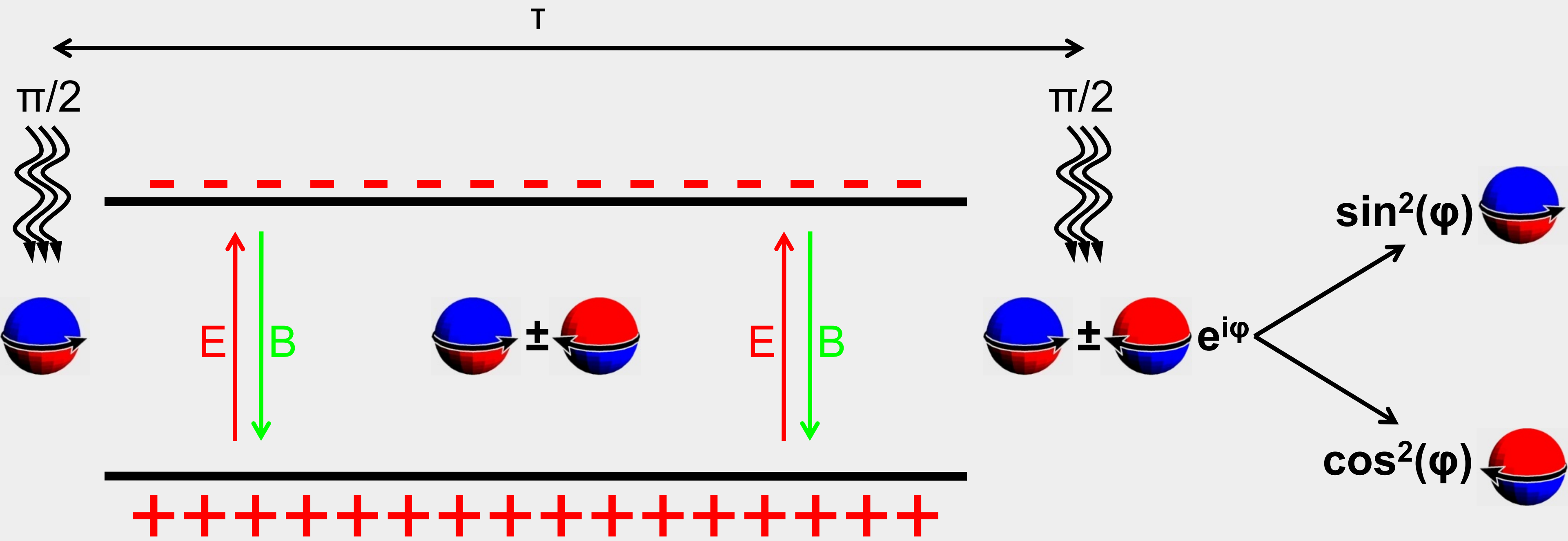
Zeeman Shift: $\Delta\nu = \frac{2\mu_B B}{h}$ ~1 kHz [for B ~ 1 mG]

- (v x E_{lab})/c^2 effects: ~15 mHz [v ~ 10^3 m/s, E_{lab} ~ 1 V/cm]
- leakage currents:

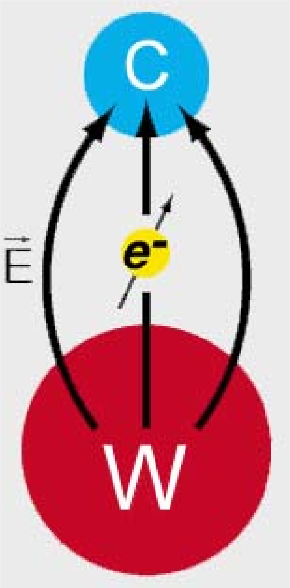
Ramsey Method



Ramsey Method



Advantages of Molecules

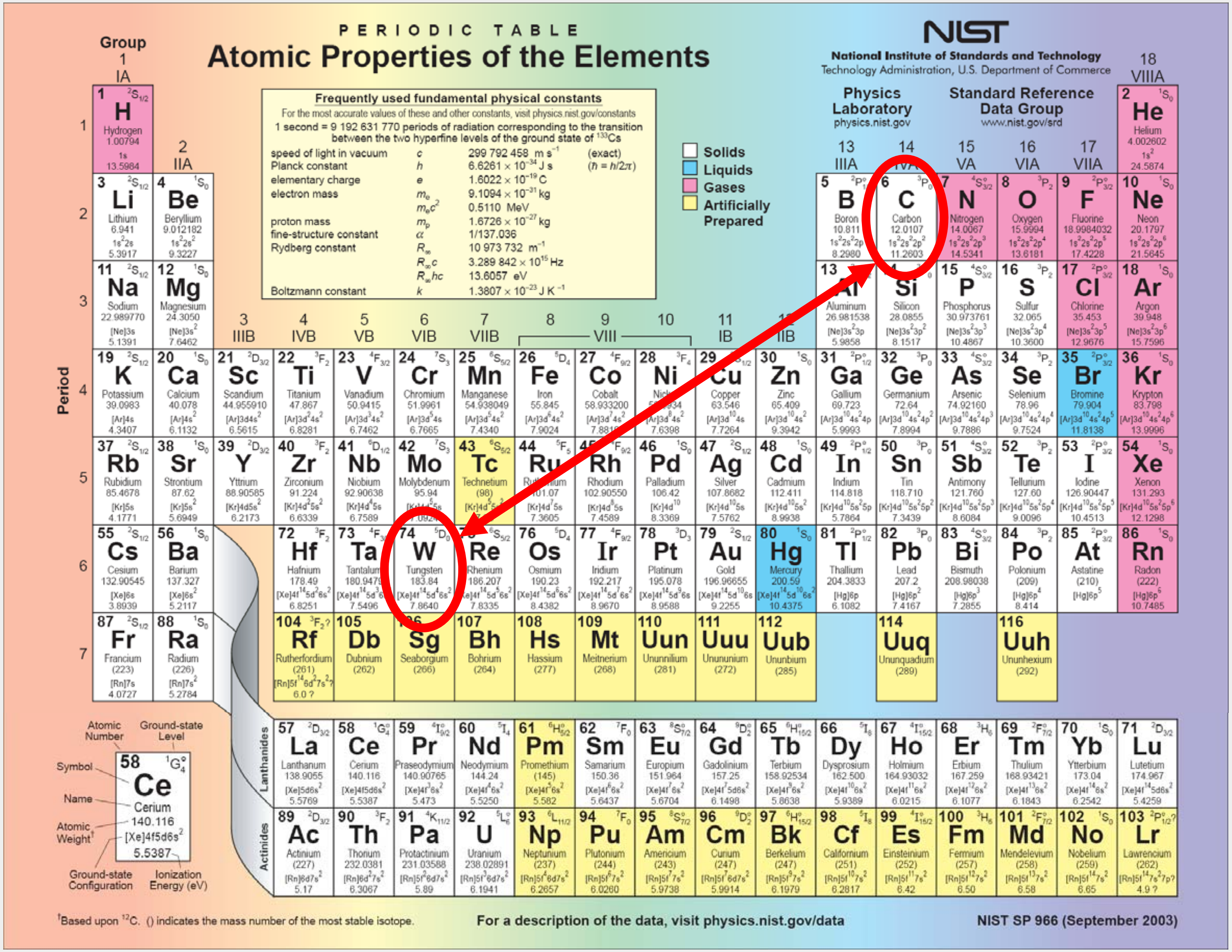


1. ***Large*** internal electric fields.
   - Effective E-field seen by e^-, $E_{eff} \sim 10^{10}$ V/cm.
   - Compared to ***maximum*** $E_{lab} \sim 10^5$ V/cm.
2. ***Accessible*** internal electric fields.
   - Easy to polarize, need only $E_{lab} \sim 1$ V/cm.
3. Rejection of systematic errors.
   - Magnetic field ***insensitive*** transitions.
   - E_{eff} ***independent*** of E_{lab}.

Molecules of Choice:

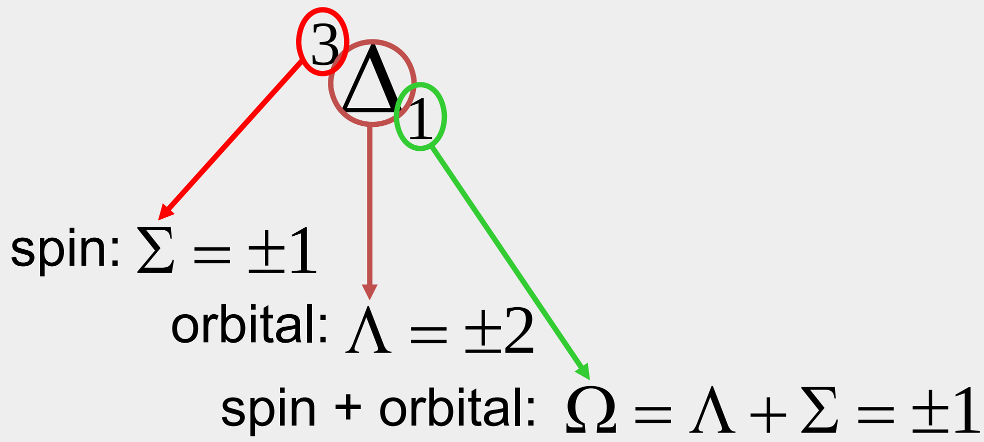
- Harvard: ThO
- Imperial College, London: YbF
- JILA: HfF^+
- Michigan: WC
- Oklahoma: PbF
- Yale: PbO

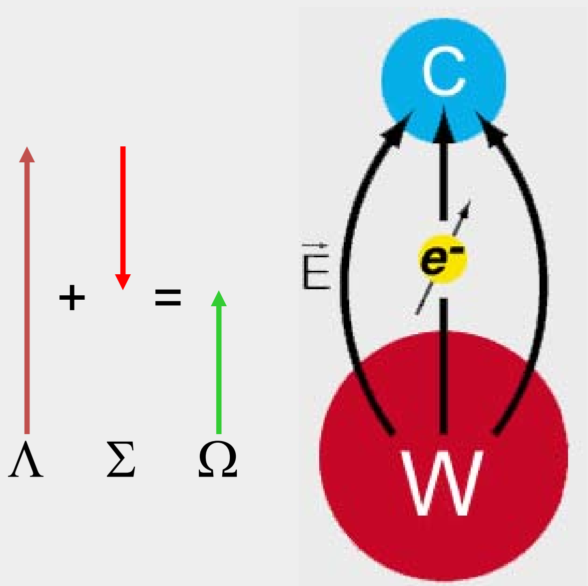
Tungsten Carbide

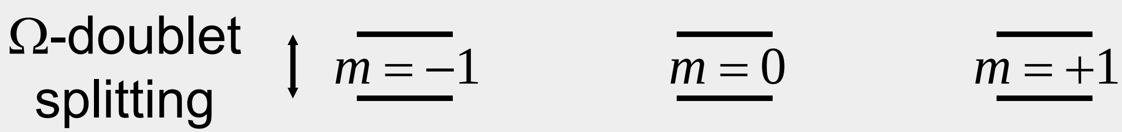


WC in the $^3\Delta_1$ State

- Net e^- spin: $|\Sigma|=1$
- Small magnetic moment: $\mu_m \ll \mu_B$
- W nucleus: I=0 & I=1/2 isotopes







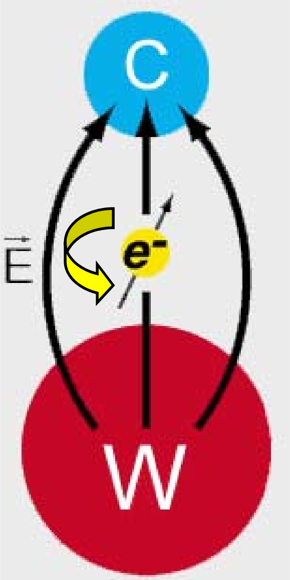
$^3\Delta_1$ e^- EDM Theory: Meyer *et. al.*, PRA **73**, 062108 (2006).

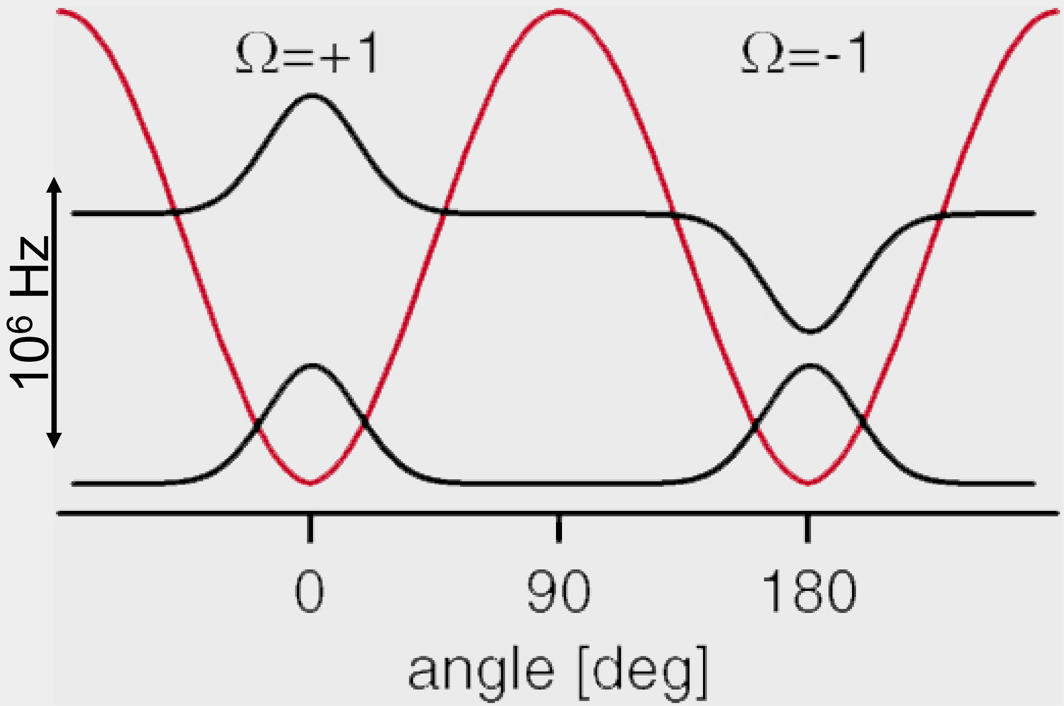
Polar Molecules

- Molecules do ***not*** have permanent electric dipole moments.
- Molecules do have closely spaced levels of opposite parity.
    - Ω-doubling ~10^6 Hz vs. s/p splitting ~10^{14} Hz in atoms.

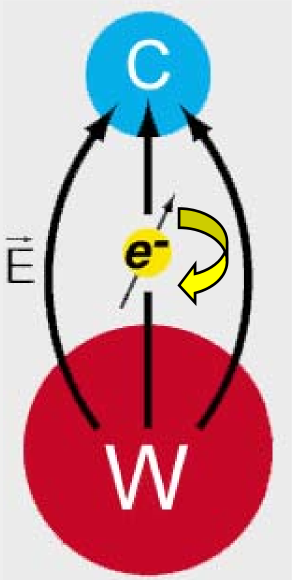
Ω = projection of e^- angular momentum along molecular axis.

Ω = +1



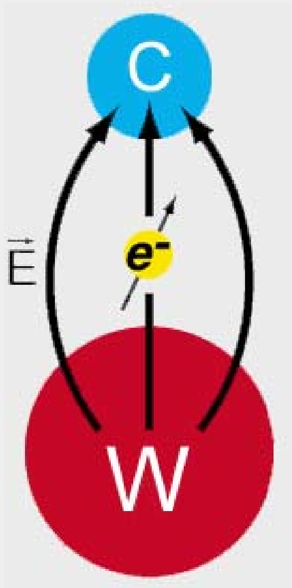


Ω = -1



Intramolecular Electric Fields

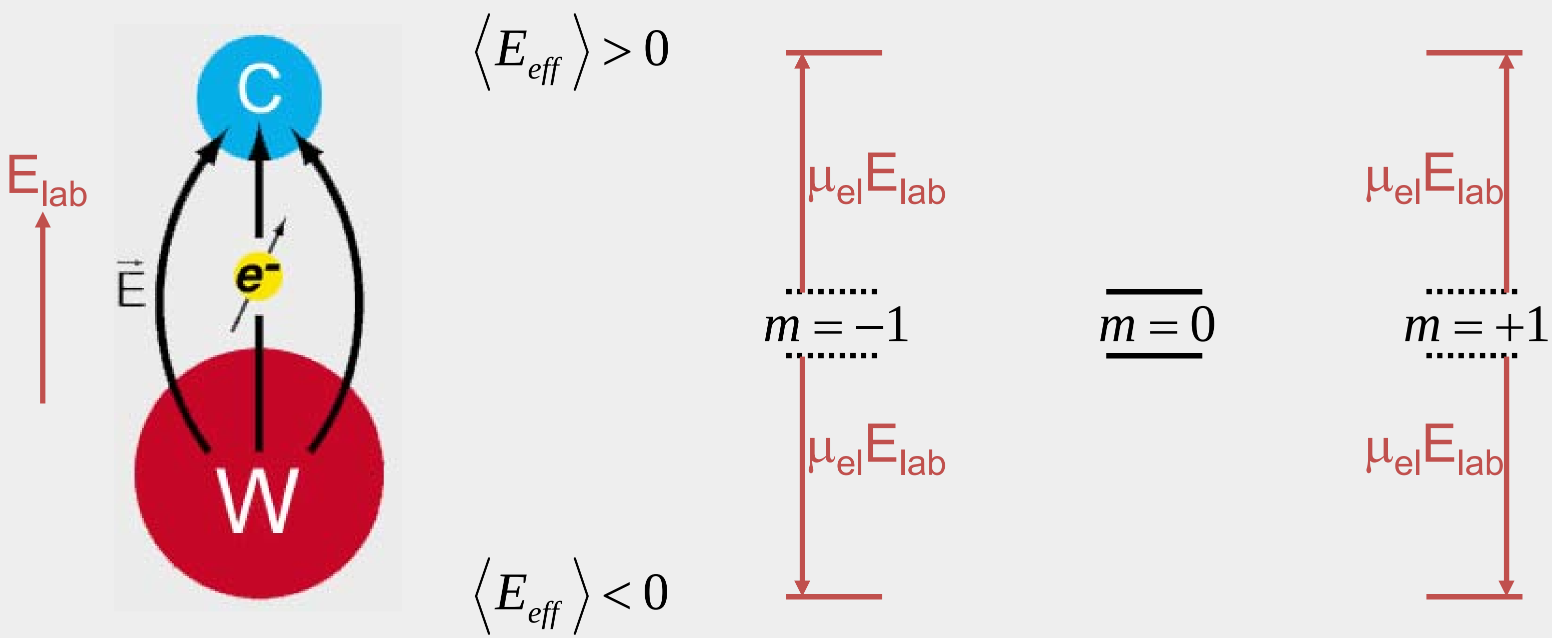
- E_{lab} mixes states of opposite parity inducing a net molecular dipole moment in the lab frame.
- Sign of E_{eff} is set by sign of induced molecular dipole moment.



$$\langle E_{eff} \rangle = 0 \qquad m = -1 \qquad m = 0 \qquad m = +1$$

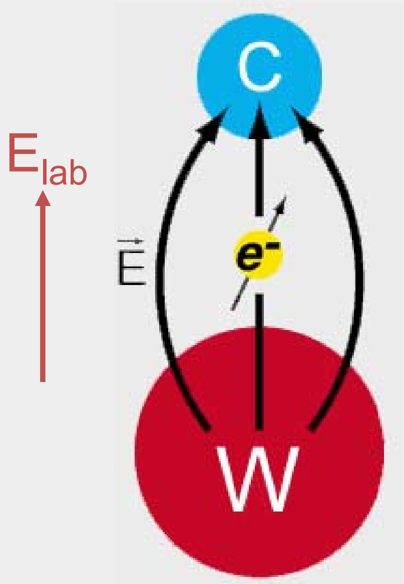
Intramolecular Electric Fields

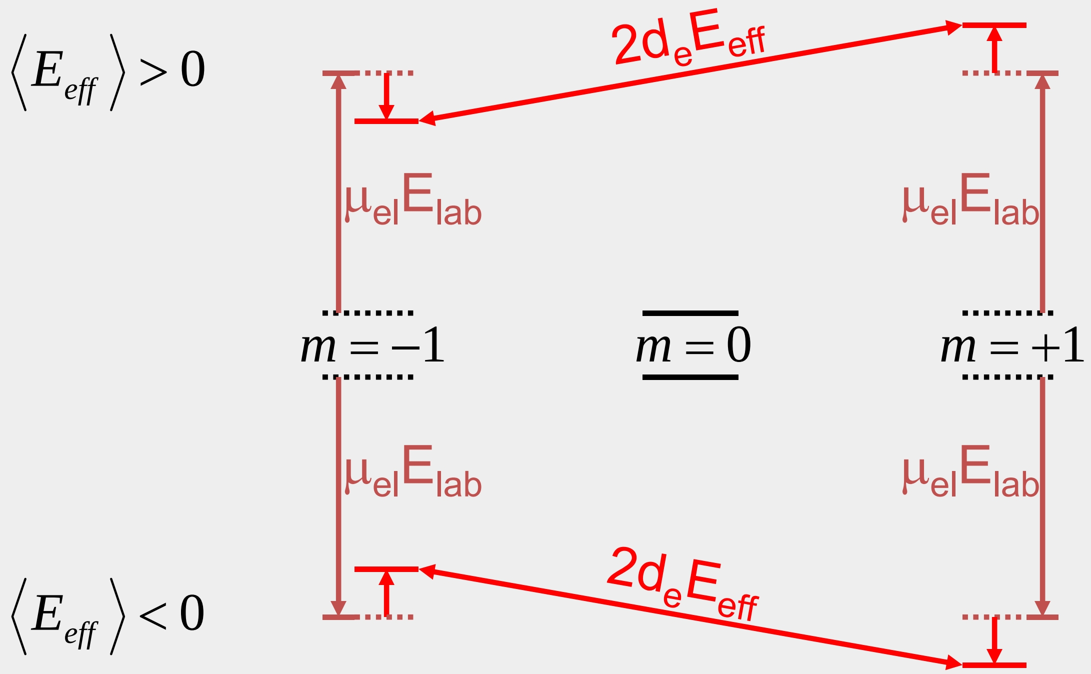
- E_{lab} mixes states of opposite parity inducing a net molecular dipole moment in the lab frame.
- Sign of E_{eff} is set by sign of induced molecular dipole moment.



Intramolecular Electric Fields

- E_{lab} mixes states of opposite parity inducing a net molecular dipole moment in the lab frame.
- Sign of E_{eff} is set by sign of induced molecular dipole moment.

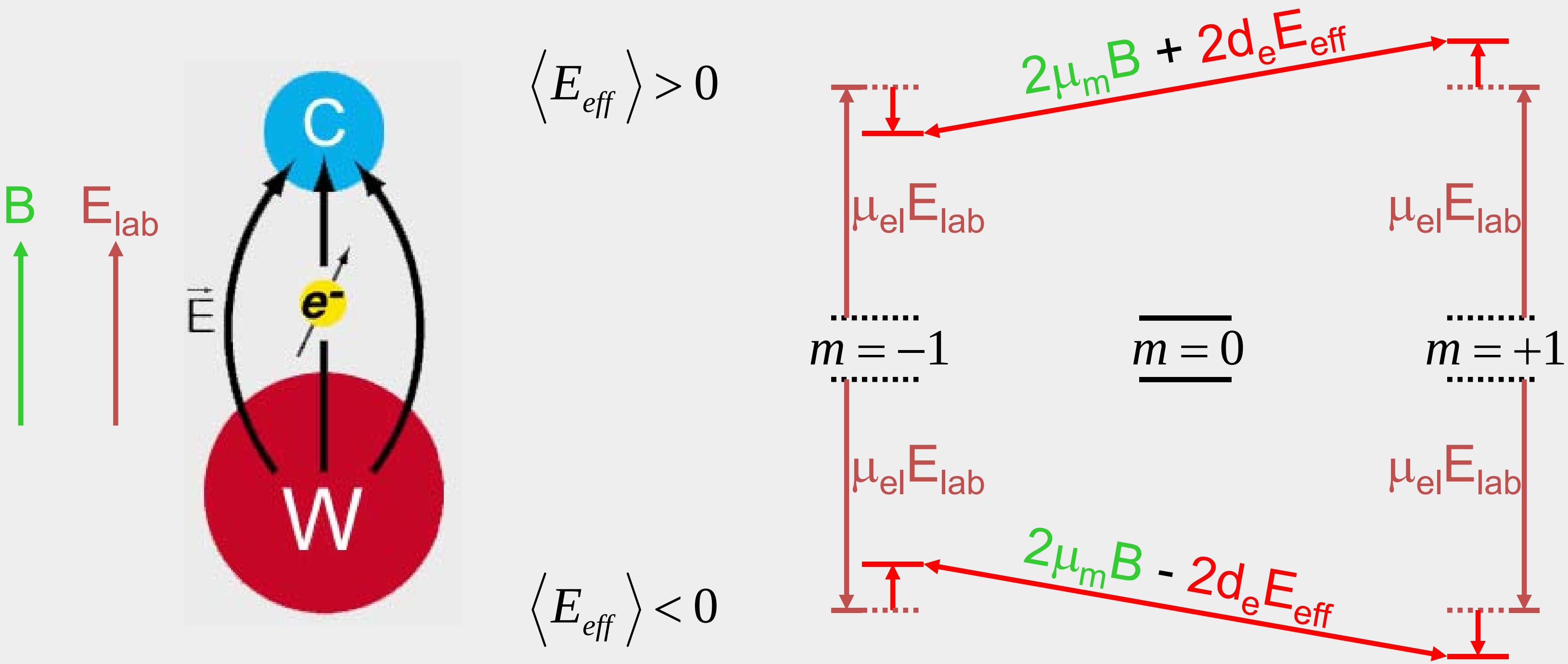




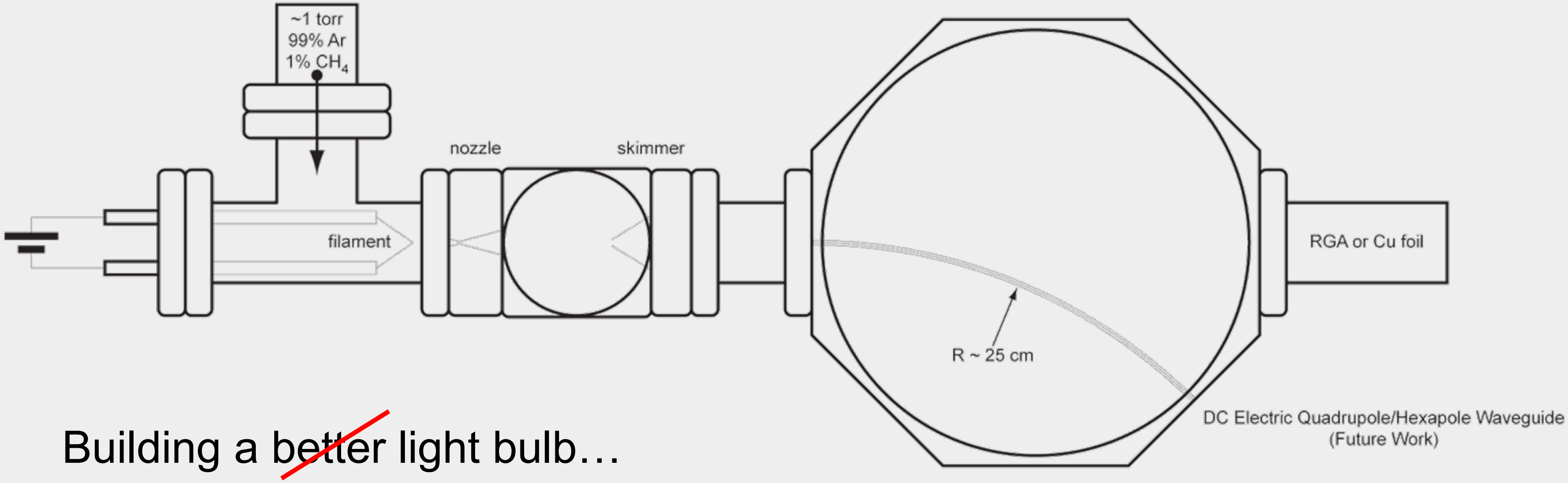
Systematic Checks

- Measure frequency splitting in both Ω-doublet levels.
  - Zeeman shift is ***common mode***.

- Vary magnitude of E_{lab}.
  - Linear Stark shift implies fully mixed states of opposite parity and E_{eff} nominally ***independent*** of E_{lab}.

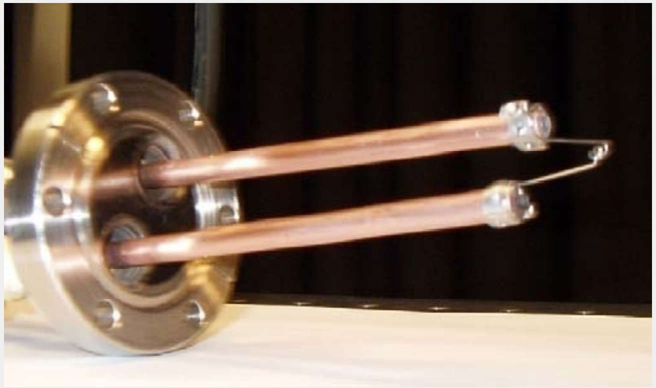


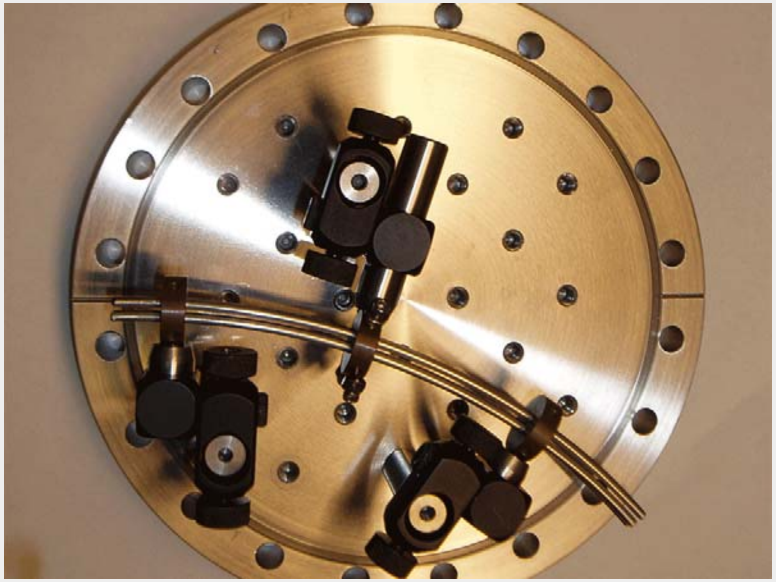
Tungsten Carbide Beamline



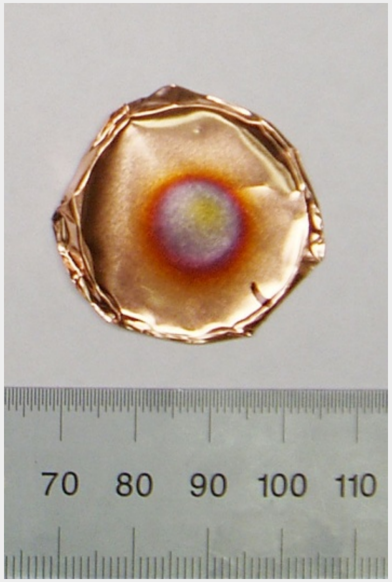
Building a ~~better~~ light bulb…

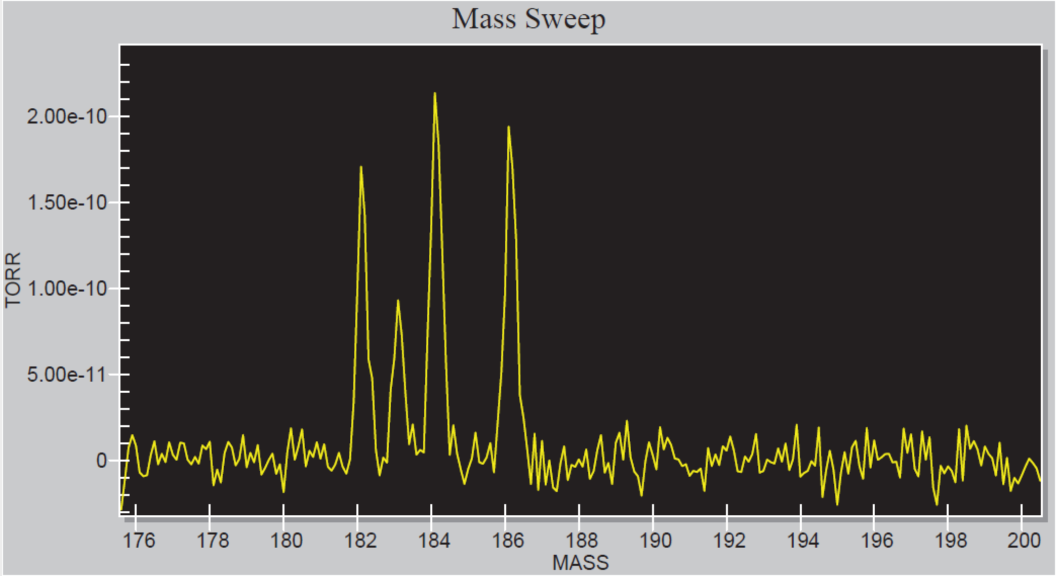
worse



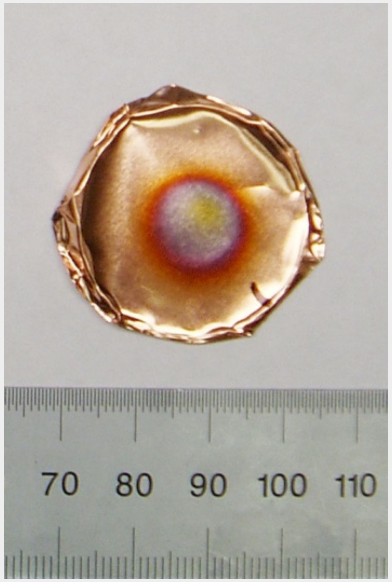


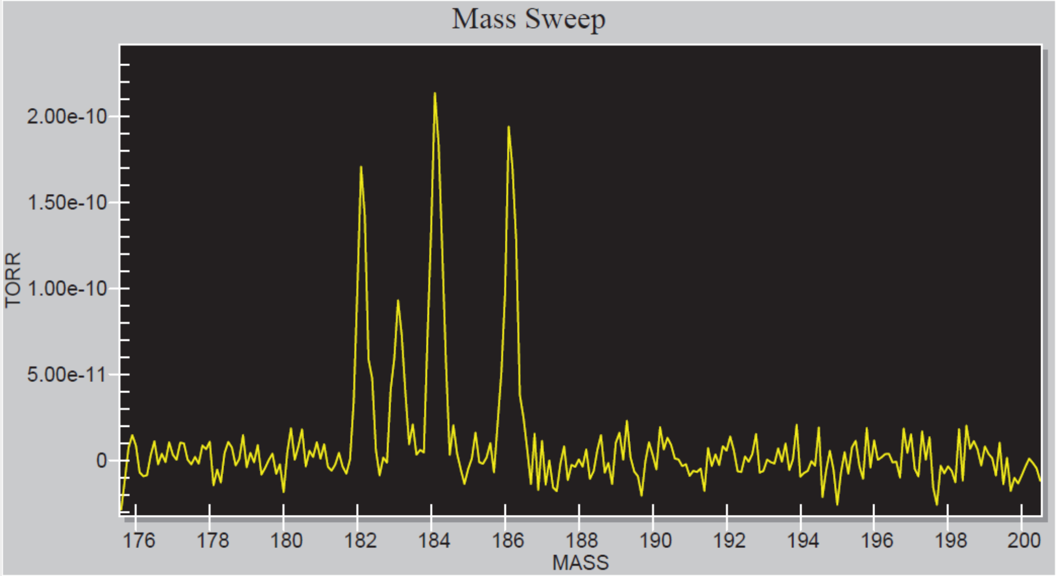
W Sputtering and Mass Spectrometry

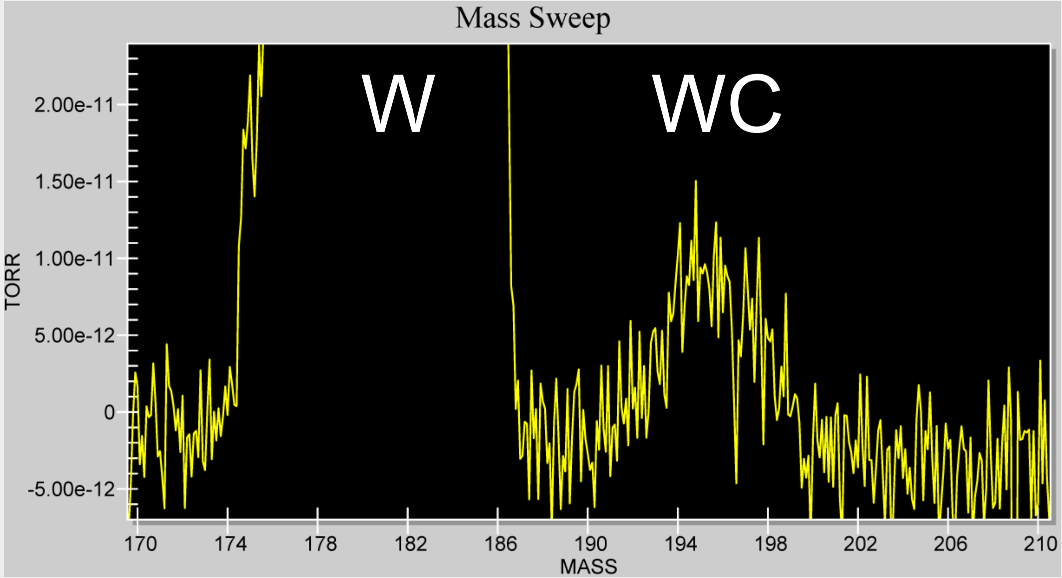




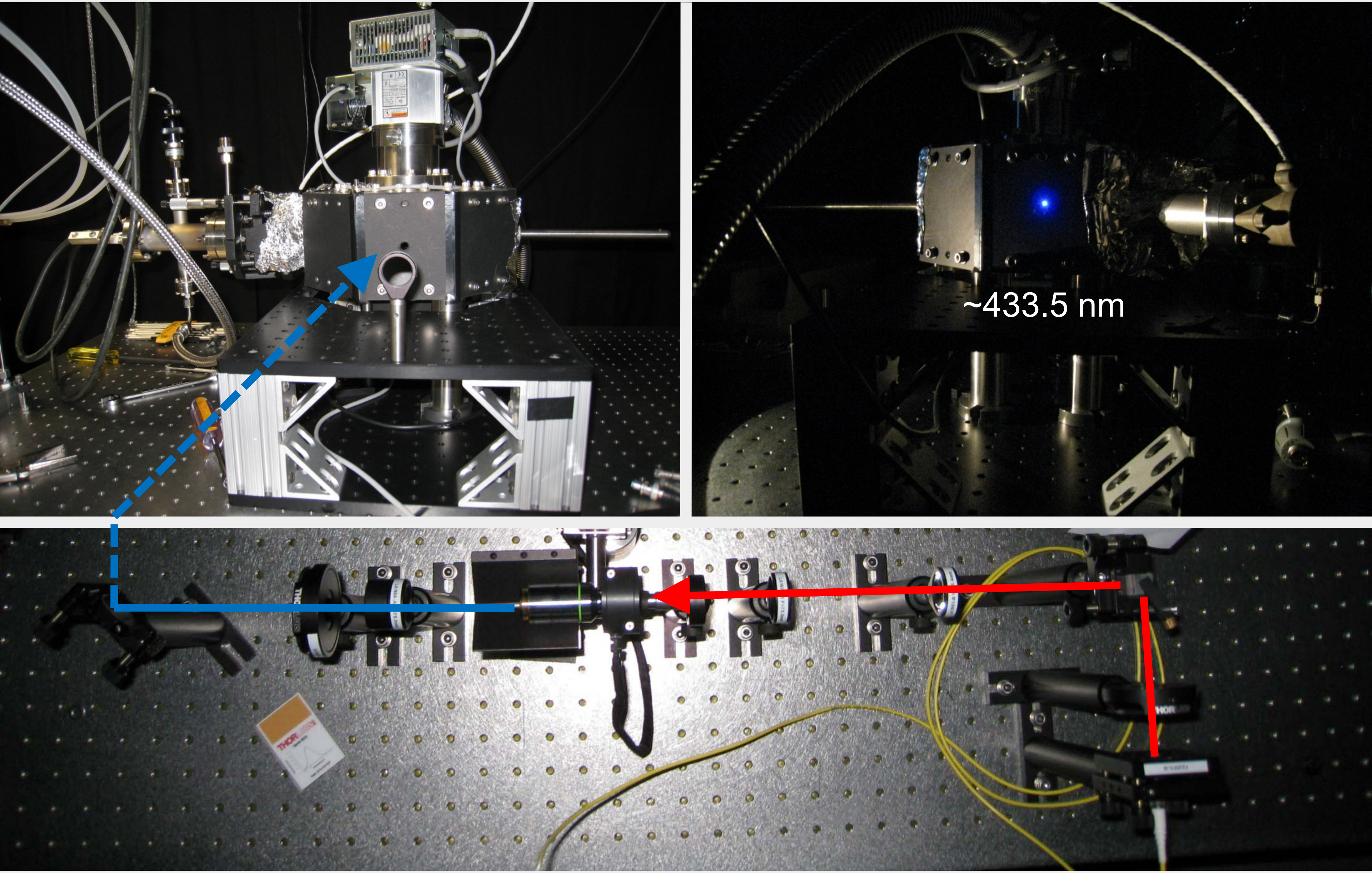
$W + CH_4 \rightarrow WC + 2H_2$



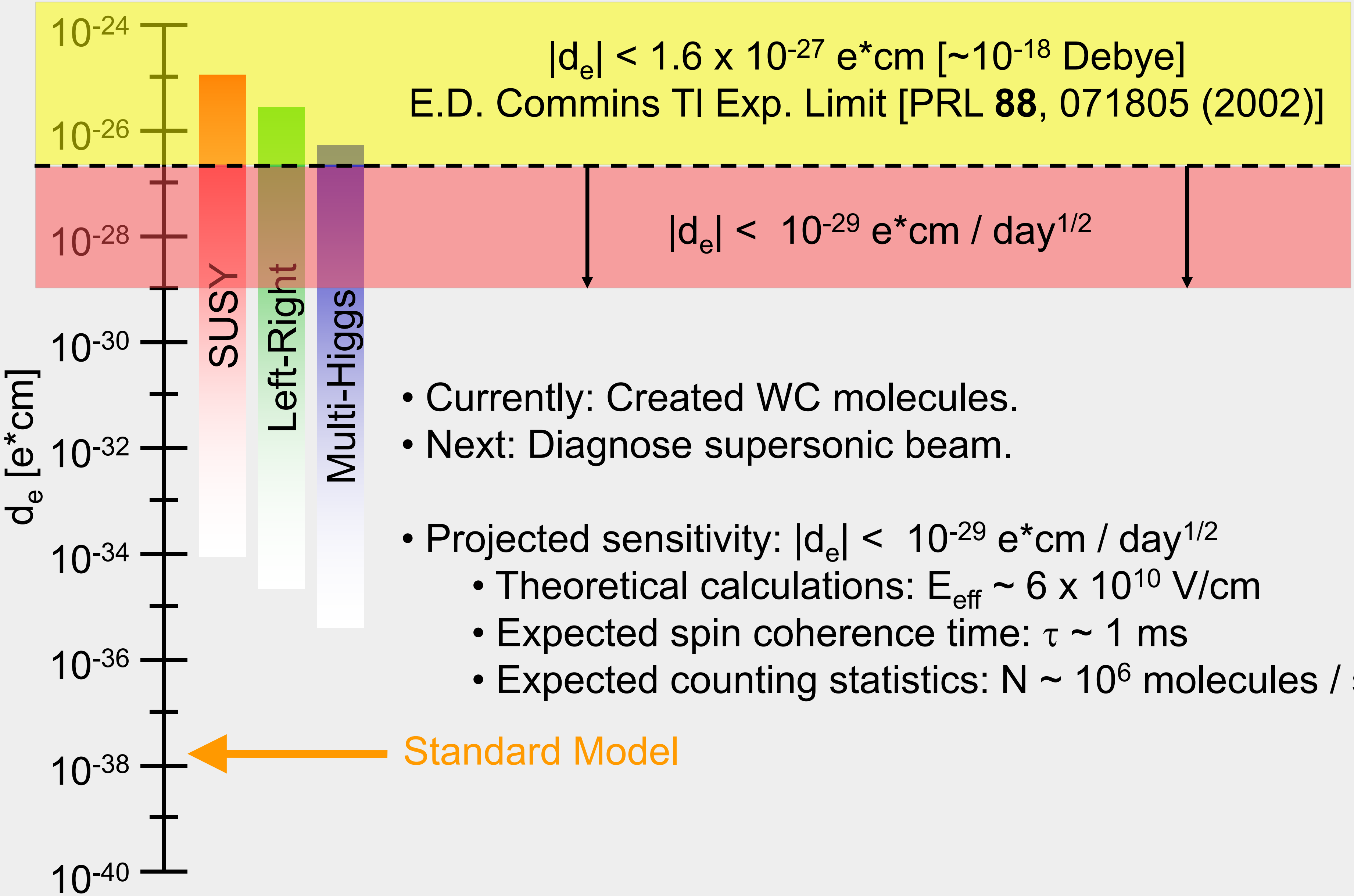




Optical Spectroscopy (in progress…)

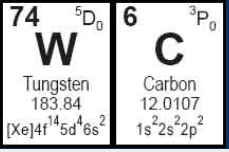


e^- EDM Search Outlook



- Currently: Created WC molecules.
- Next: Diagnose supersonic beam.

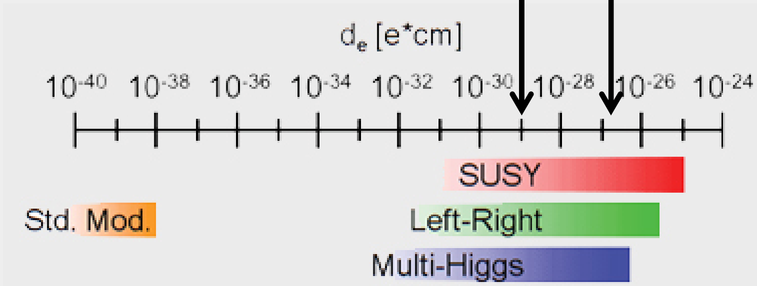
- Projected sensitivity: $|d_e| < 10^{-29}$ e*cm / day$^{1/2}$
  - Theoretical calculations: $E_{eff} \sim 6 \times 10^{10}$ V/cm
  - Expected spin coherence time: $\tau \sim 1$ ms
  - Expected counting statistics: $N \sim 10^6$ molecules / s



Tungsten Carbide e^- EDM Search

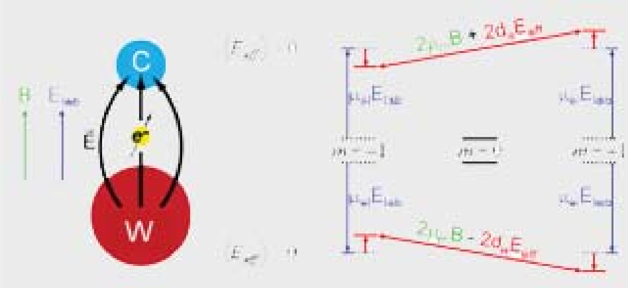
Motivation

Extensions to the Standard Model predict permanent electric dipole moments (EDMs) that are within experimental reach.



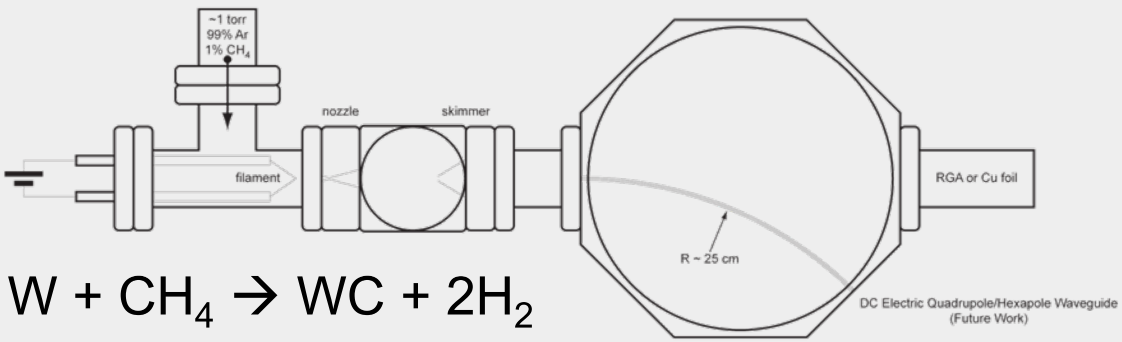
Technique

Precision spectroscopy in a WC molecular beam to search for an energy splitting between spin states that is proportional to an ***electric*** field.

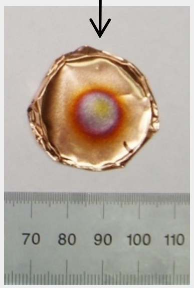


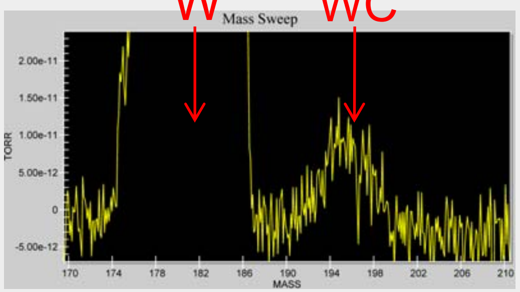
Progress

Beam diagnostics: sputtering & RGA



$W + CH_4 \rightarrow WC + 2H_2$





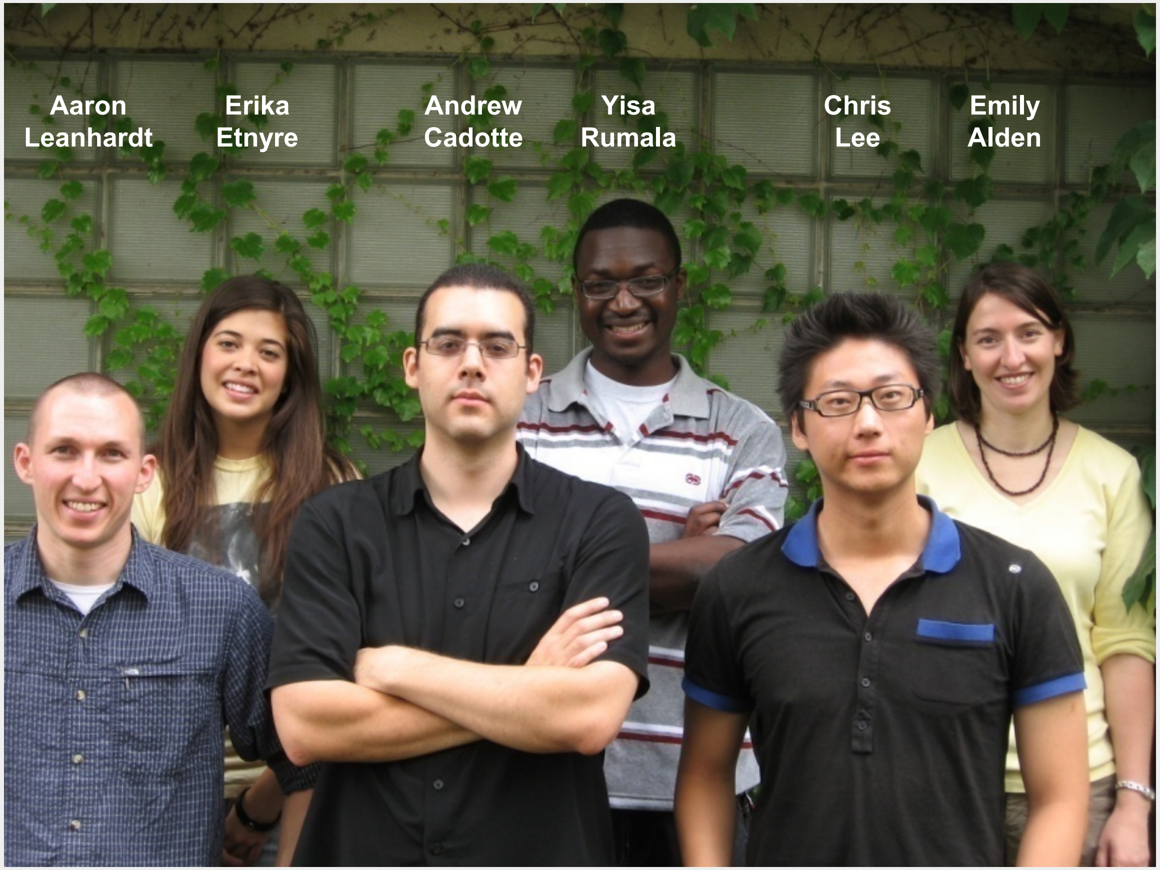
Group Members

Graduate Students: Emily Alden, Chris Lee, Yisa Rumala

Undergraduate Students: Andrew Cadotte, Erika Etnyre

Summer REU Student: Rabin Paudel

"Frosty the Jack-o-lantern"



Rabin Paudel