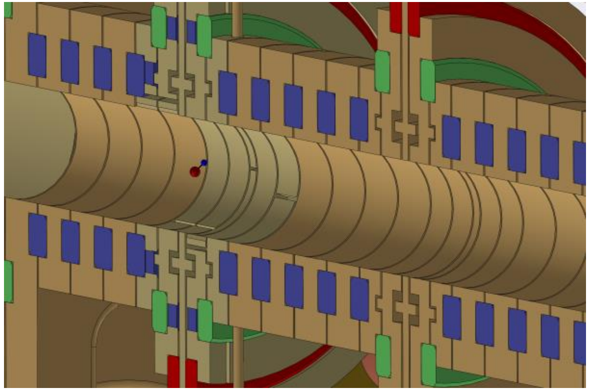
Measuring Electroweak Nuclear Properties using a Single Molecule in a Penning Trap

Massachusetts Institute of Technology

Scott Moroch— MIT Department of Physics

ECCTI Conference — 08/07/24



Outline

- Motivation
- Probing Electroweak Nuclear Structure using Molecules
- NEPTUNE project at MIT
- Status and Outlook

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$$\mathcal{O}(10^{-6})$$

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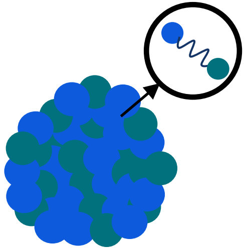
Nuclear Physics

Electroweak effects have been measured only in a single system (Cesium) with low precision



P-odd forces

Single atomic measurement in tension with accelerator experiments

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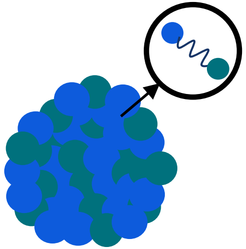

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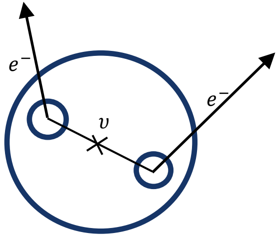
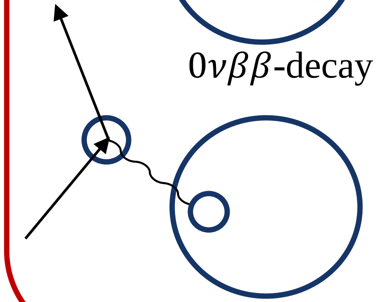
New Physics Searches

Electroweak forces are critical for understanding BSM processes



$0\nu\beta\beta$-decay



WIMP Detection

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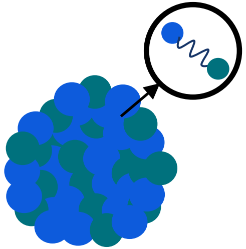

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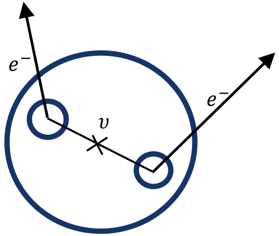

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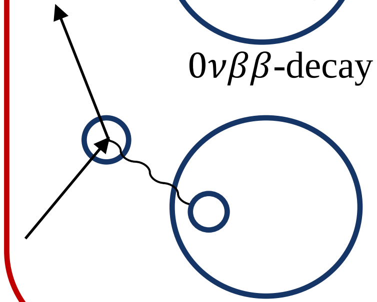
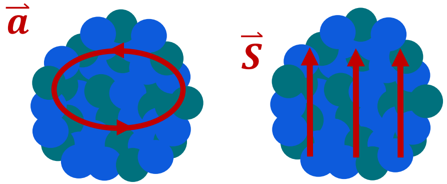


WIMP Detection

Fundamental Symmetries

CP violation is a critical ingredient to understand the observed matter – antimatter asymmetry

$$H_W = H_{PV} + H_{CPV} + ?$$



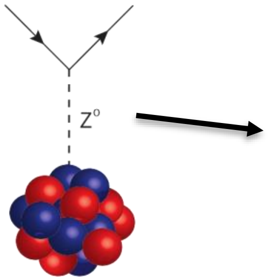
P-odd forces CP-odd forces

Searches for new sources of CP violation

Weak Interaction in Atomic System

- Weak Interaction in atomic/molecular systems arises from two dominant contributions

Z^0-exchange



Short range!
(<1 fm)

Nuclear Spin-Dependent ($I \neq 0$)

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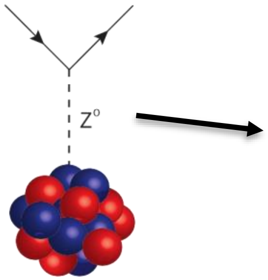

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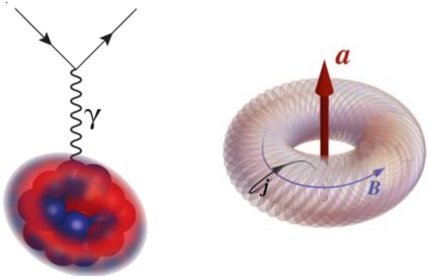
Nuclear Anapole Moment



Nucleon-nucleon, weak interactions within the nucleus give rise to a toroidal magnetic field

Figure from: M. S. Safronova, et. al. Rev. Mod. Phys., 90:025008, Jun 2018.

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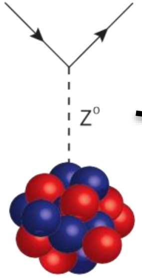

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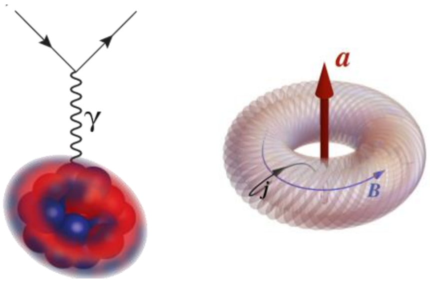

Nucleon-nucleon, weak interactions within the nucleus give rise to a toroidal magnetic field

$$H \sim (\eta_Z + \eta_{NAM})\vec{\alpha} \cdot \vec{I}\, \delta^3(\vec{r})$$

$\eta_{NAM} \to \sim A^{2/3}$

Figure from: M. S. Safronova, et. al. Rev. Mod. Phys., 90:025008, Jun 2018.

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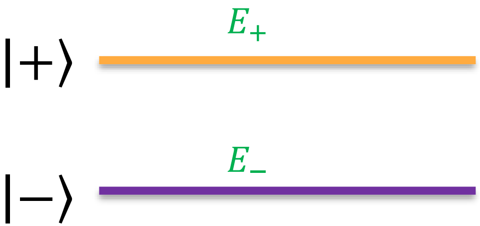
Weak-Induced State Mixing

- Consider any system in the absence of the Weak Interaction

The eigenstates of the Hamiltonian are states of **well-defined Parity**



$$H = \begin{pmatrix} E_- & 0 \\ 0 & E_+ \end{pmatrix}$$

Weak-Induced State Mixing

Consider this system in the presence of the Weak Force

Weak Force violates parity: $H(\vec{r}) \neq H(-\vec{r})$

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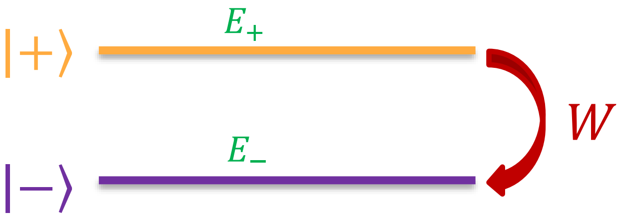

$$H = \begin{pmatrix} E_- & \langle -|H_{PV}|+\rangle \\ \langle +|H_{PV}|-\rangle & E_+ \end{pmatrix}$$

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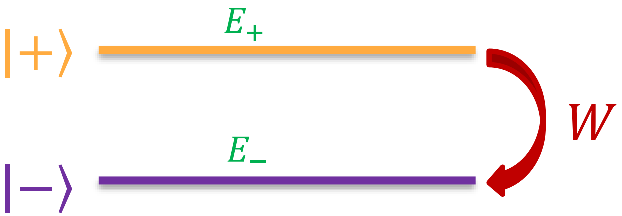

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Perturbation theory

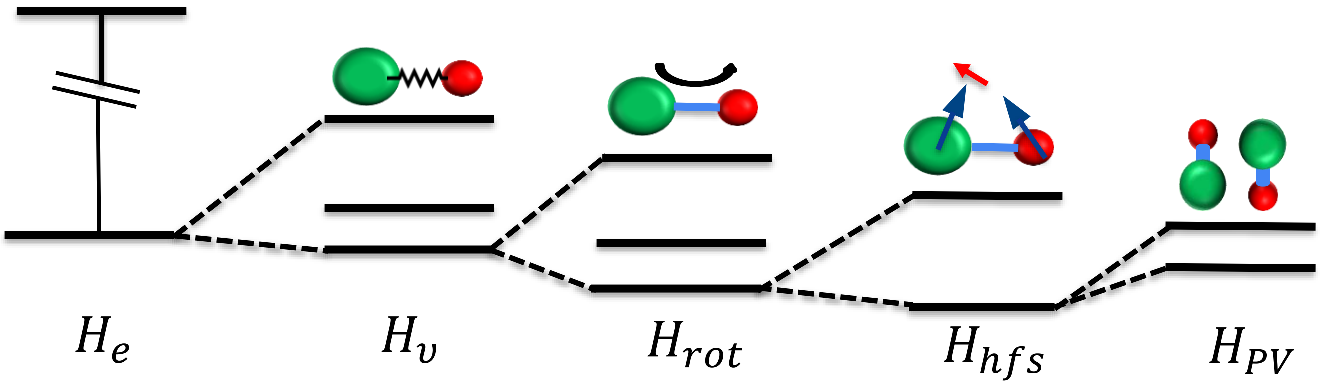
$$|+'\rangle = |+\rangle + \frac{\langle +|H_{PV}|-\rangle}{E_+ - E_-}|-\rangle$$

Mixing: $\frac{1}{\Delta}$

We want a system with a small Δ!

Why Molecules?

- Small energy splitting between rotational levels in a molecule→five order of magnitude enhancement to PV effects, relative to atoms



$$H_{mol} = H_e + H_v + H_{rot} + \cdots + H_{hfs} + H_{PV} + H_{PTV}$$

[eV] ~ 2 10^{-2} 10^{-5} 10^{-8} 10^{-12} 10^{-15}

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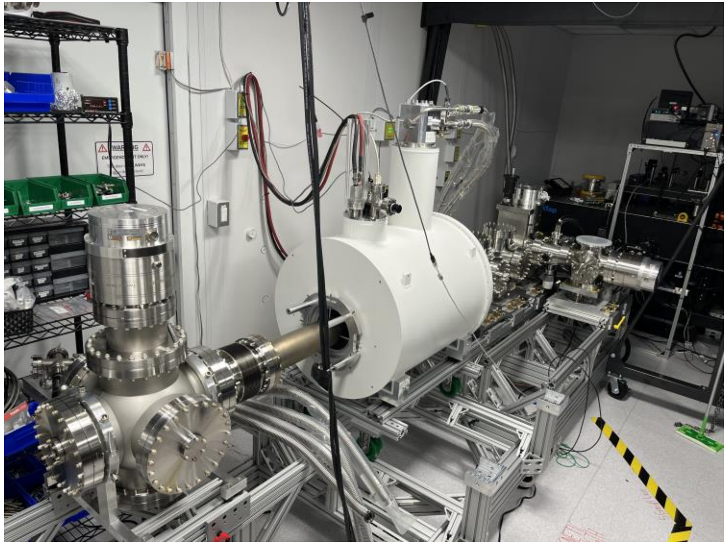
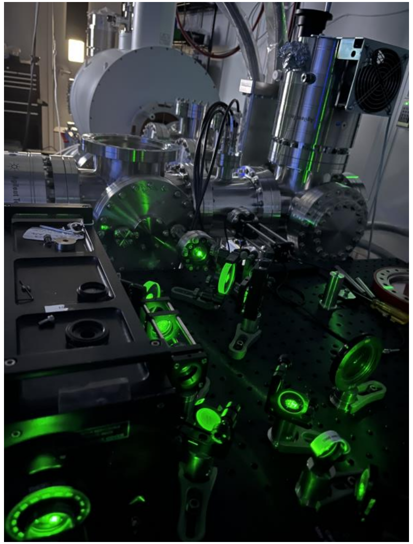
NEPTUNE Project

Nuclear Electroweak Measurements in a Penning Trap Using Near-Degenerate Energy States of Molecules





Accepted Paper

Electroweak nuclear properties from single molecular ions in a Penning trap

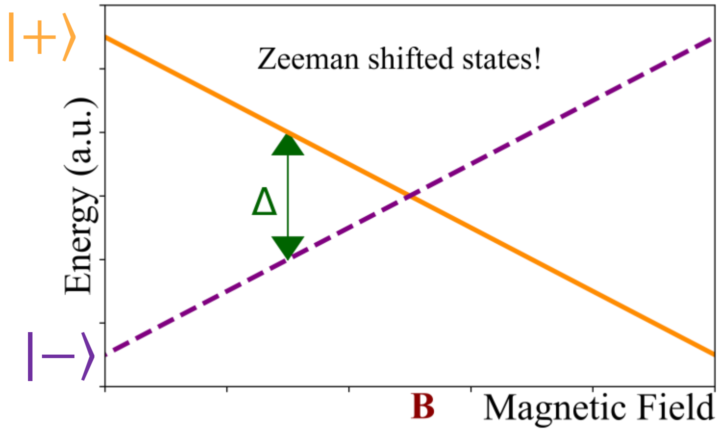
Phys. Rev. Lett.

J. Karthein, S. M. Udrescu, S. B. Moroch, I. Belosevic, K. Blaum, A. Borschevsky, Y. Chamorro, D. DeMille, J. Dilling, R. F. Garcia Ruiz, N. R. Hutzler, L. F. Pašteka, and R. Ringle

Accepted 18 April 2024

Measurements in a Penning Trap

Zeeman Shifting Molecular States



$$|+'\rangle = |+\rangle + \frac{\langle + | H_{PV} | - \rangle}{E_+ - E_-} |-\rangle$$

10^{11} enhancement of PV effects in Molecules!

Altuntaş, Emine, et al., Phys. Rev. Lett. 120.14, 142501 (2018)

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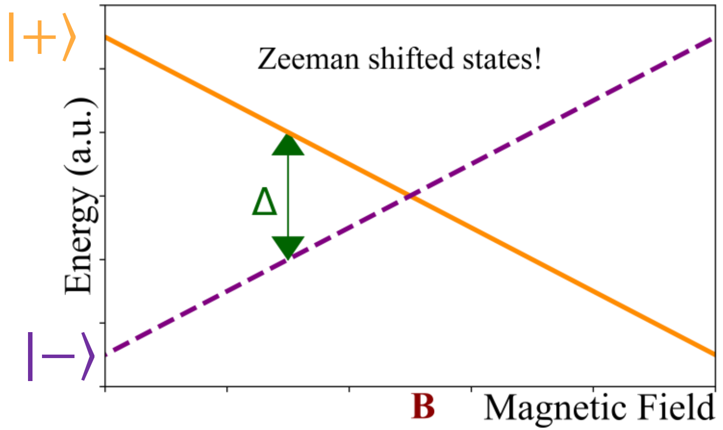

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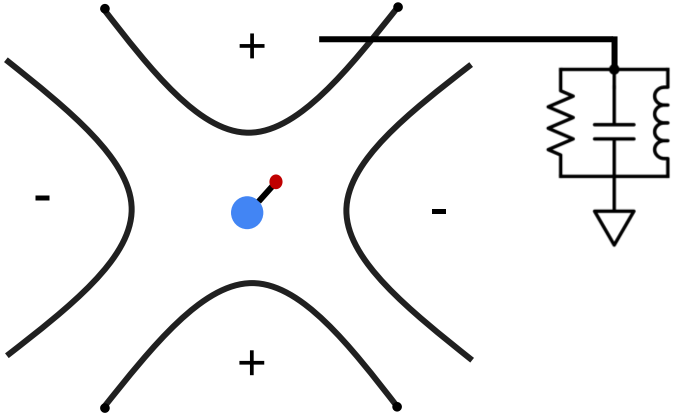
Motional Cooling and Coherence Time

Resistive and sympathetic cooling techniques enable low motional temperatures (≤4 K)

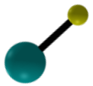


Coherence times of ms, compared to μs in a neutral beam experiment

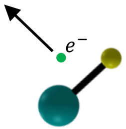
Altuntaş, Emine, et al., Phys. Rev. Lett. 120.14, 142501 (2018)

Experimental Procedure

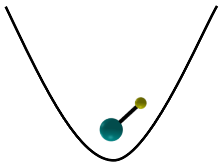
Molecule Formation



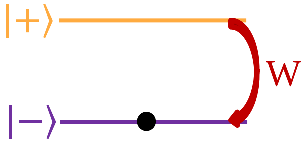
Ionization



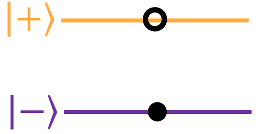
Trapping



Tuning

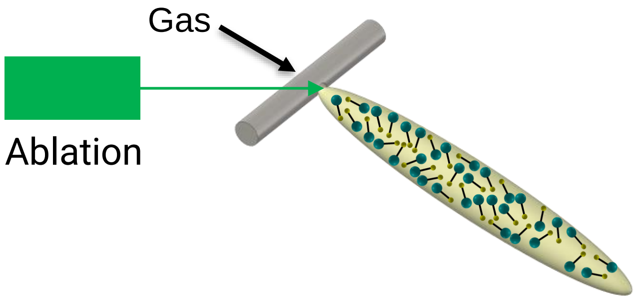


Counting



Molecule Formation

Supersonic expansion molecular source for producing rotationally cold molecules (N<20)



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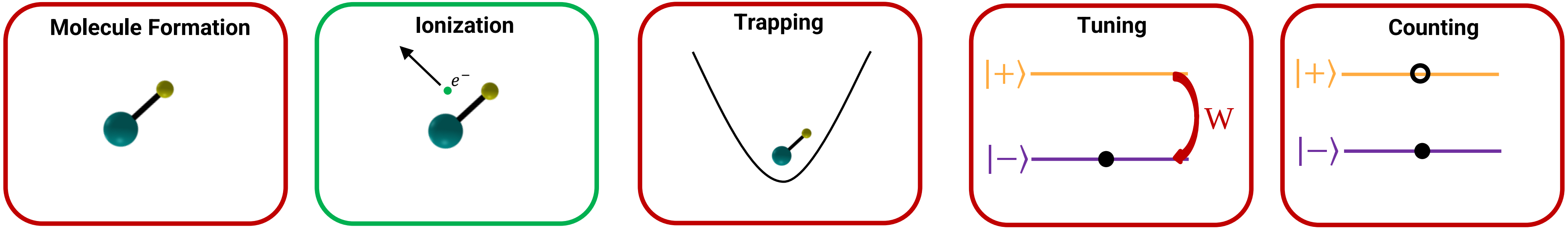
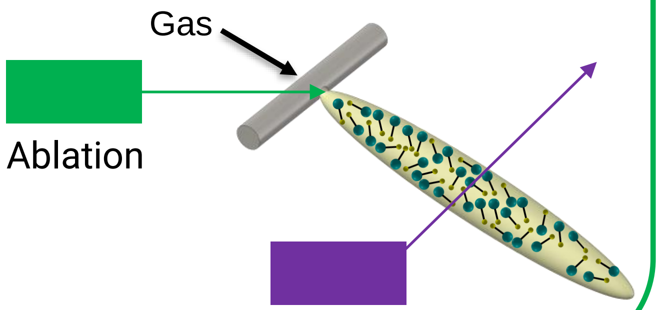


Resonant Photoionization

Resonantly ionize the molecules using a multi-step process



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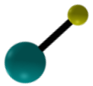

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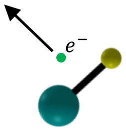

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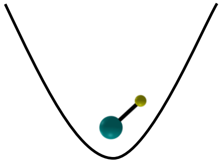

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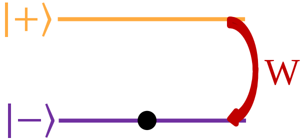

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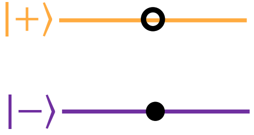
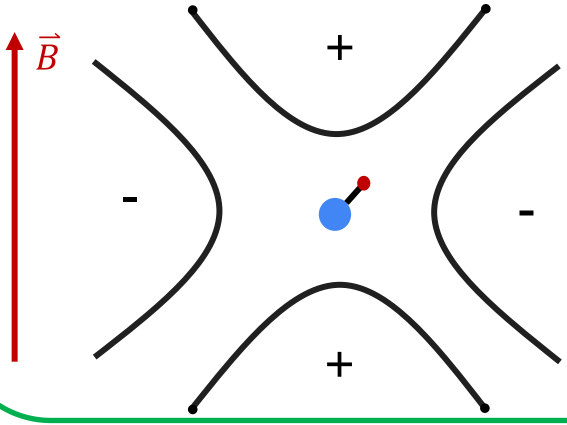


Trapping

Decelerate, trap and cool the molecules



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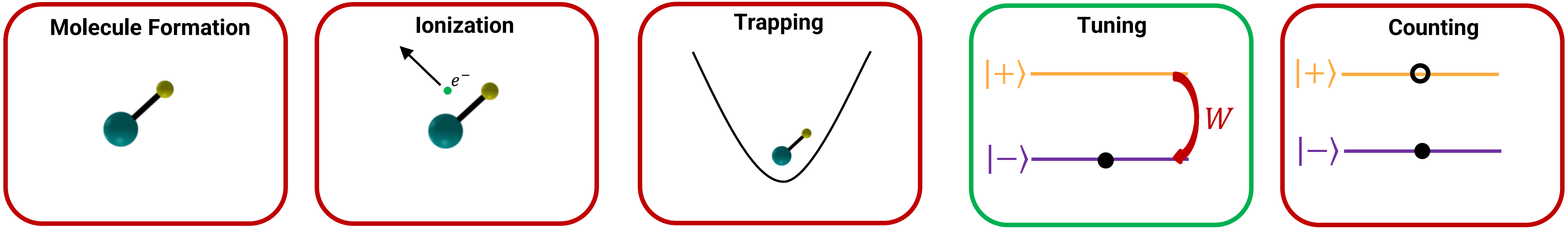
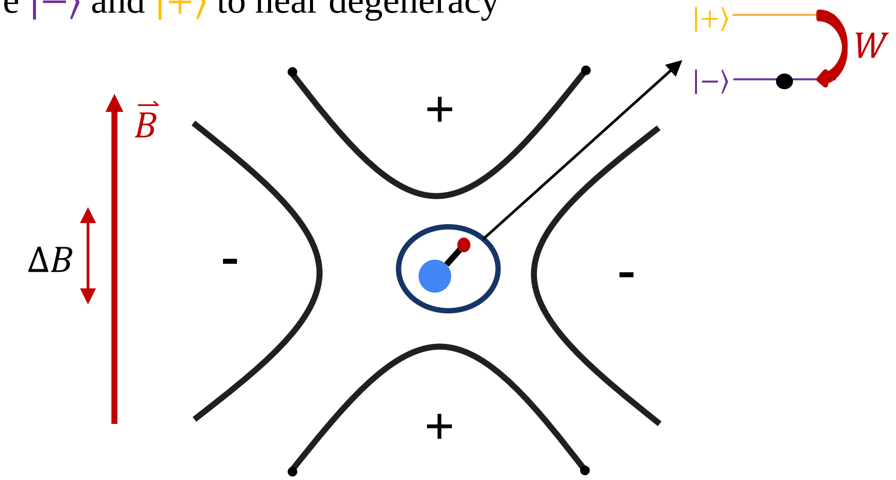


Tune Levels to Degeneracy

Drive $|-\rangle$ and $|+\rangle$ to near degeneracy



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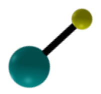

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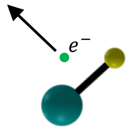

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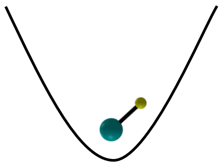

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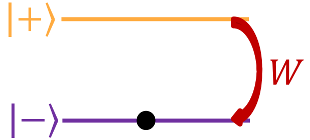

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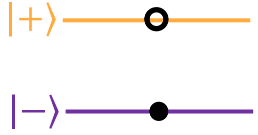
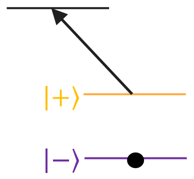
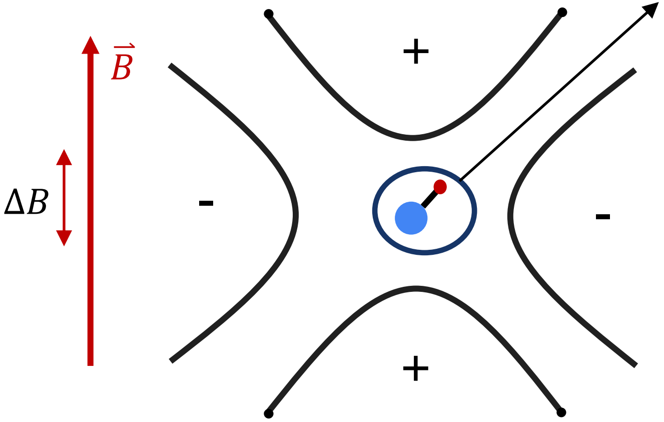


Counting

Measure population transfer between levels





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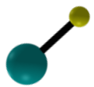

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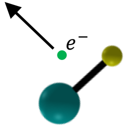

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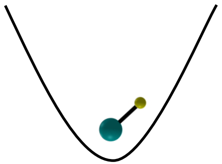

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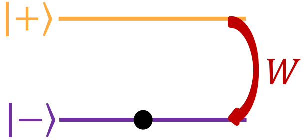

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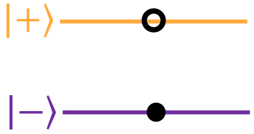
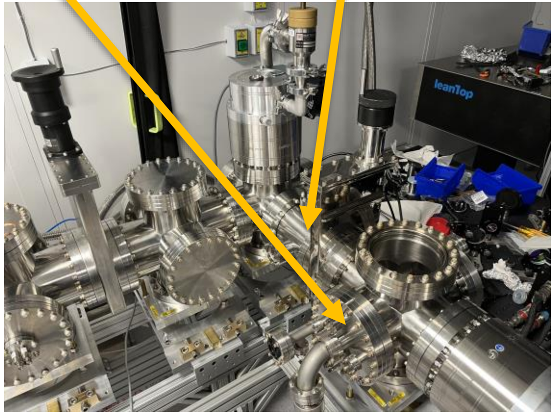
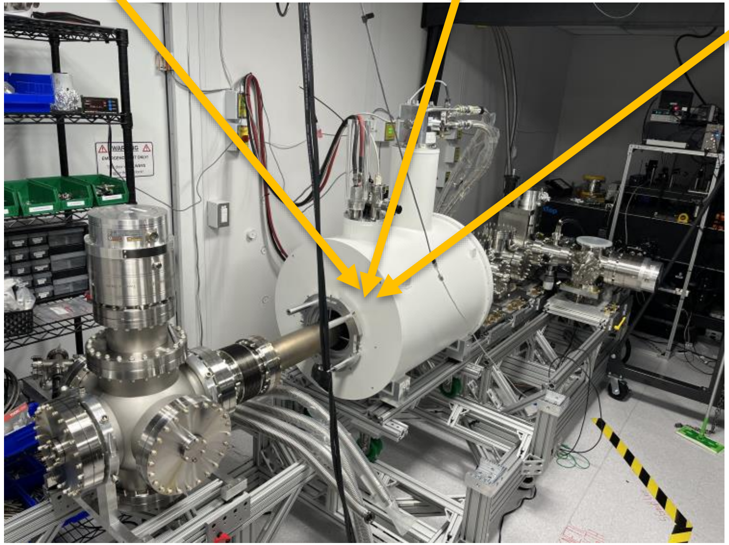
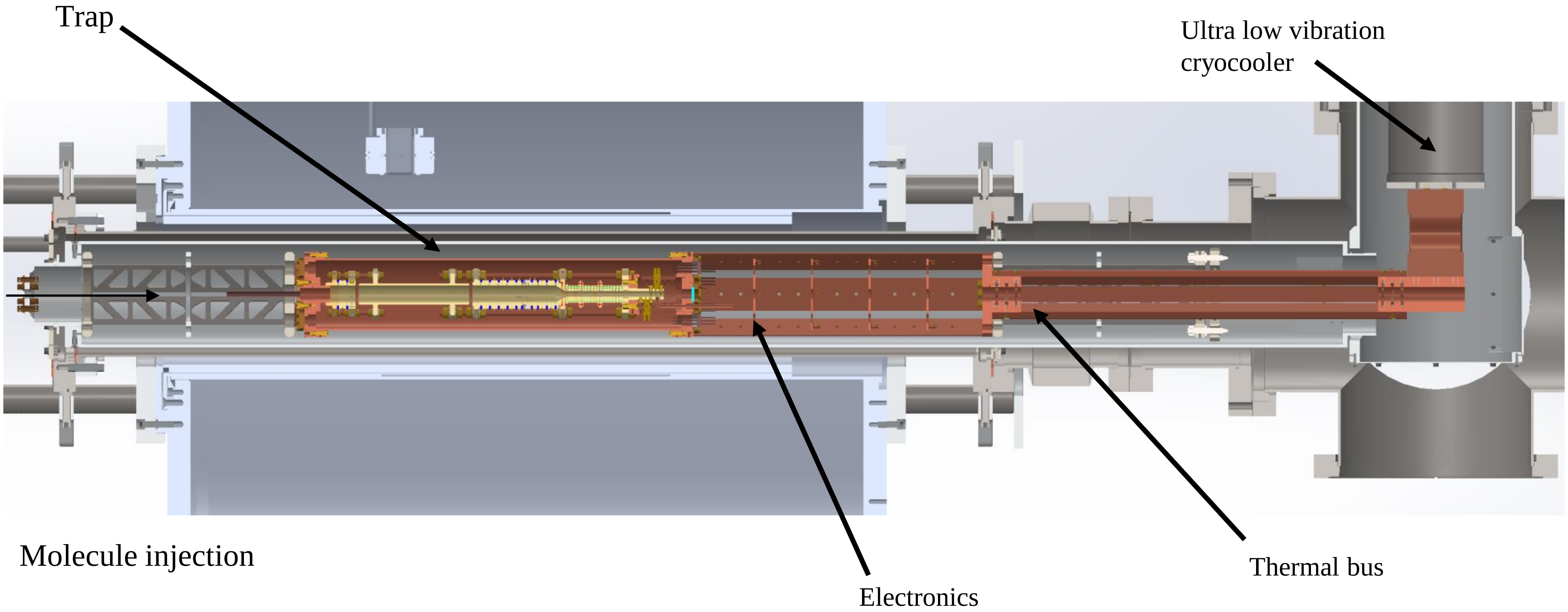


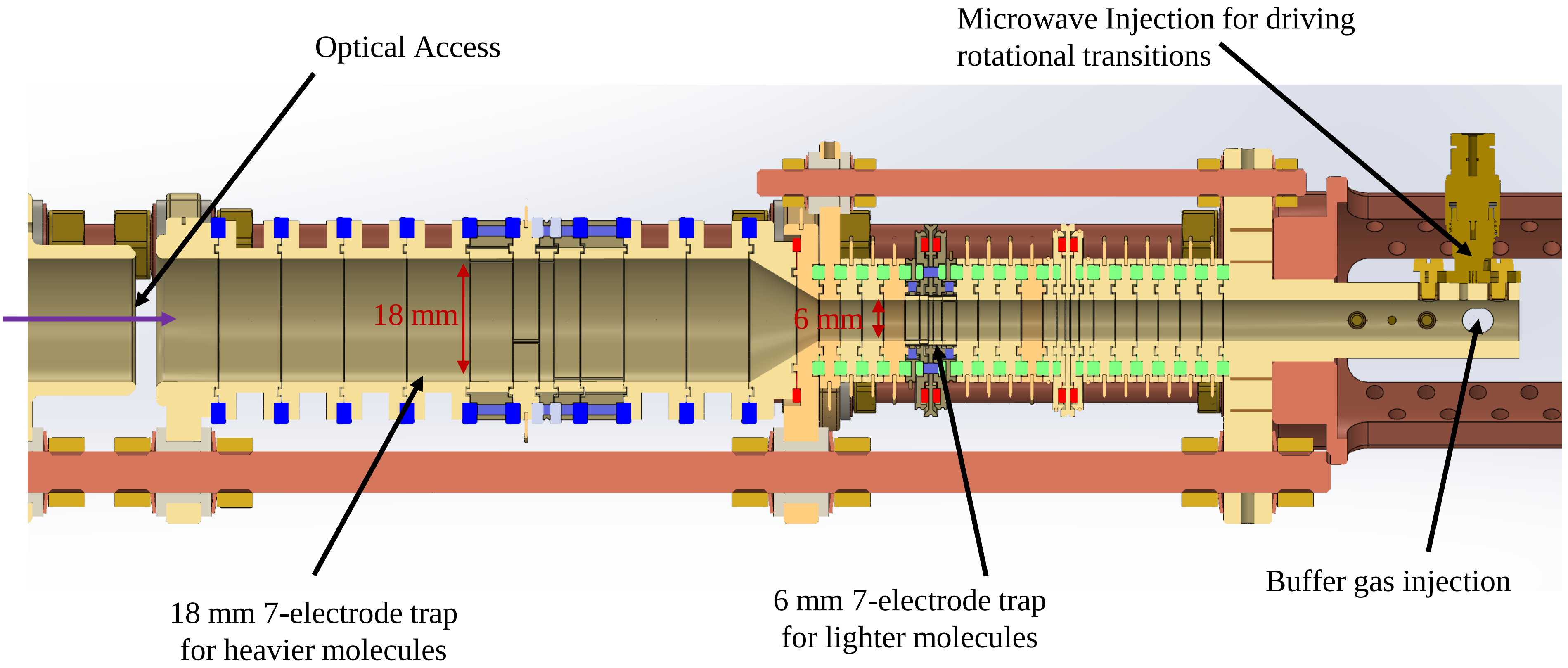




Penning Trap Design

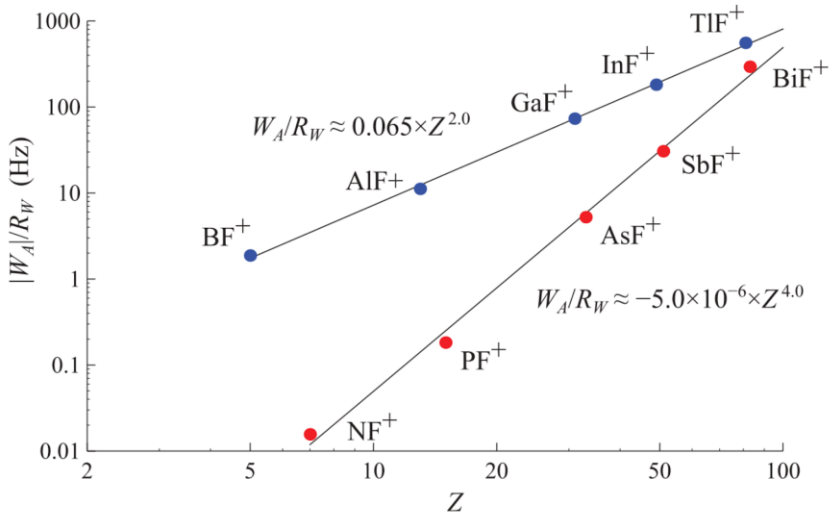


Penning Trap



Future Outlook

- To extract nucleon-nucleon electroweak interactions – must disentangle different contributions
- Rely on the scaling of different effects and studying in different nuclei
- Once demonstrated the experiment can be implemented at a radioactive ion beam facility
  - Generating and cooling single molecular ions is much simpler than neutral molecules



Borschevsky, A. *et al.* PRA 86, 050501(R) (2012).

Summary

- Electroweak properties of nuclei are poorly understood
- Molecules are very sensitive to parity-violating electroweak effects due to rotational levels
- We propose the use of a single ion in a Penning trap to measure these effects by the induced mixing between two states
- Experimental procedure is applicable across the nuclear chart

NEPTUNE Collaboration


Prof. Ronald Garcia Ruiz (MIT)


Silviu Udrescu (MIT)


Scott Moroch (MIT)


Haruka Kakioka (MIT)

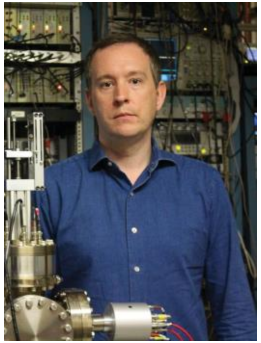

Dr. Jonas Karthein (MIT)


Prof. David DeMille (UChicago)


Prof. Nick Hutzler (Caltech)


Prof. Jens Dilling (Duke/ORNL)


Prof. Klaus Blaum (MPIK)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Dr. Xing Fan (Northwestern/Harvard)

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S. Ebadi


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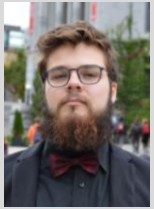
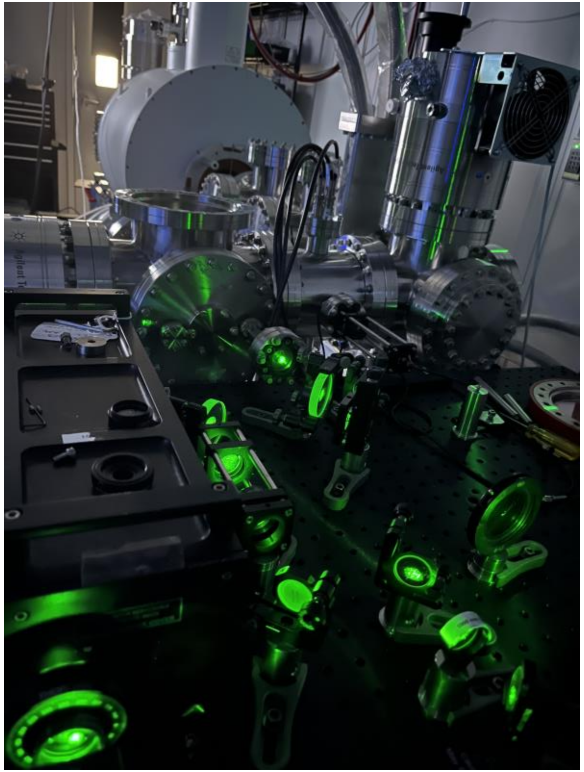

A. Belly

PI


R.F. Garcia Ruiz

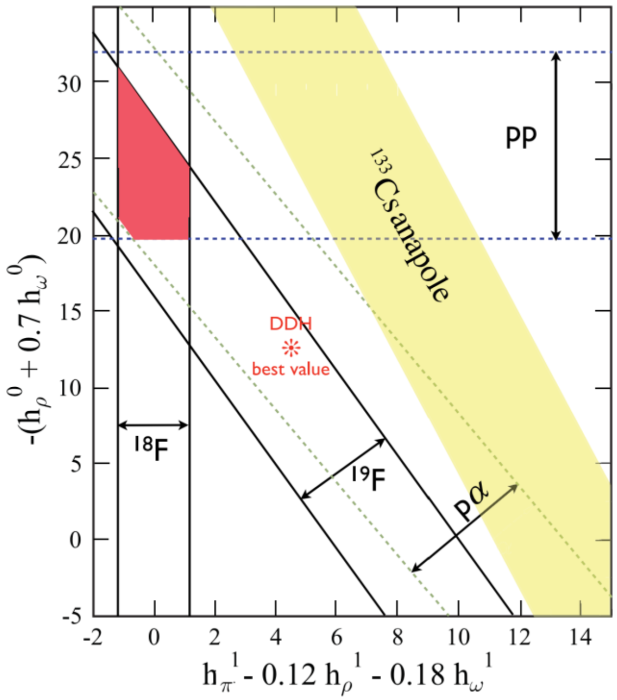
Bates Lab

Questions?



Backup Slides

Cesium Anapole Measurement



Details on Opposite Parity Mixing

- The QED Lagrangian governing AMO physics commute with P
- Considering this effect alone atoms conserve parity:
  - Easily seen by looking at an electric dipole E1 transition:

$$T_{fi}^{E1} = \langle \psi_f | D | \psi_i \rangle$$

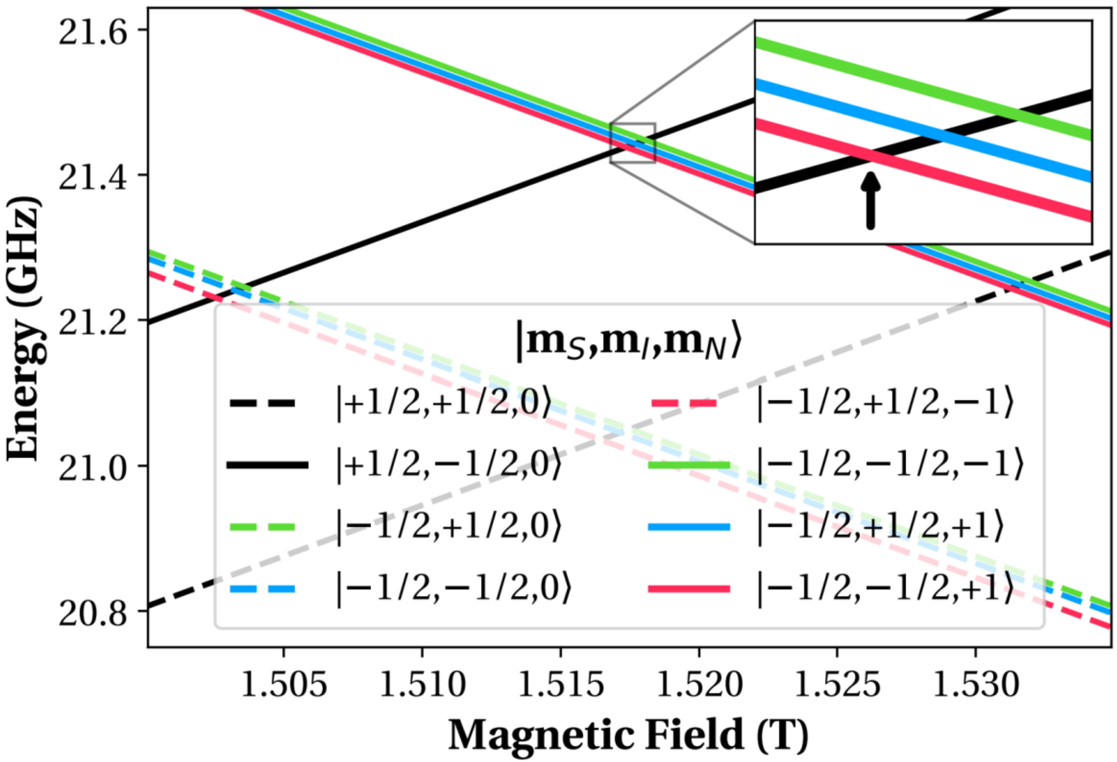
  - Insert the identity: $1 = P^{\dagger}P$

$$T_{fi}^{E1} = \langle \psi_f | P^{\dagger}P\, D | \psi_i \rangle$$

$$= -\Pi_f \Pi_i T_{fi}^{E1}$$

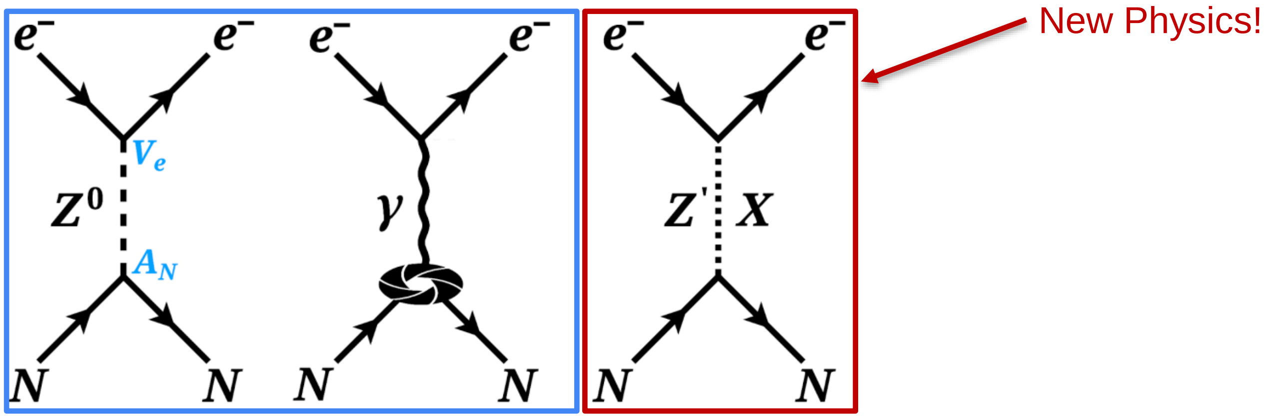
  - If the two states have the same parity then $T_{fi}^{E1} = 0$

Level Structure



New Force Searches

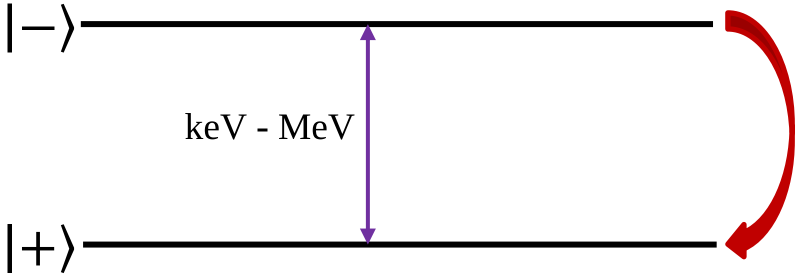
- Access to electroweak coupling parameters – few existing measurements with large uncertainties
- Constrain Standard Model contributions (Z-boson, Anapole moment, etc) – experiment provides avenue for 5th-force searches



Standard Model Effects   BSM

NN Weak Interactions - Macroscopic

- The nucleus has excited states and weak interactions will mix these levels



- The Anapole moment emerges as a P-odd moment that can exist only in the presence of this mixing

$$\vec{a} = \langle JM' | \vec{\boldsymbol{a}} | JM \rangle$$

$$\vec{a} = \frac{\left\langle J \middle| \vec{\boldsymbol{a}} \cdot \vec{\boldsymbol{J}} \middle| J \right\rangle}{J(J+1)}$$

NN Weak Interactions - Macroscopic

- In the absence of the weak interaction the $|JM\rangle$ states are states of definite parity and $\vec{a} = 0$
- In the presence of the weak interaction these states are mixed:

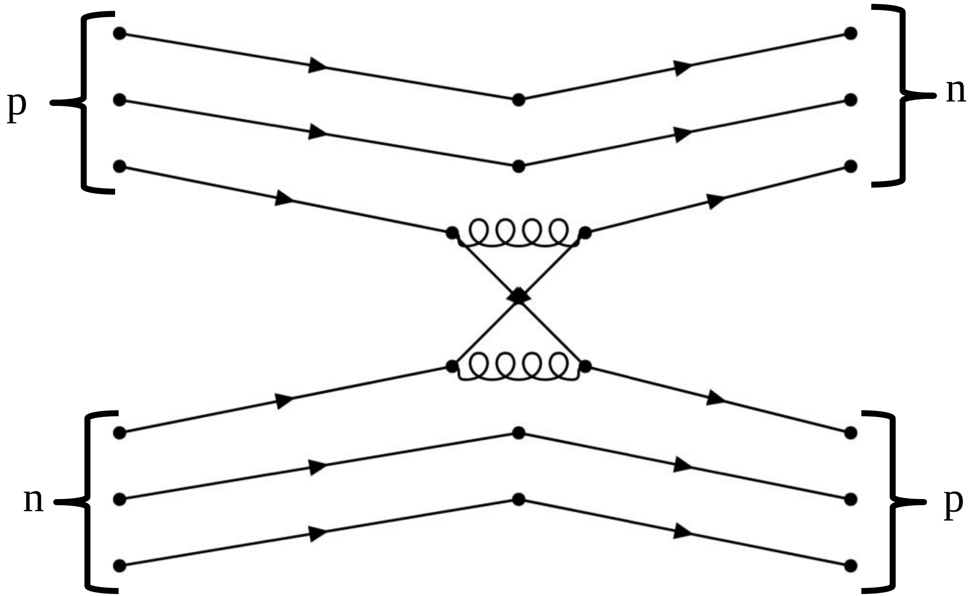
$$|J\rangle = |J;0\rangle + \sum_{k\neq 0} \frac{\langle J;k|W|J;0\rangle}{E_0 - E_k} |J;k\rangle$$

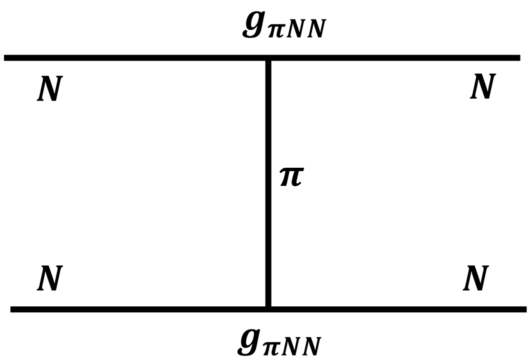
- Now the nucleus can acquire a non-zero anapole moment:

$$\langle a\rangle = 2\,Re \sum_{k\neq 0} \frac{\langle J;0|a|J;k\rangle\langle J;k|W|J;0\rangle}{E_0 - E_k}$$

NN Weak Interactions - Microscopic

- Microscopically electroweak nuclear interactions arise at the individual quark-level





NN Weak Interactions - Microscopic

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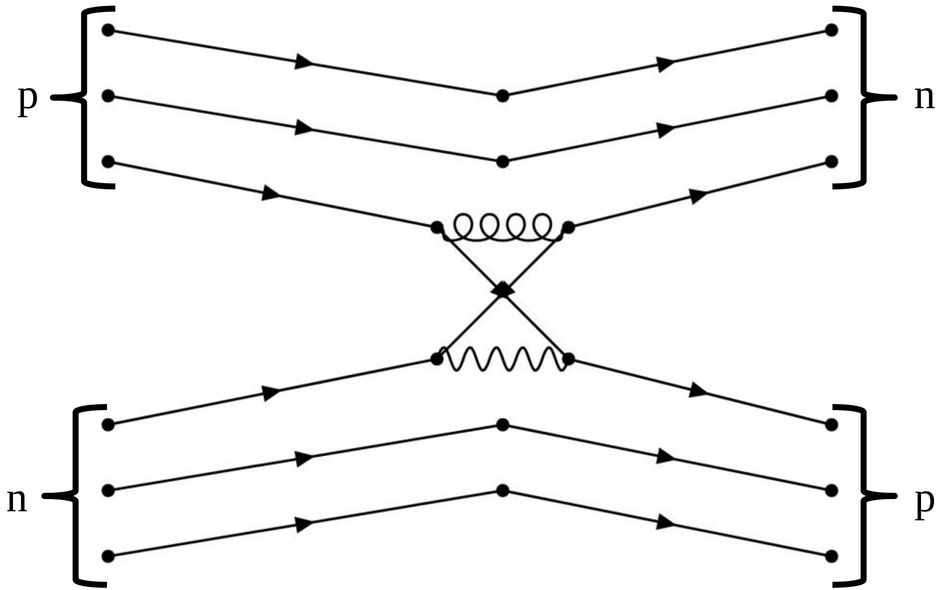
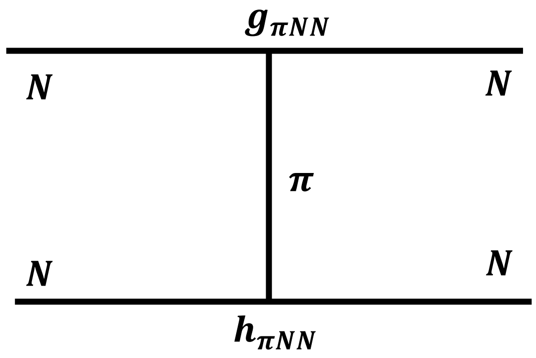
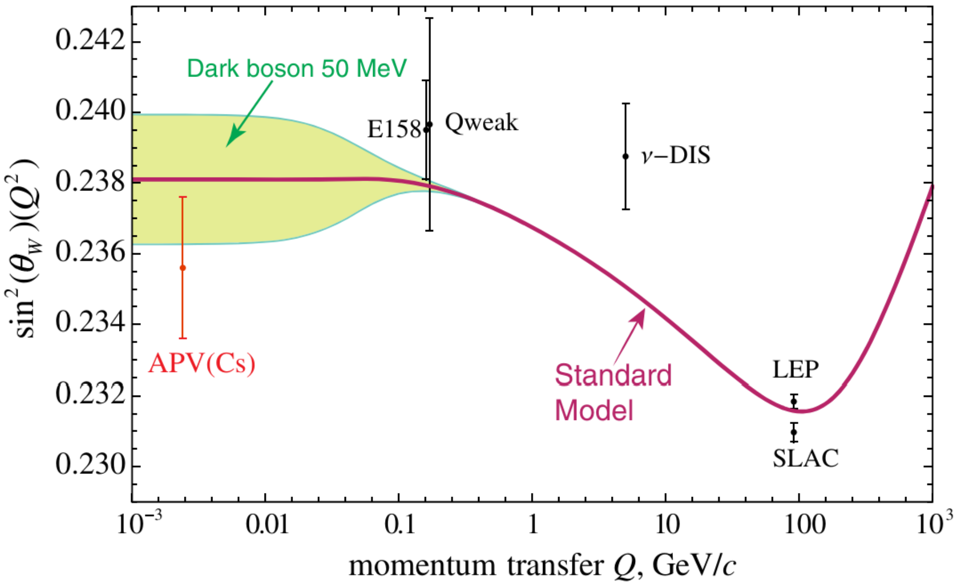




Nuclear Spin Independent PV

- Nuclear Spin-Independent Parity Violation measurements (Z exchange) in atoms provide a low-energy test of the Standard Model



Interference Technique

- Consider the case of Cesium: ground state is $6S_{1/2}$
- Electric dipole transition to excited state of the same parity is forbidden:

$$\left\langle 6S_{1/2} \middle| D \middle| 7S_{1/2} \right\rangle = 0$$

- Weak interactions lead to small mixing between states of opposite parity giving a non-zero matrix element (10^{-11}):

$$E_{PV} = \left\langle \widetilde{6S_{1/2}} \middle| D \middle| \widetilde{7S_{1/2}} \right\rangle \neq 0$$

- In an interference technique an electric field is added to provide a strong E1 pathway with transition amplitude $\beta\mathcal{E}$
- The transition rate is proportional to the square of the transition amplitude: $E_{PV}^2 + (\beta\mathcal{E})^2 + (\beta\mathcal{E}E_{PV})$
- By reversing the electric field one can extract E_{PV}

Molecular Hamiltonian

- Since the weak interactions are essentially contact interactions we rely on molecular states with strong overlap of the electron with the nucleus
- We consider diatomic molecules with a single valence electron in a $^2\Sigma$ electronic state. This is the molecular equivalent of alkali atoms (in particular a Hund's case b)
- We have one nucleus with non-zero spin ($I = \frac{1}{2}$) that couples to the electron by NSD-PV interaction and a second nucleus with zero spin ($I = 0$)
- Lowest energy levels are described by the Hamiltonian:

$$H = B_e \boldsymbol{N}^2 + \gamma \boldsymbol{N} \cdot \boldsymbol{S} + b \boldsymbol{I} \cdot \boldsymbol{S} + c(\boldsymbol{I} \cdot n) \times (\boldsymbol{S} \cdot n)$$

  - B_e - rotational constant
  - γ – Spin-rotation constant
  - b/c – Hyperfine constants
- $B_e \gg \gamma, b, c$ so N is a good quantum number and $E_N = B_e N(N+1)$ and $P = (-1)^N$

Molecular Hamiltonian

- The magnetic field needed to bridge the rotational energy:

$$E_1 - E_0 \approx 2B_e$$

- The magnetic field decouples S, I and N such that the molecular states can be considered in the decoupled basis:

$$|\psi\rangle = \left|N, m_N\right\rangle |S, m_s\rangle |I, m_I\rangle$$

- The Zeeman effect is dominated by the coupling to the electron spin:

$$H_Z \cong -g\mu_B S \cdot B$$

- The state of opposite of interest are:

$$\left|\psi_\uparrow^+\right\rangle = \left|N = 0, m_N = 0\right\rangle |S = 1/2, m_s = 1/2\rangle |I = 1/2, m_I\rangle$$

$$\left|\psi_\downarrow^-\right\rangle = \left|N = 1, m_N\right\rangle |S = 1/2, m_s = -1/2\rangle |I = 1/2, m_I{}'\rangle$$

Rotational Cooling

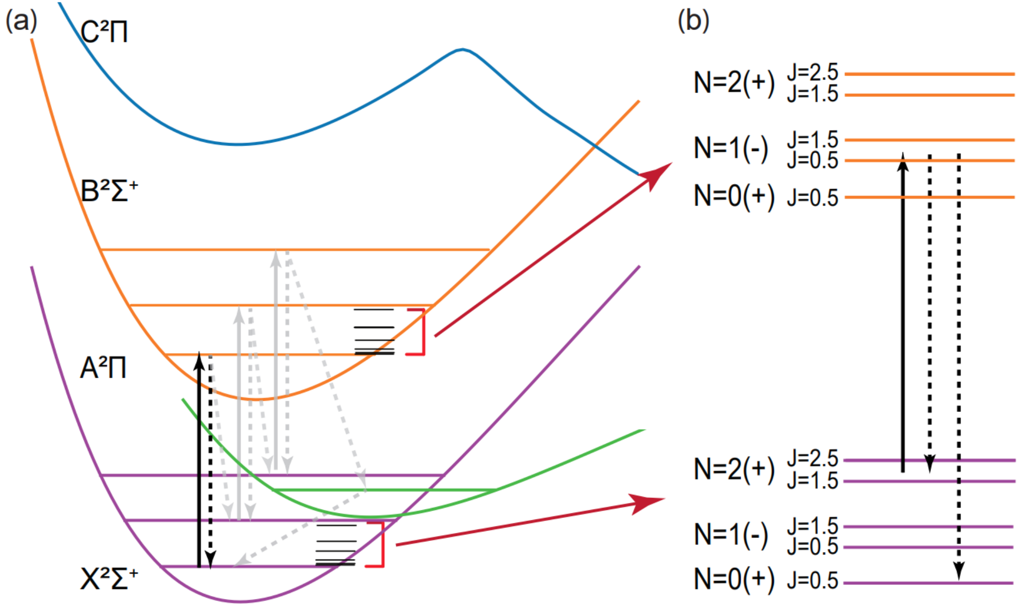


Figure from: Stollenwerk P.R. et al., Phys. Rev. Lett. 125 (2020)