Energy-Selective Annihilation of Trapped $\bar{H}$ via Positron Spin Flips

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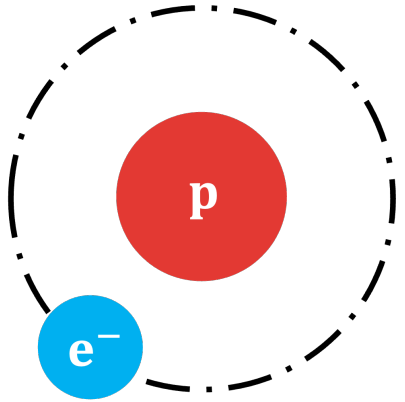
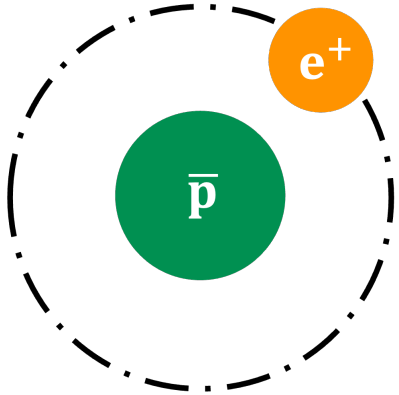
Overview

- Introduction to ALPHA
- Motivation and background
- Energy dependent position spin flip technique
- Applications
  - Energy distribution characterization
  - Studies of energy exchange between motional degrees of freedom
- Conclusion and future steps





Antihydrogen Laser PHysics Apparatus

- ALPHA investigates the baryon asymmetry problem using antihydrogen ($\overline{\mathrm{H}}$)
- $\overline{\mathrm{H}}$ is an attractive candidate
  - Simplest anti-atom
  - Extensive characterization of its matter counterpart
- ALPHA produces and traps neutral $\overline{\mathrm{H}}$

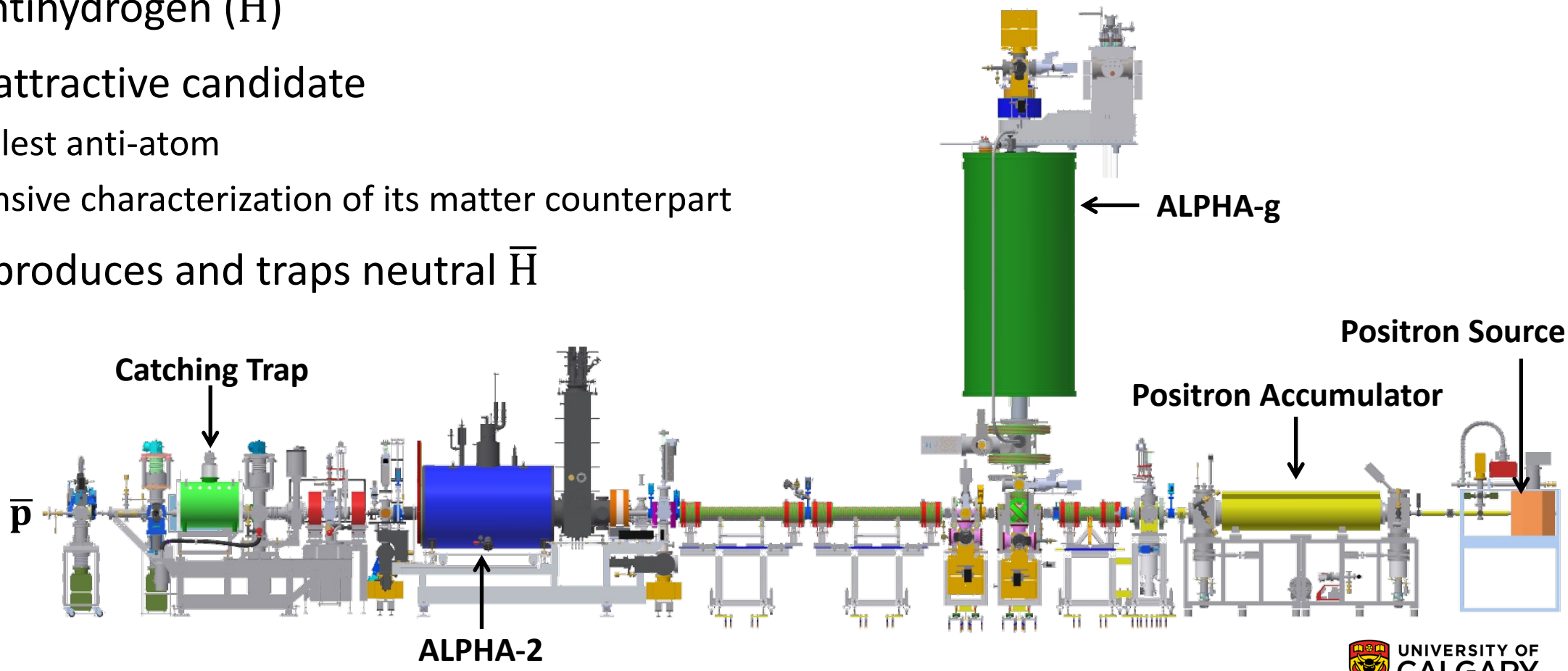
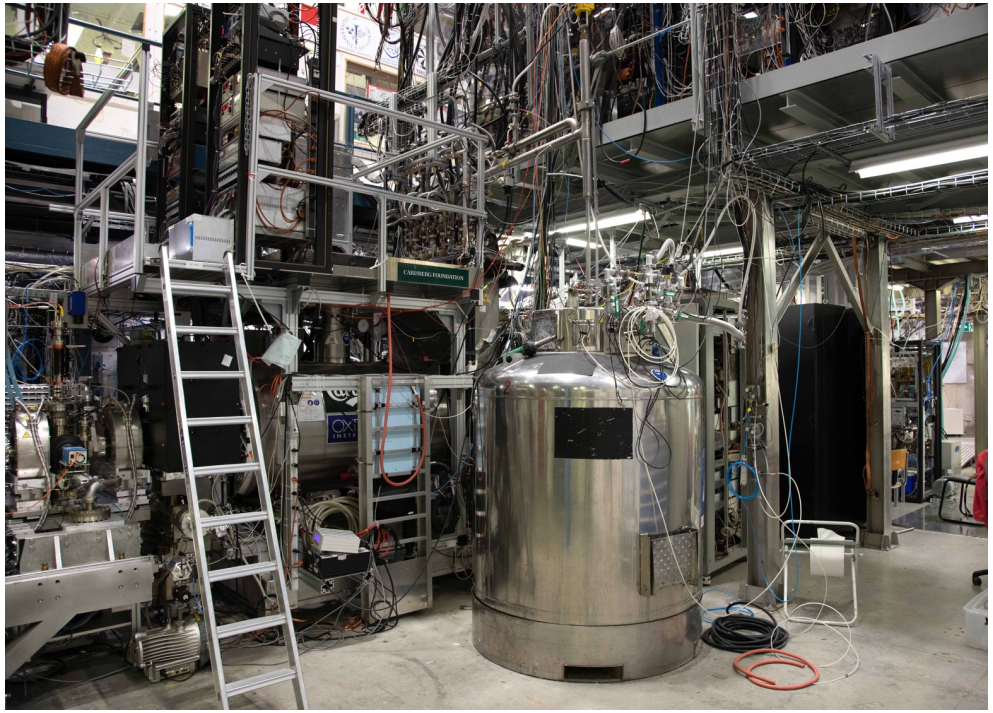


Image Credit: Prof. Steven Armstrong Jones and The ALPHA Collaboration

Motivation

- Here we present two new experimental studies aiming to improve future precision

1) A novel method for characterizing $\overline{\mathrm{H}}$ energy distributions
   - Accessible beyond the limits of current diagnostics
   - Reduces systematic uncertainties
   - Allows direct simulation benchmarking
2) The first experimental study of energy exchange in trapped $\overline{\mathrm{H}}$
   - Important for laser cooling, gravity measurements, and spectroscopy experiments
   - Enables direct benchmarking of intriguing simulation predictions[1]

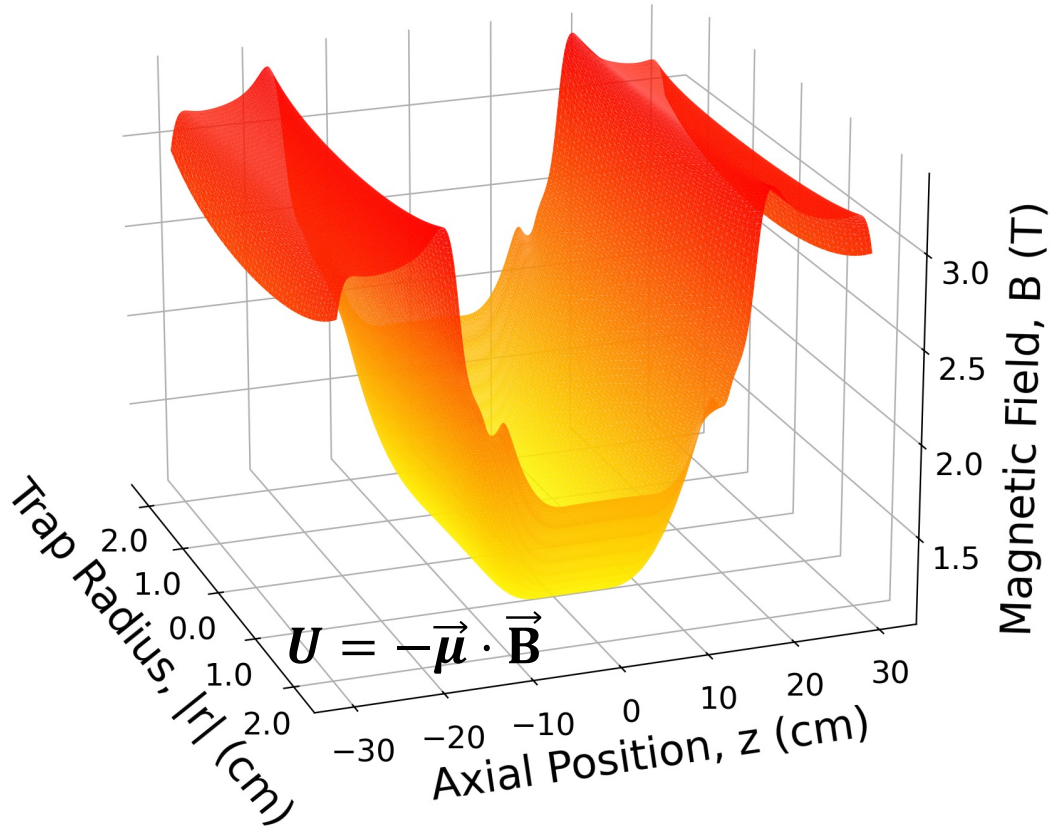


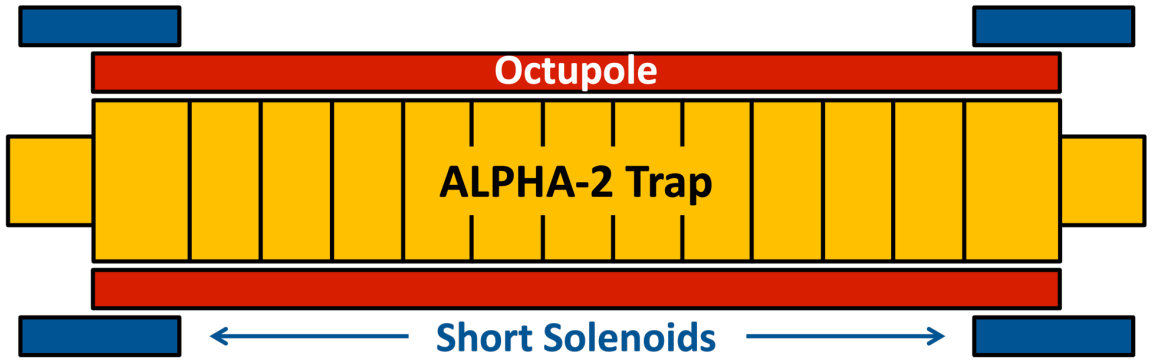
A section of the ALPHA experiment at CERN. ALPHA©

[1]Zhong, A. et al., *New J. Phys.* **20**, 053003 (2018).

Magnetic Trapping of Antihydrogen

- ALPHA uses an octupole and short solenoids to form a magnetic minimum trap





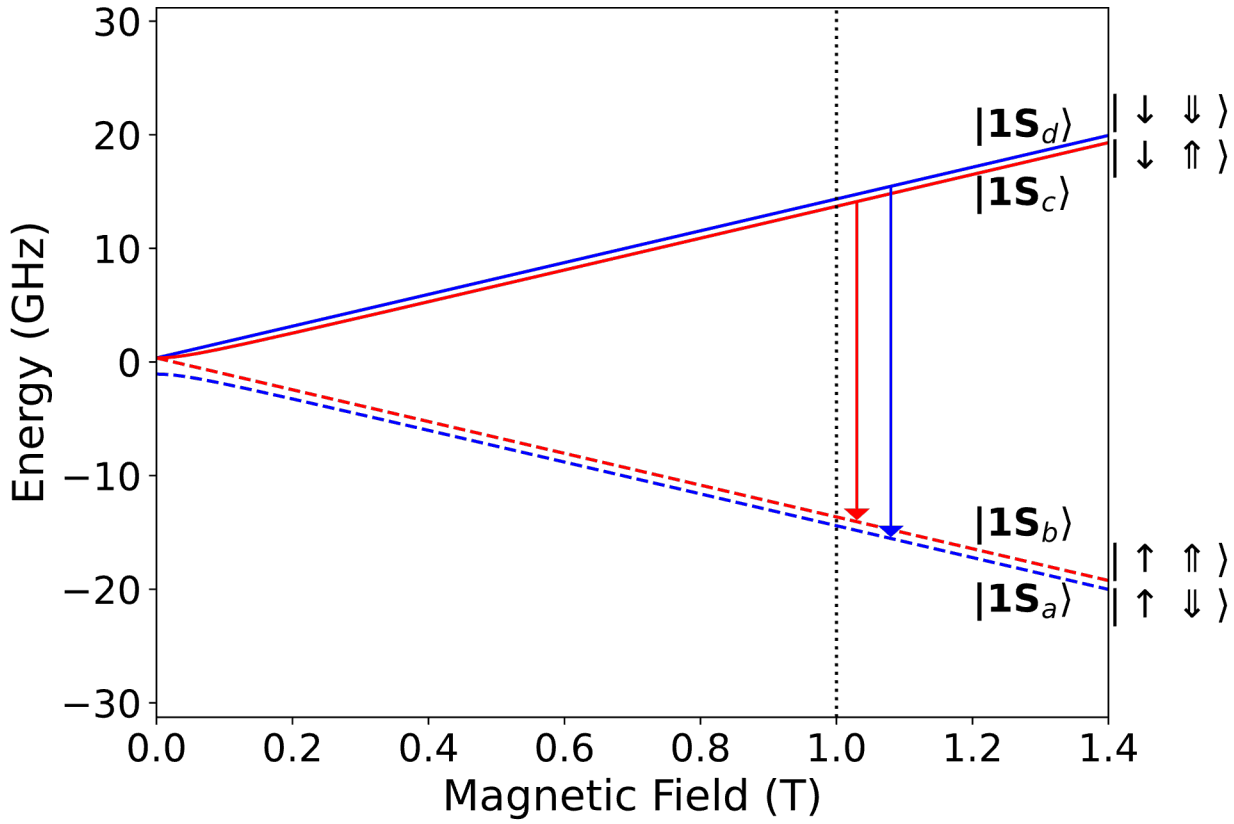
$\vec{\mu}$ = magnetic dipole moment

$\vec{\mathbf{B}}$ = magnetic field

$\mathbf{U}$ = potential

Magnetic Trapping of Antihydrogen

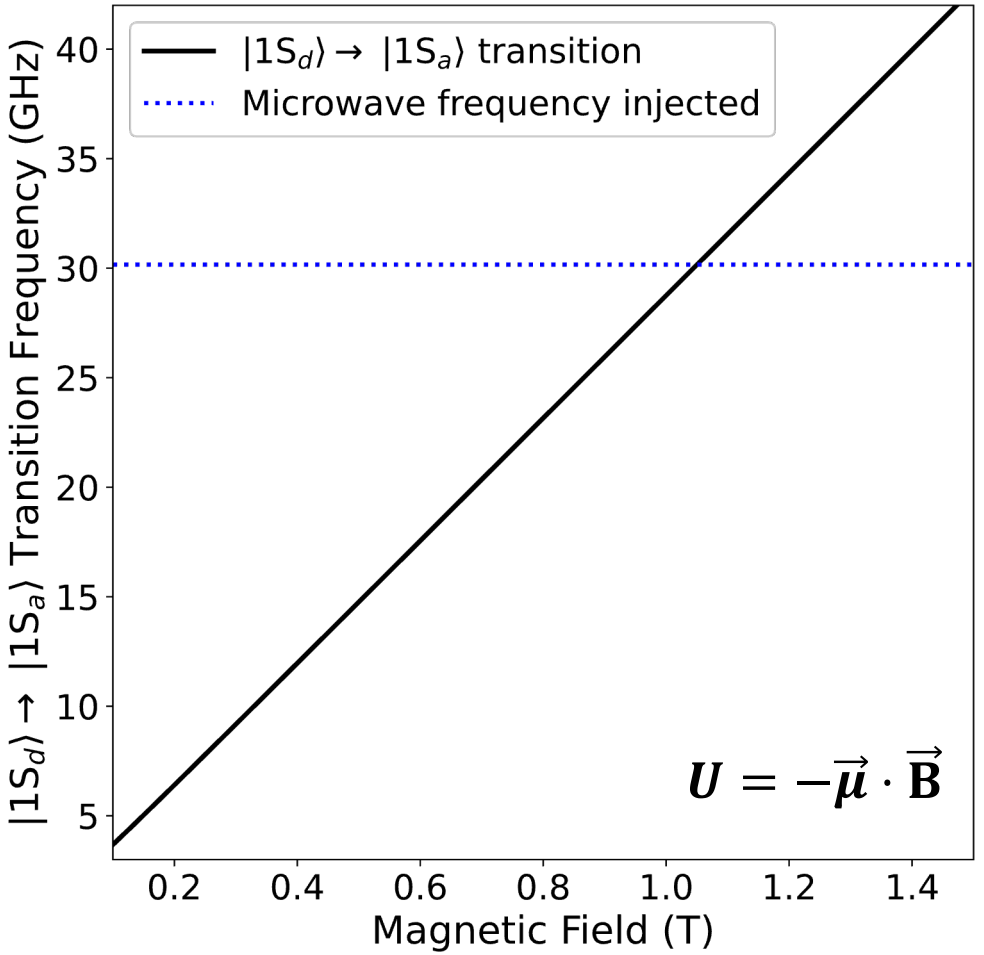
- $\overline{\mathrm{H}}$ is trappable in low field seeking states
- Resonant microwave radiation can induce a positron spin flip transition to an untrappable state



Energy Dependence of Positron Spin Flips

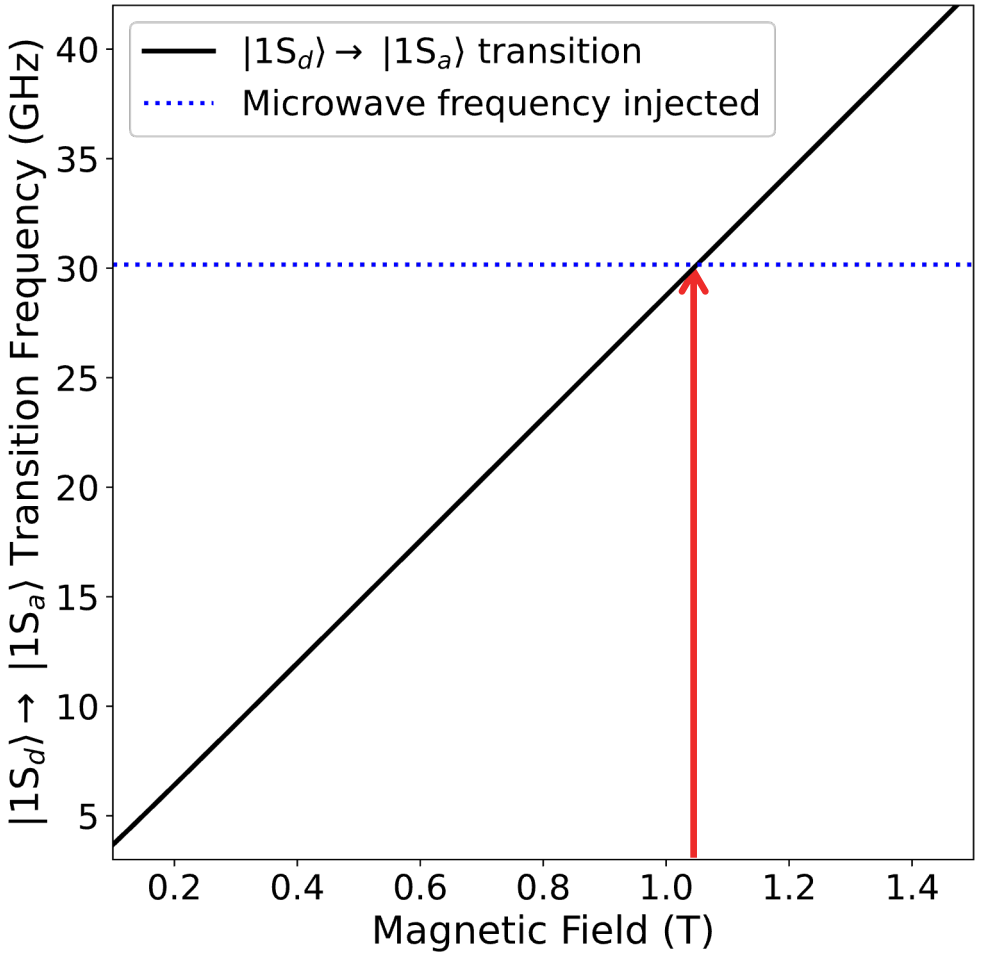
- $\overline{\mathrm{H}}$ must be at a specific $|\vec{\mathrm{B}}|$ to be impacted by injected microwaves

- This technique has several applications
  1) Characterizing trapped anti-atom energy distributions
  2) Investigating energy exchange between motional degrees of freedom
  3) Truncating energy distributions to reduce mean energies



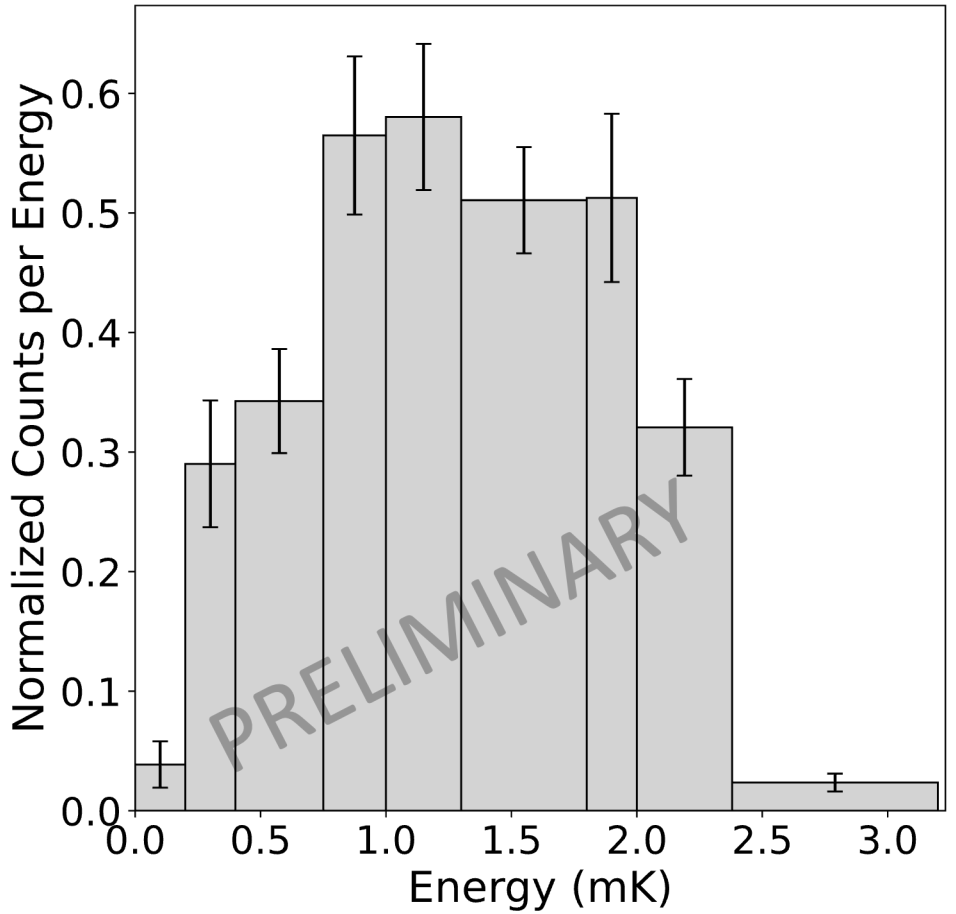
Energy Distribution Characterization

- The energy dependence of positron spin flips allows $\overline{H}$ to be ejected at sequentially decreasing energies
  - Enabling energy distribution characterization
- Current characterization methods include
  - Laser induced ejection with time-of-flight detection (limited to ~1 mK by photon recoil)
  - Magnetic release (fully destructive)



Energy Distribution Characterization Results

- **Results**
  - Preliminary energy distribution characterization
  - Preliminary identification of sub-mK $\overline{\mathrm{H}}$ population
- **Future applications**
  - Simulation benchmark
  - Cross-check magnetic release energy distribution mapping method
  - Technique can potentially be made less destructive by reducing microwave power



Energy Exchange

- Trapped anti-atoms have axial ($E_{\parallel}$) and transverse ($E_{\perp}$) energy
  - $E_{total} = E_{\parallel} + E_{\perp}$
- Simulations predict two categories of anti-atoms[1]
  - **Mix $\bar{H}$**: exchange $E_{\parallel}$ and $E_{\perp}$
  - **No mix $\bar{H}$**: do not exchange $E_{\parallel}$ and $E_{\perp}$
- Energy mixing is caused by azimuthal field asymmetries
- Experimental goals
  - First direct observation of no-mix anti-atoms
  - Characterization of energy exchange timescale
  - Benchmark simulations

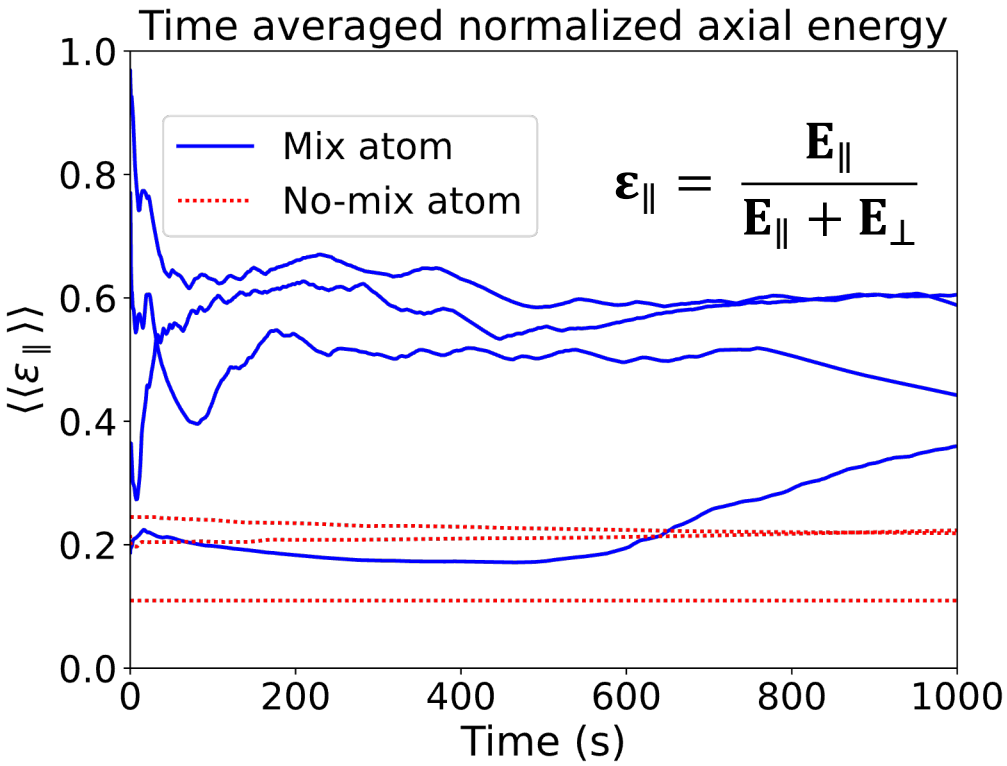
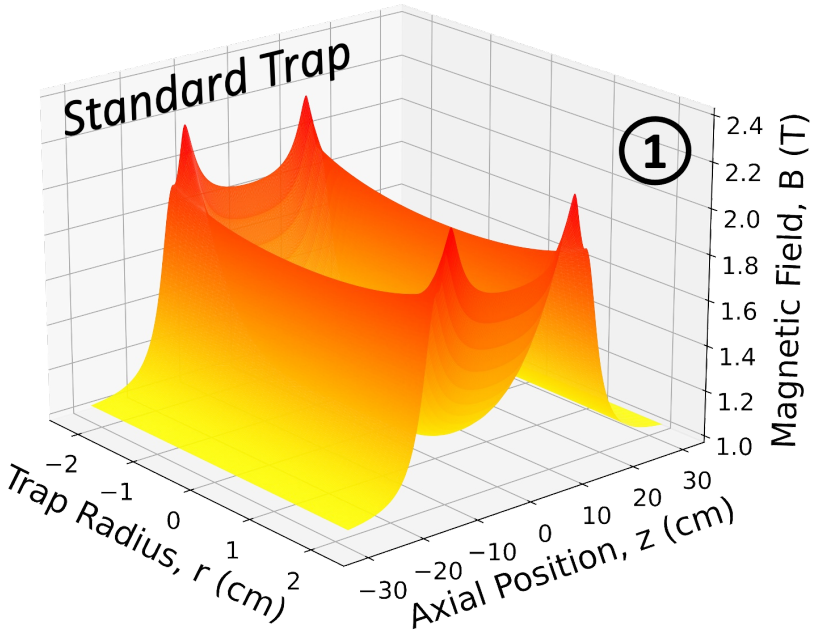


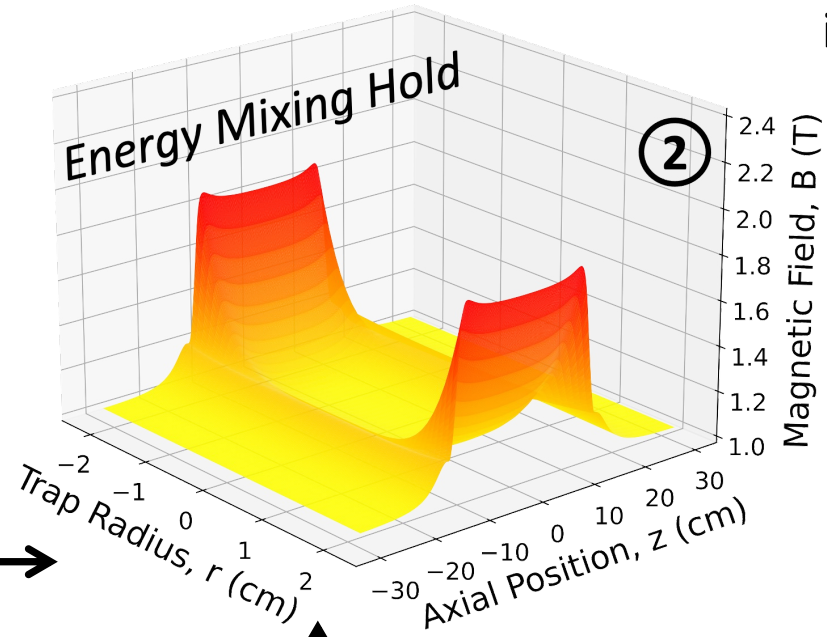
Image Credit: Figure adapted from results of Ref. 1.

[1]Zhong, A. et al., *New J. Phys.* **20**, 053003 (2018).

Energy Exchange Experiment

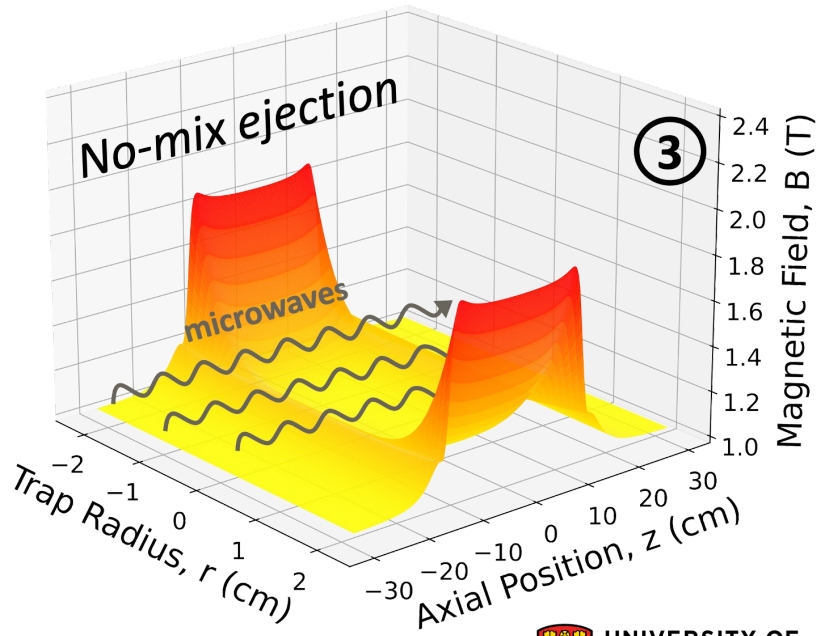


First $\bar{H}$ with $E_{\parallel}$ > trap depth escapes



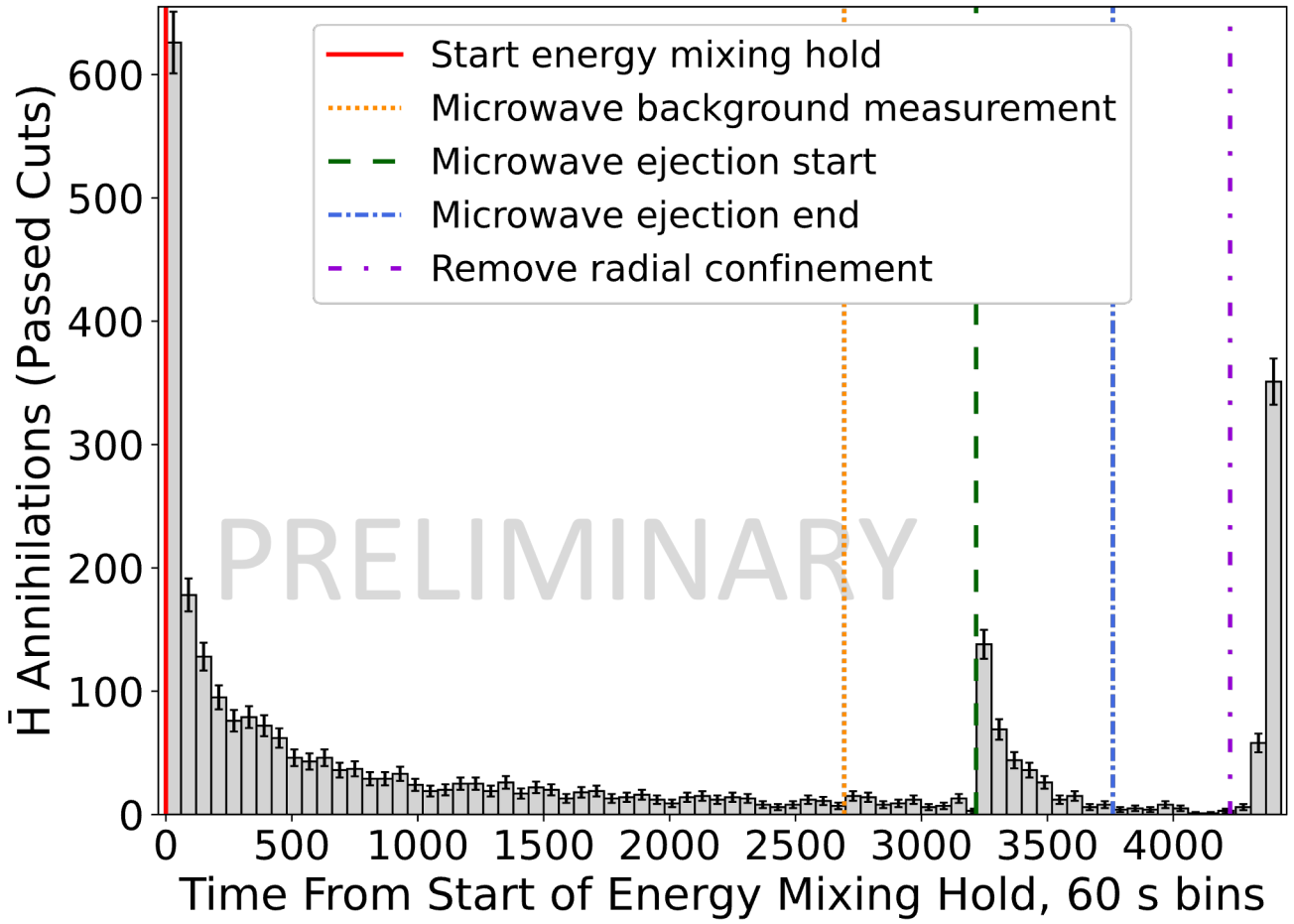
Over time $\bar{H}$ escapes by exchanging $E_{\perp}$ with $E_{\parallel}$

$\bar{H}$ sampling the magnetic field just above the axial trap depth transitions to an untrappable state via microwave induced positron spin flip



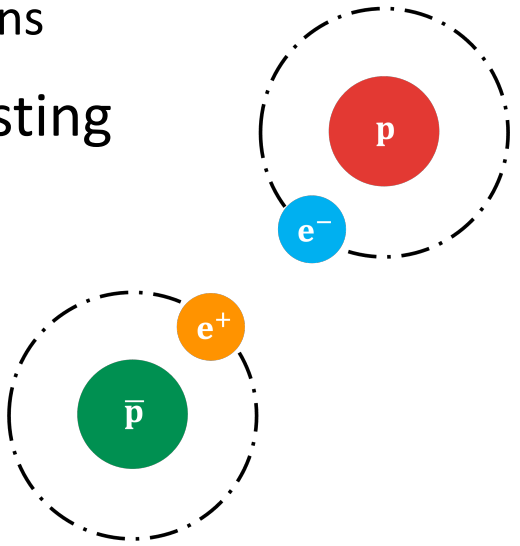
Energy Exchange Results and Implications

- **Results**
  - First direct observation of no-mix $\overline{\mathrm{H}}$
  - Insight into energy exchange timescale
  - Direct simulation benchmark
- **Implications**
  - Energy exchange impacts most experiments moving to higher precision
  - Timescale directly impacts gravity experiments, laser cooling, and spectroscopy
  - Motivation for future experiments, quantifying energy exchange in laser cooled populations



Conclusion and Next Steps

- The energy selective positron spin flip technique has been utilized for multiple experimental applications
  - First investigation of energy mixing
  - Novel method to characterize magnetically trapped anti-atom energy distributions
- These applications can be used to increase precision in experiments testing fundamental symmetries
  - Reduced systematic uncertainties
  - Direct simulation benchmarks
  - Characterization of sub-mK energy distributions



- We are working toward the publication of the results presented here

Acknowledgments

- This work is presented on behalf of the ALPHA collaboration
- The energy exchange experiment was proposed Prof. Joel Fajans (UC Berkeley), Prof. Jonathan Wurtele (UC Berkeley), and Prof. Mike Hayden (Simon Fraser University)
- Prof. William Bertsche (University of Manchester) was closely involved in developing energy distribution characterization procedures

Extra Slides