Towards a High Precision Measurement of the Hyperfine Structure of Antihydrogen

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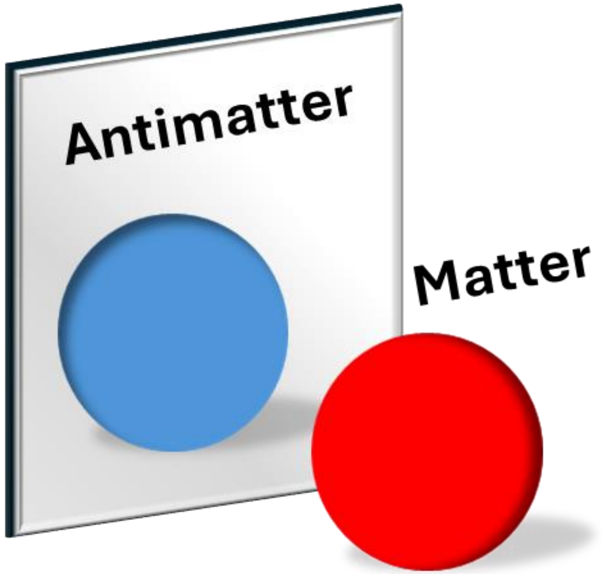
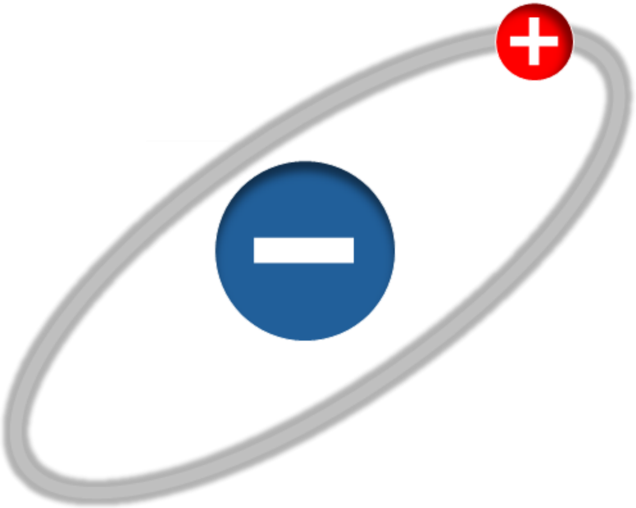
WNPPC 2025

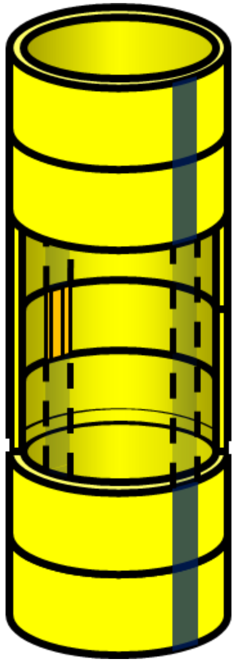
Outline



Matter and Antimatter **Symmetry**

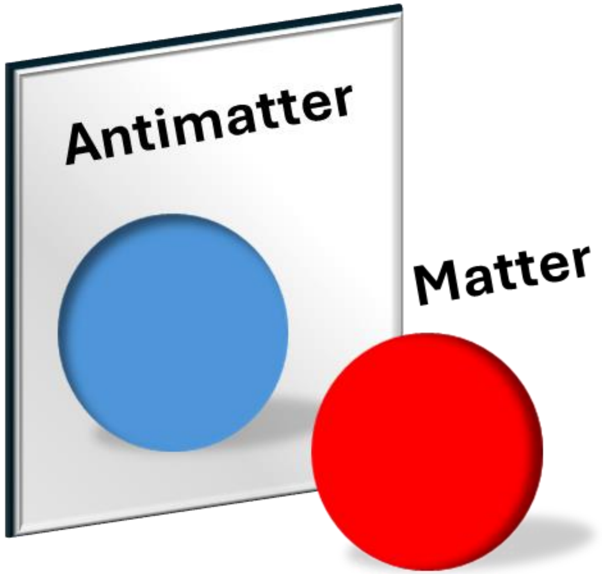


Hyperfine Structure of Antihydrogen



NMR Spectroscopy Experiment

Matter and Antimatter Symmetry



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Hyperfine Structure of Antihydrogen

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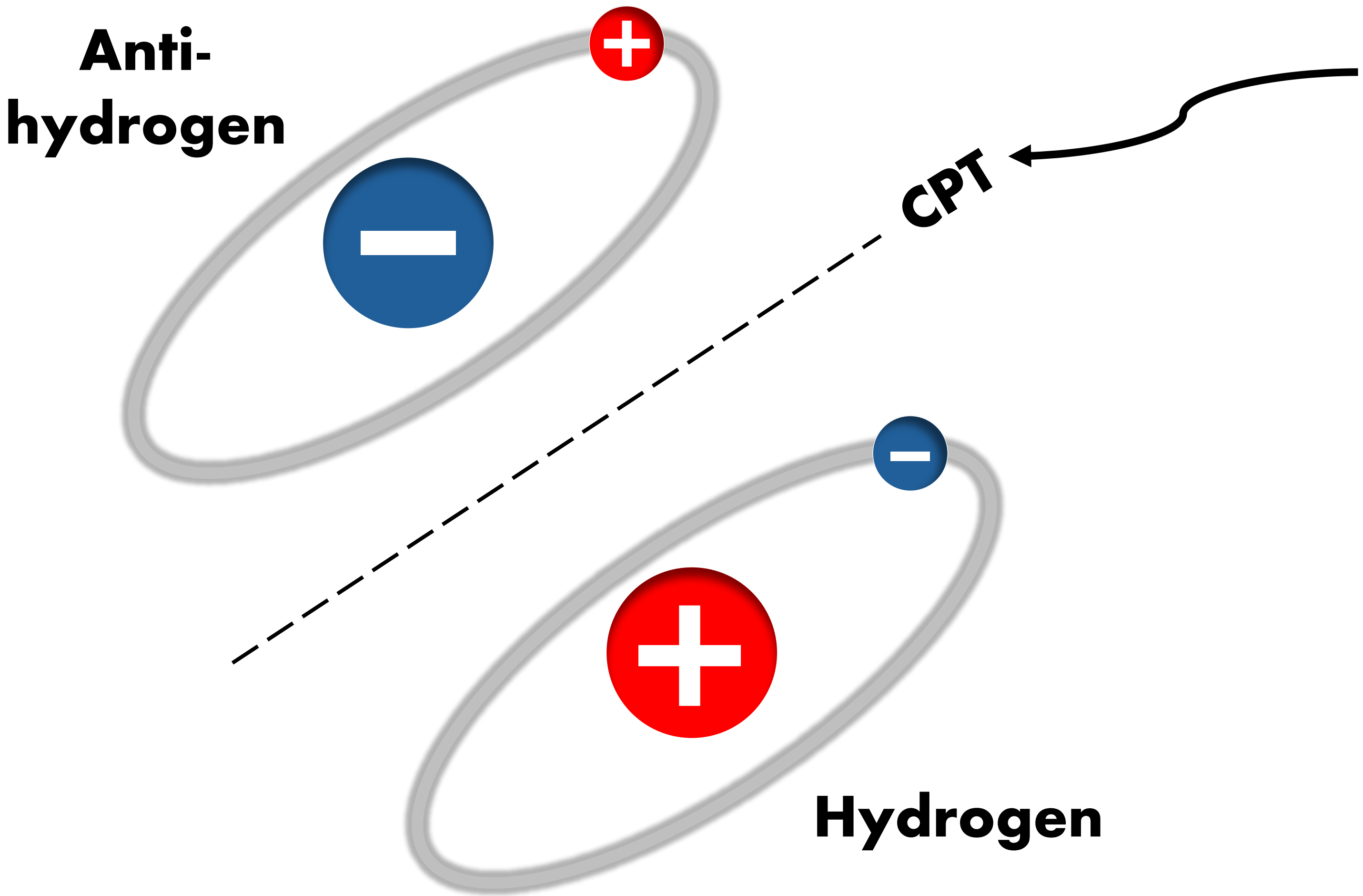
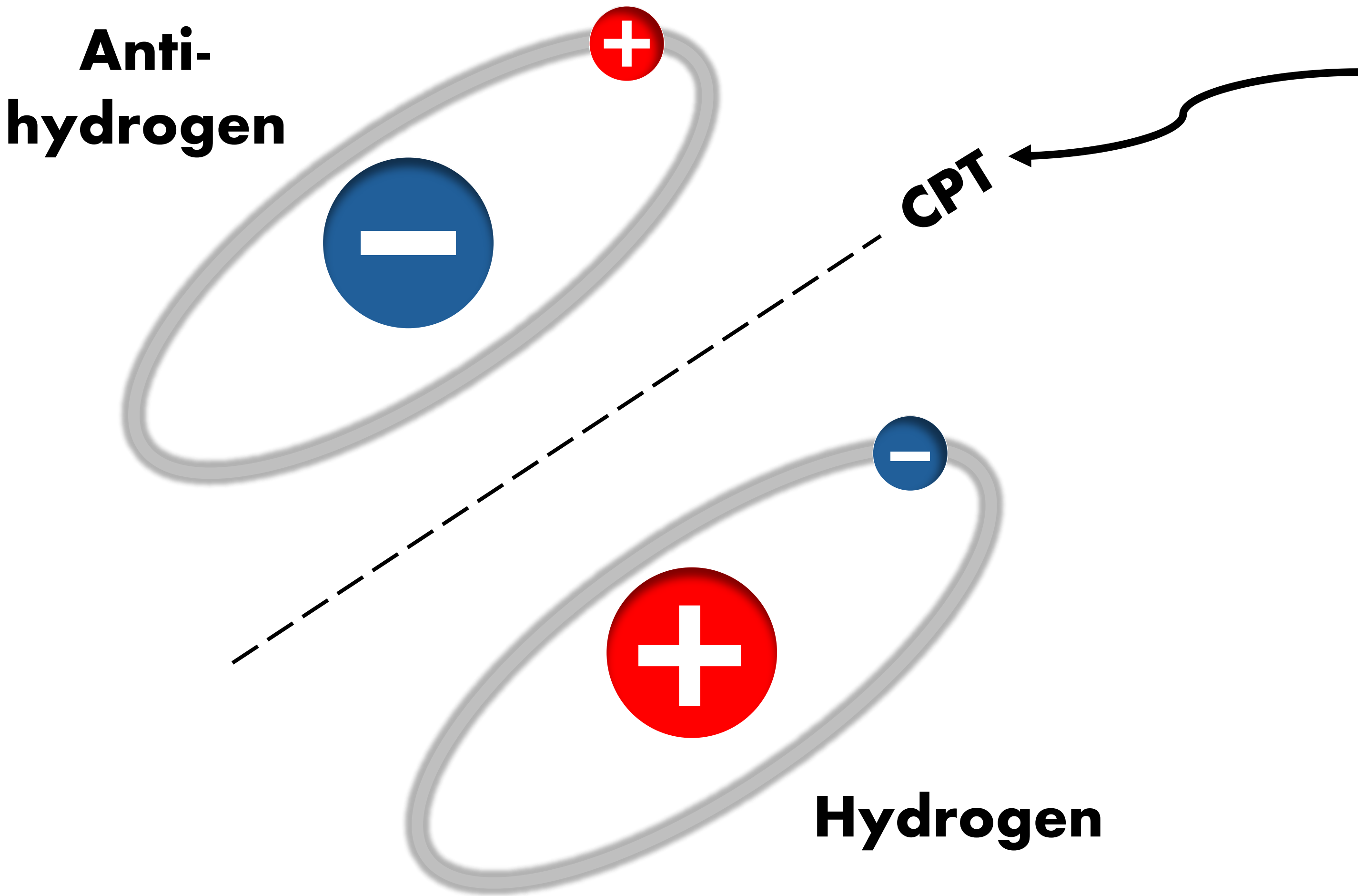
Matter and Antimatter Symmetry



Fundamental Symmetry:
Charge, **Parity**, and **Time**

Matter and Antimatter Symmetry



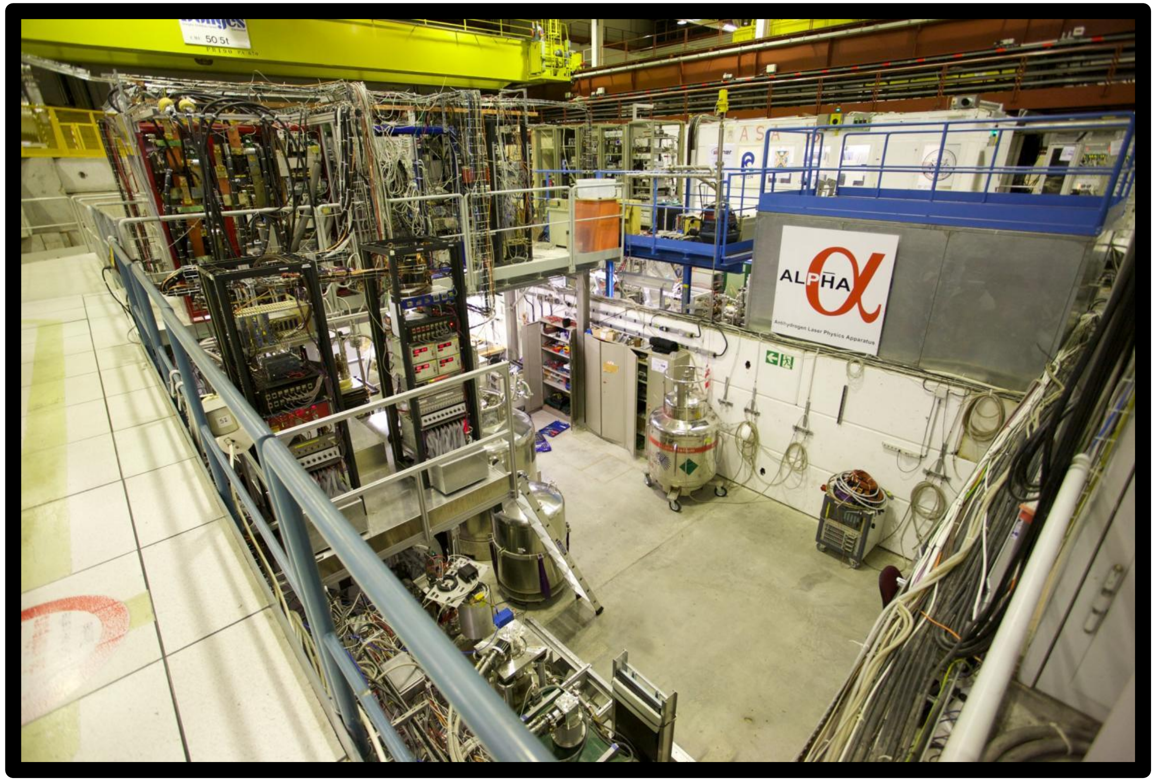
Fundamental Symmetry:
Charge, **Parity**, and **Time**

⇩

Predicts equal abundances of matter and antimatter...

...but what if CPT symmetry is **violated?**

ALPHA Experiment



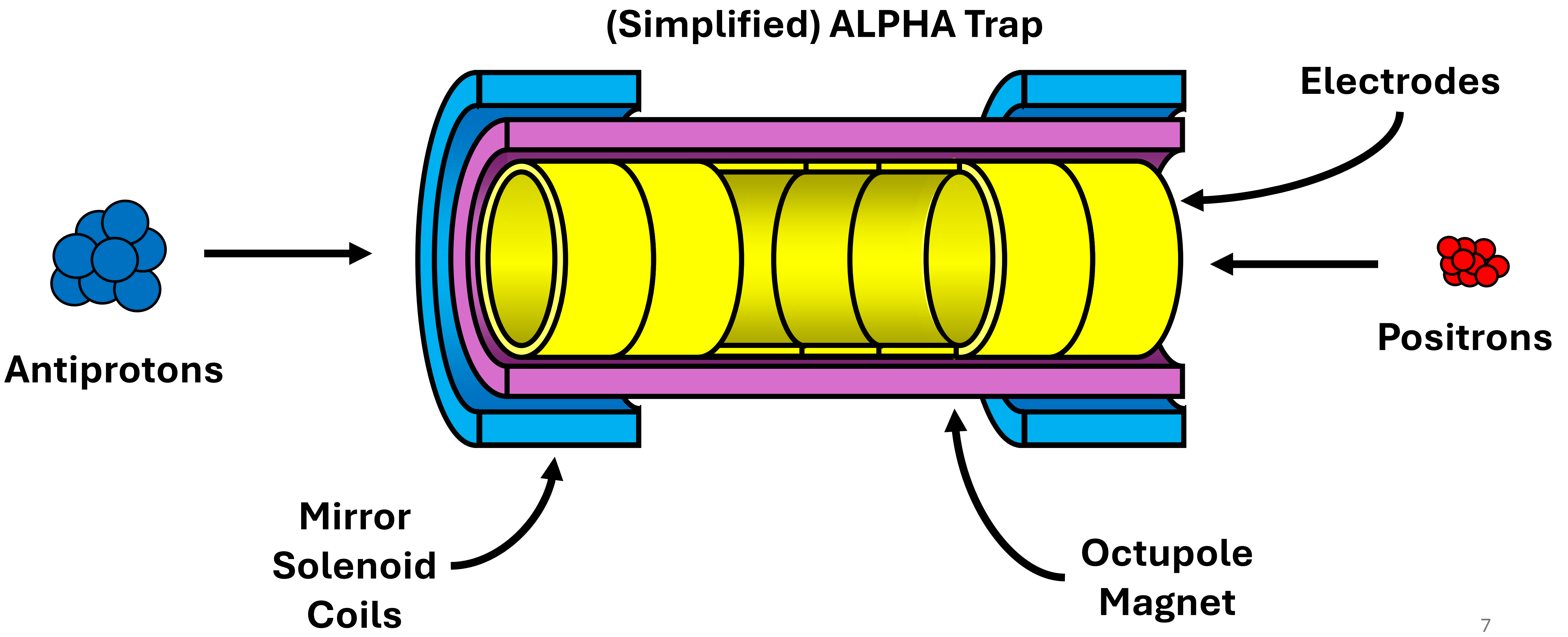
ALPHA Experiment

Courtesy of https://alpha.web.cern.ch/

ALPHA:

- Seek to study fundamental symmetries by precise comparison of **hydrogen** and **antihydrogen**
- Spectroscopy of antihydrogen
- Gravitational trajectory experiments

Trapping Antimatter at ALPHA



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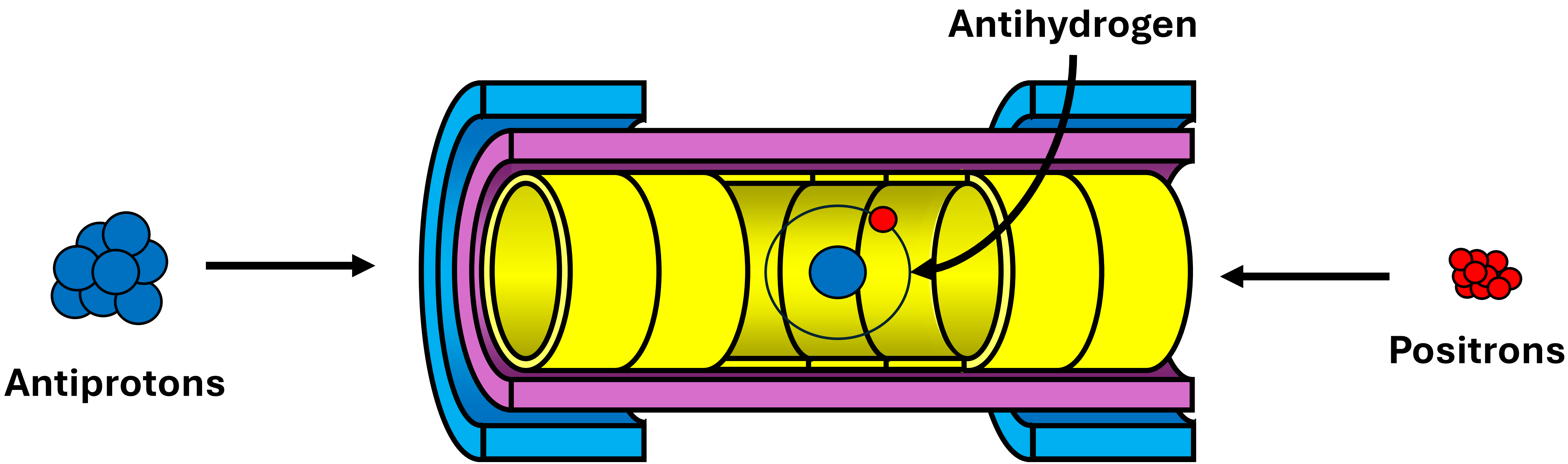
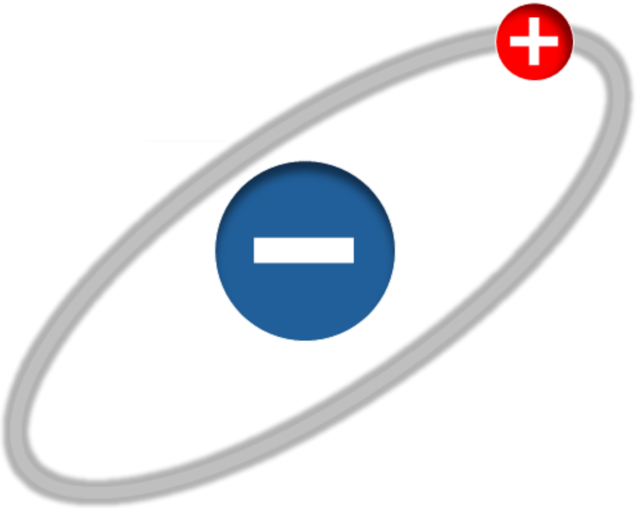


Can produce over **100** antihydrogen atoms in a single mixing step

Thousands of antihydrogen atoms available for each measurement

Hyperfine Structure

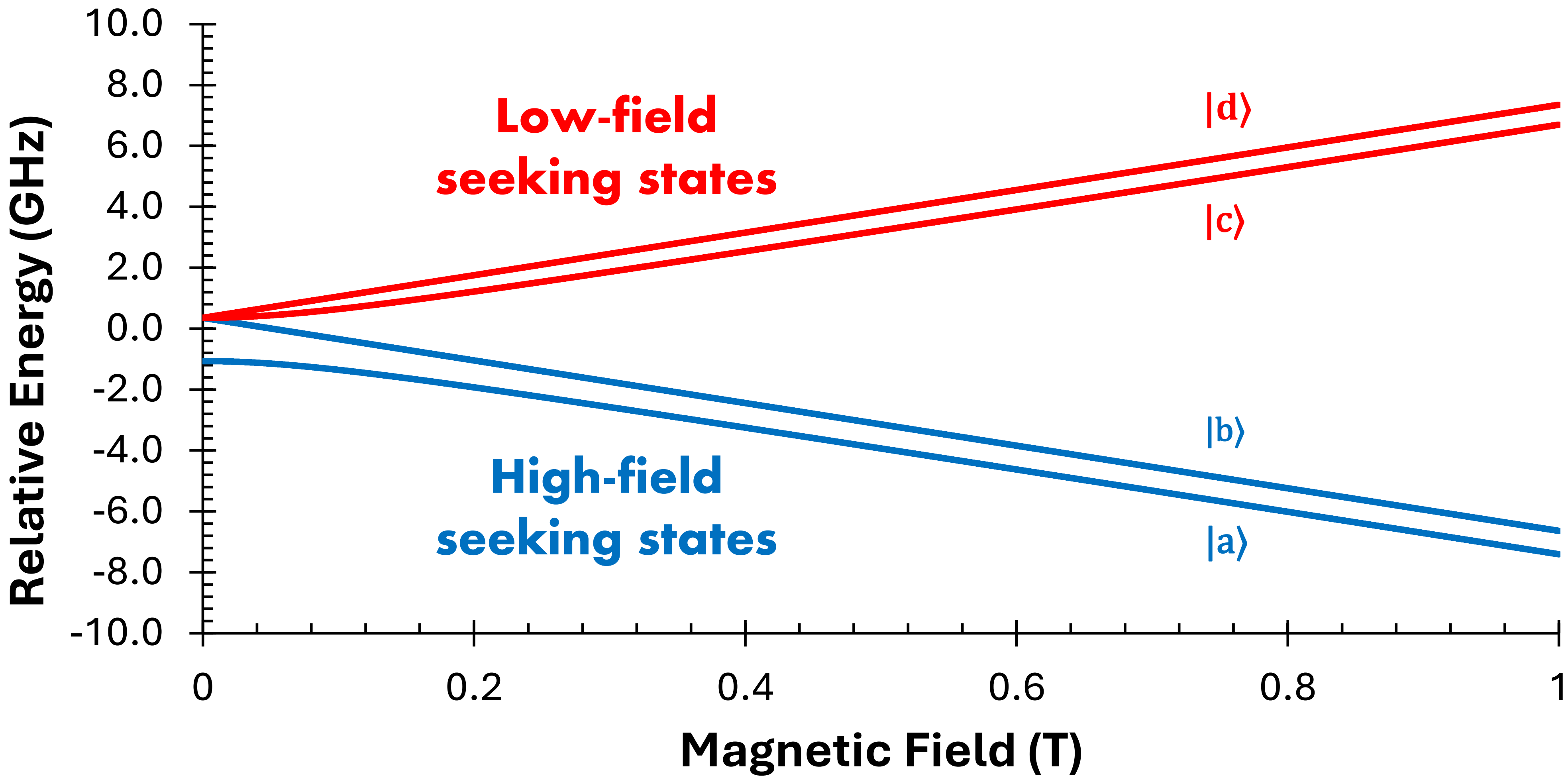


Matter and Antimatter **Symmetry**

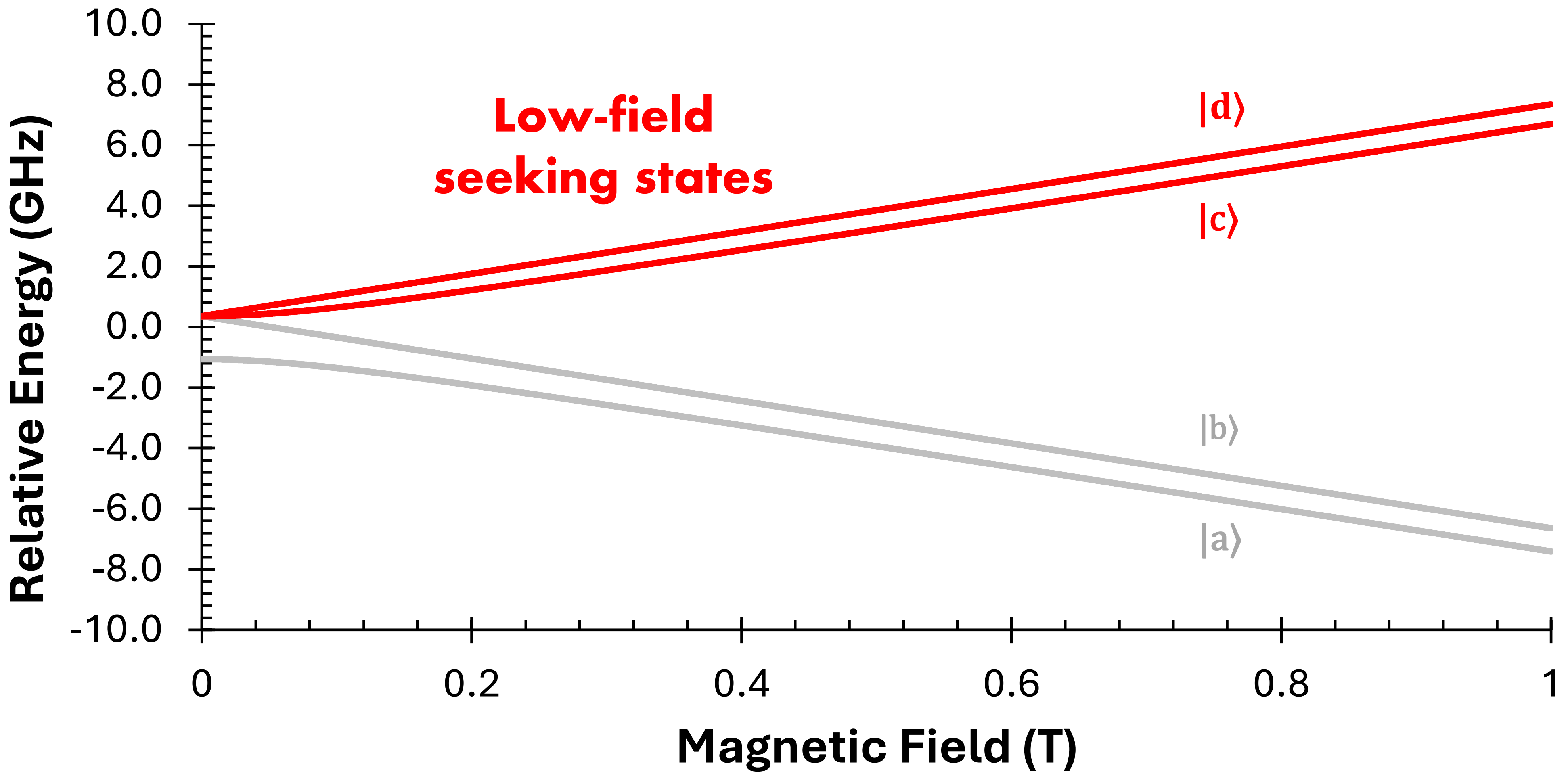
Hyperfine Structure of Antihydrogen

NMR Spectroscopy Experiment

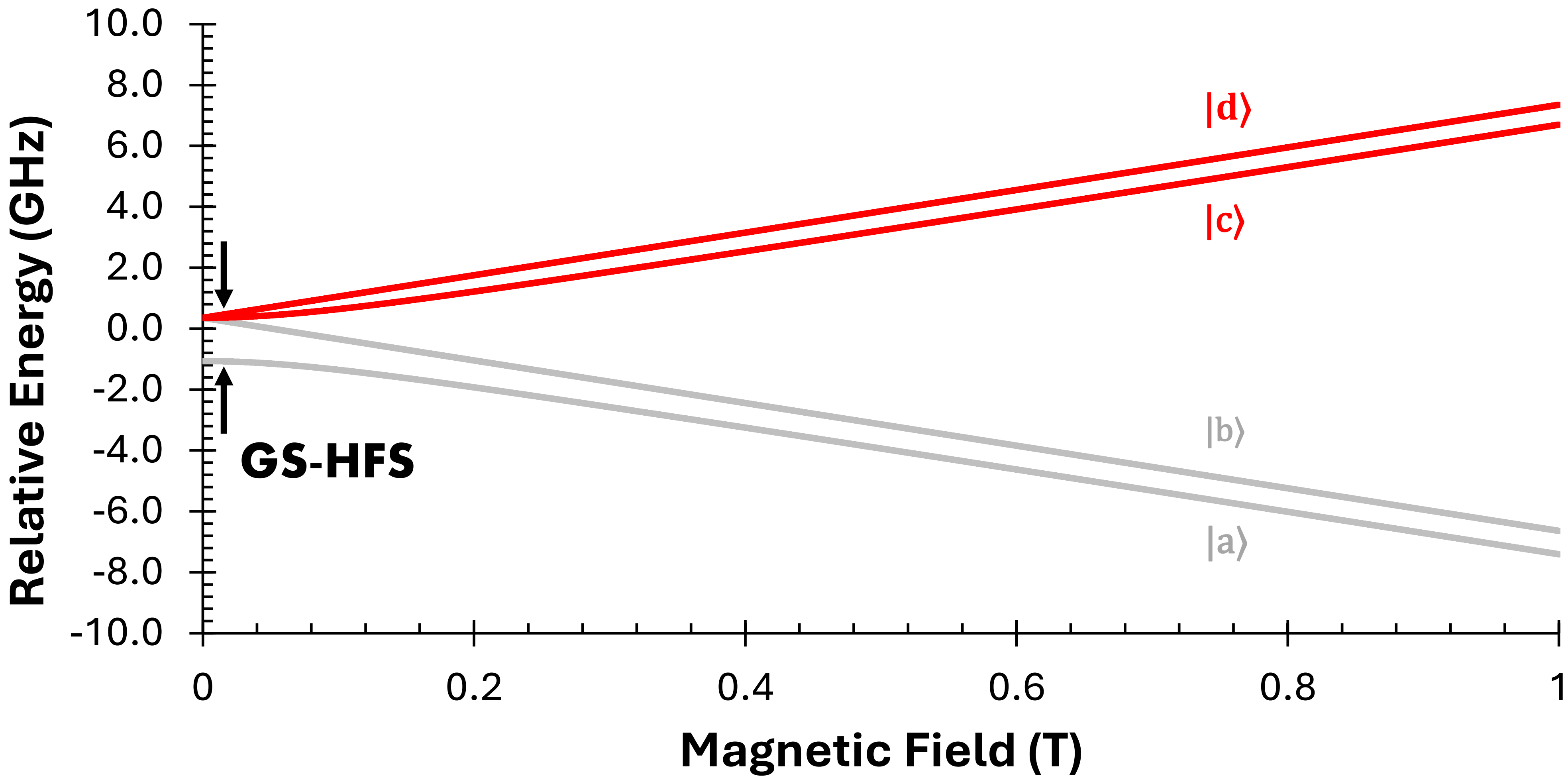
Ground State Hyperfine Structure



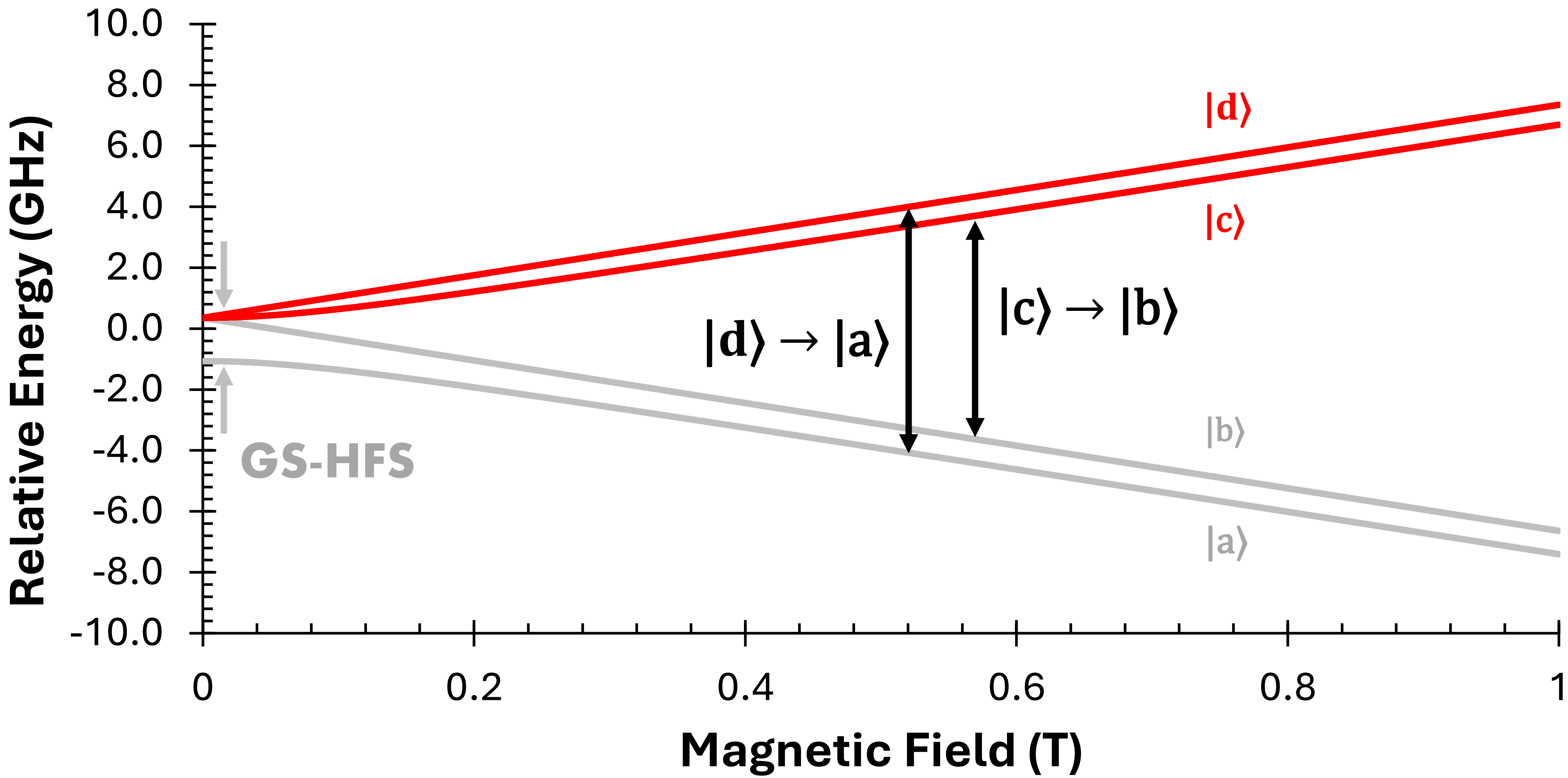
Ground State Hyperfine Structure



Ground State Hyperfine Structure



Ground State Hyperfine Structure



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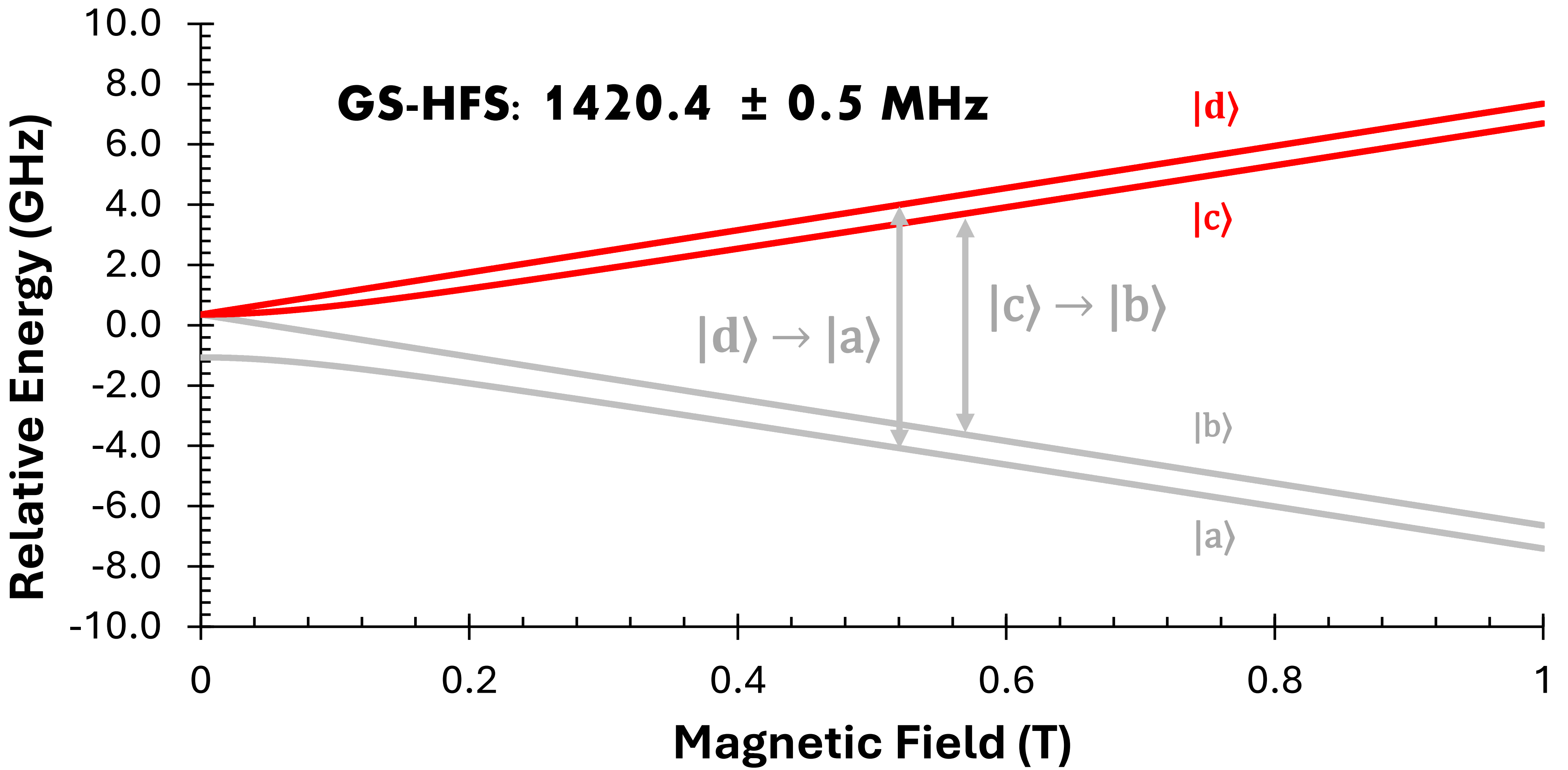
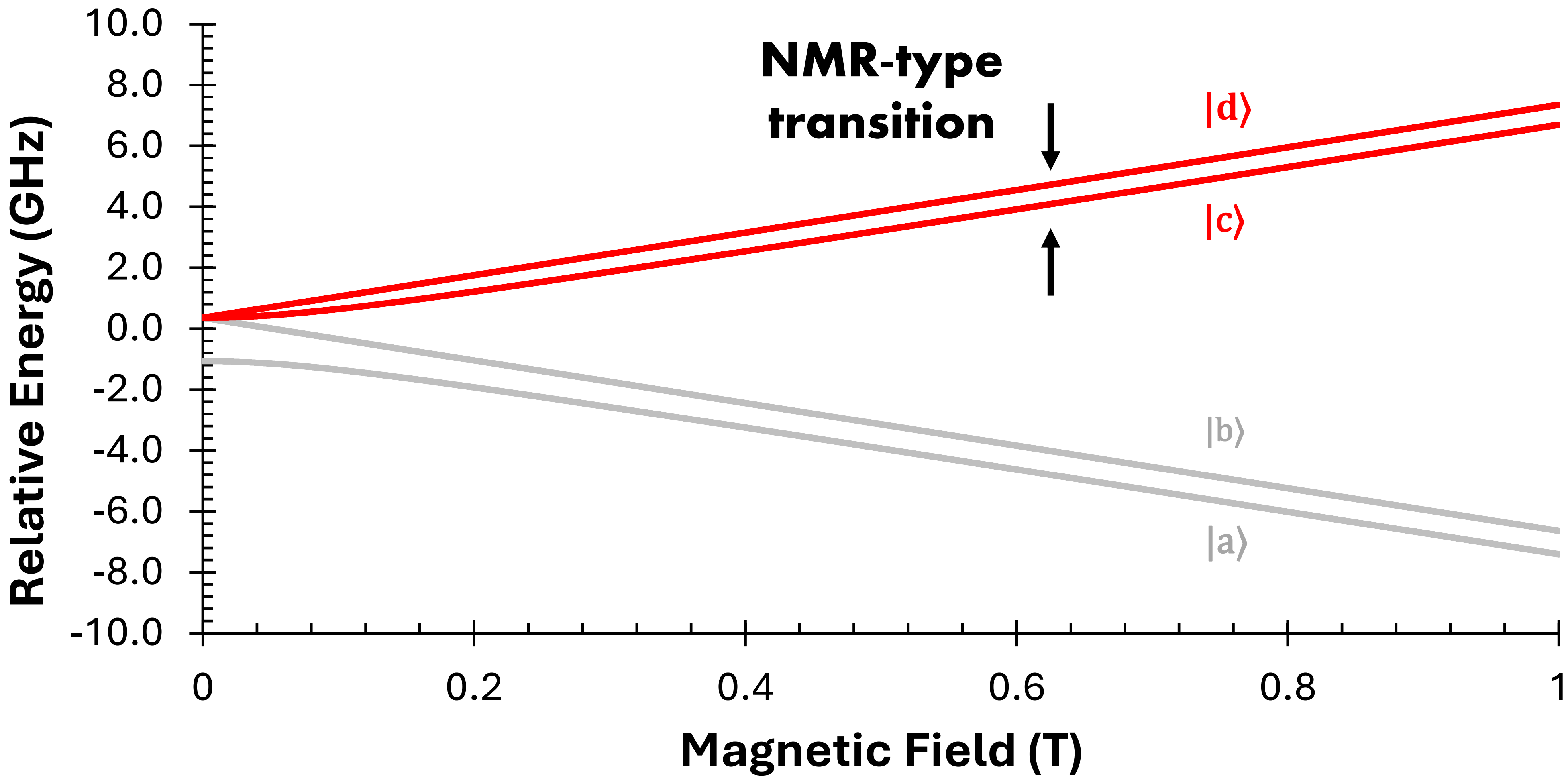
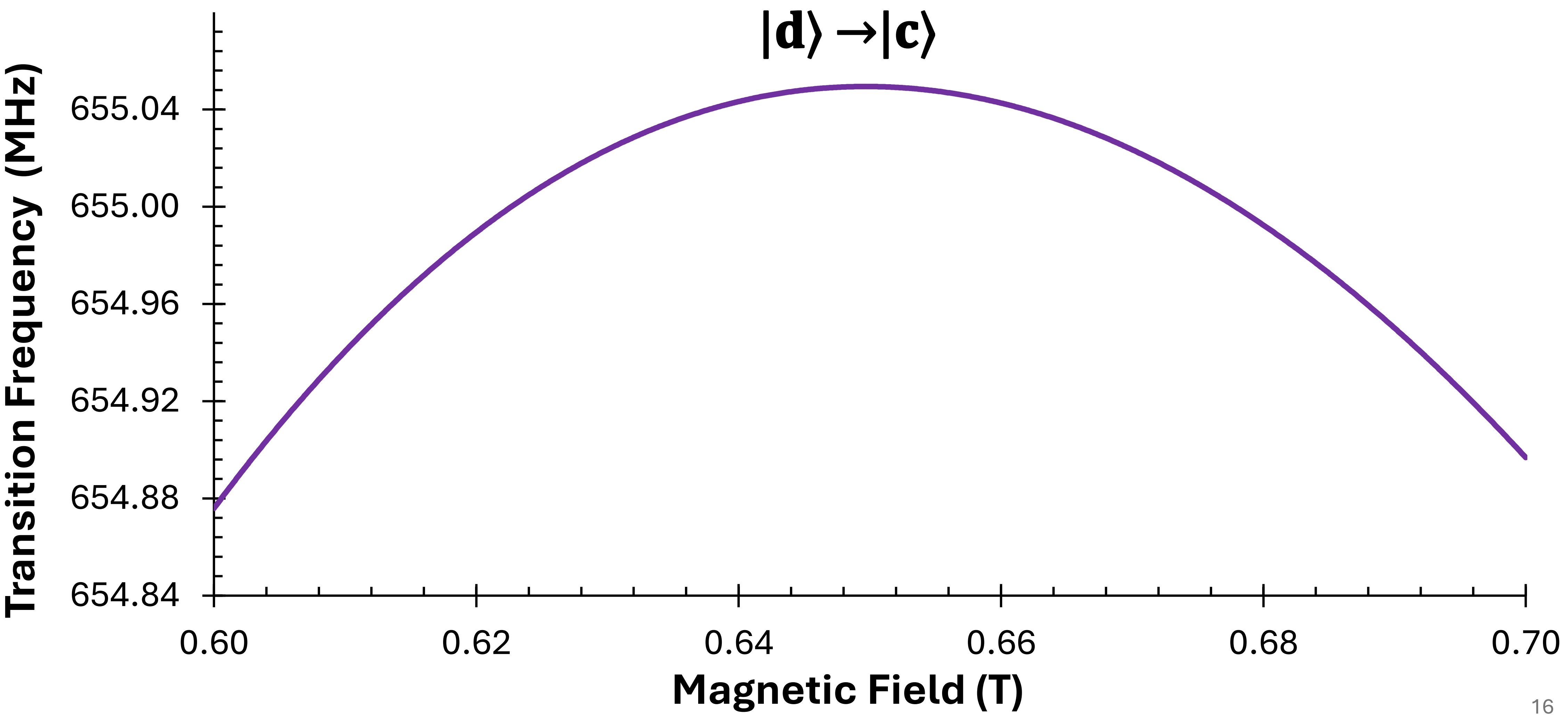


ALPHA Collaboration, **Nature**, 2017

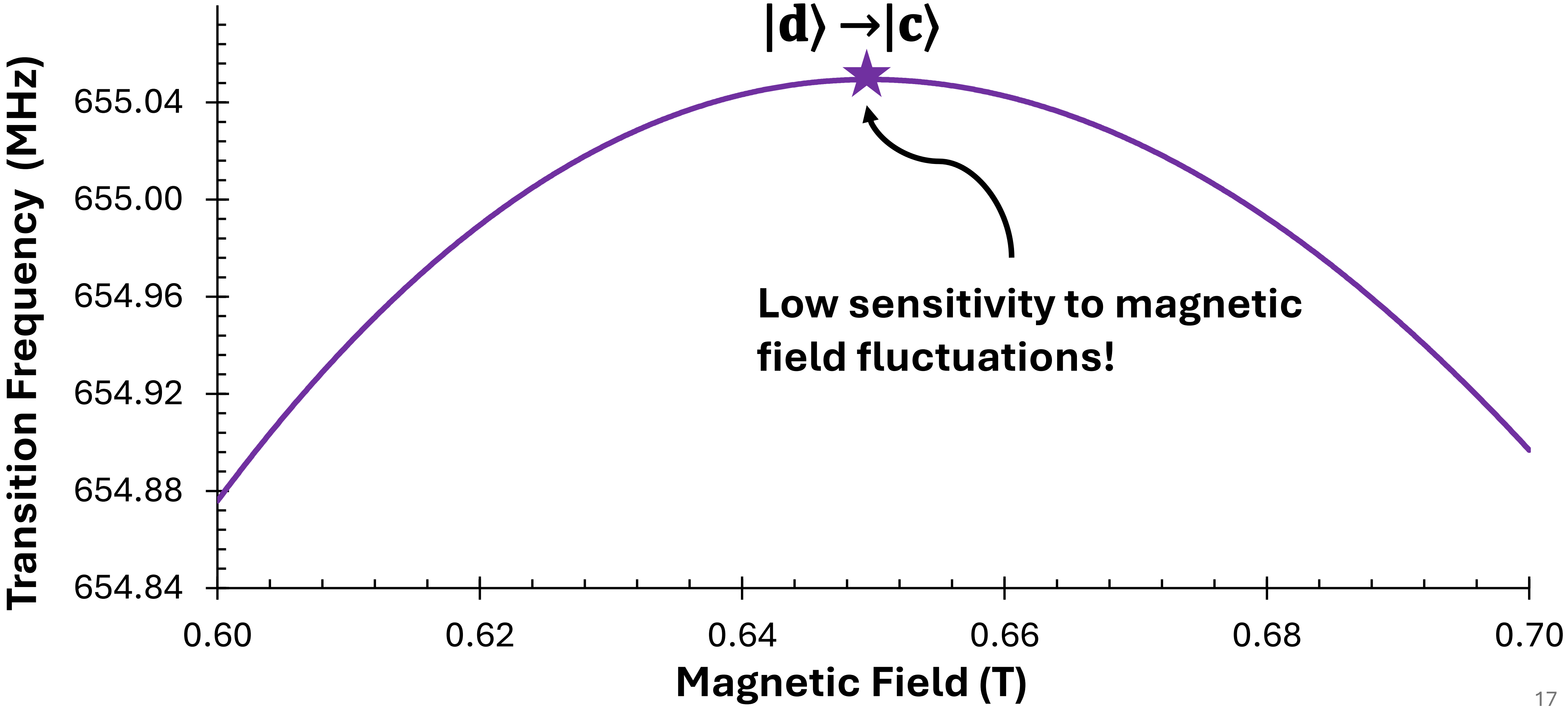
Ground State Hyperfine Structure



NMR-type Transition



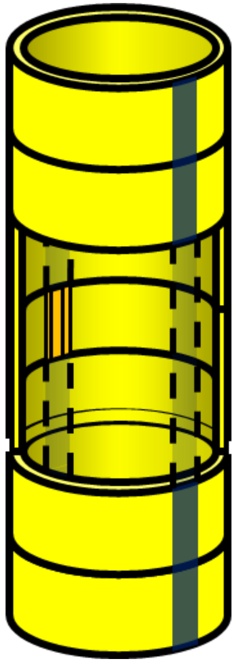
NMR-type Transition



NMR Spectroscopy

Matter and Antimatter **Symmetry**

Hyperfine Structure of Antihydrogen

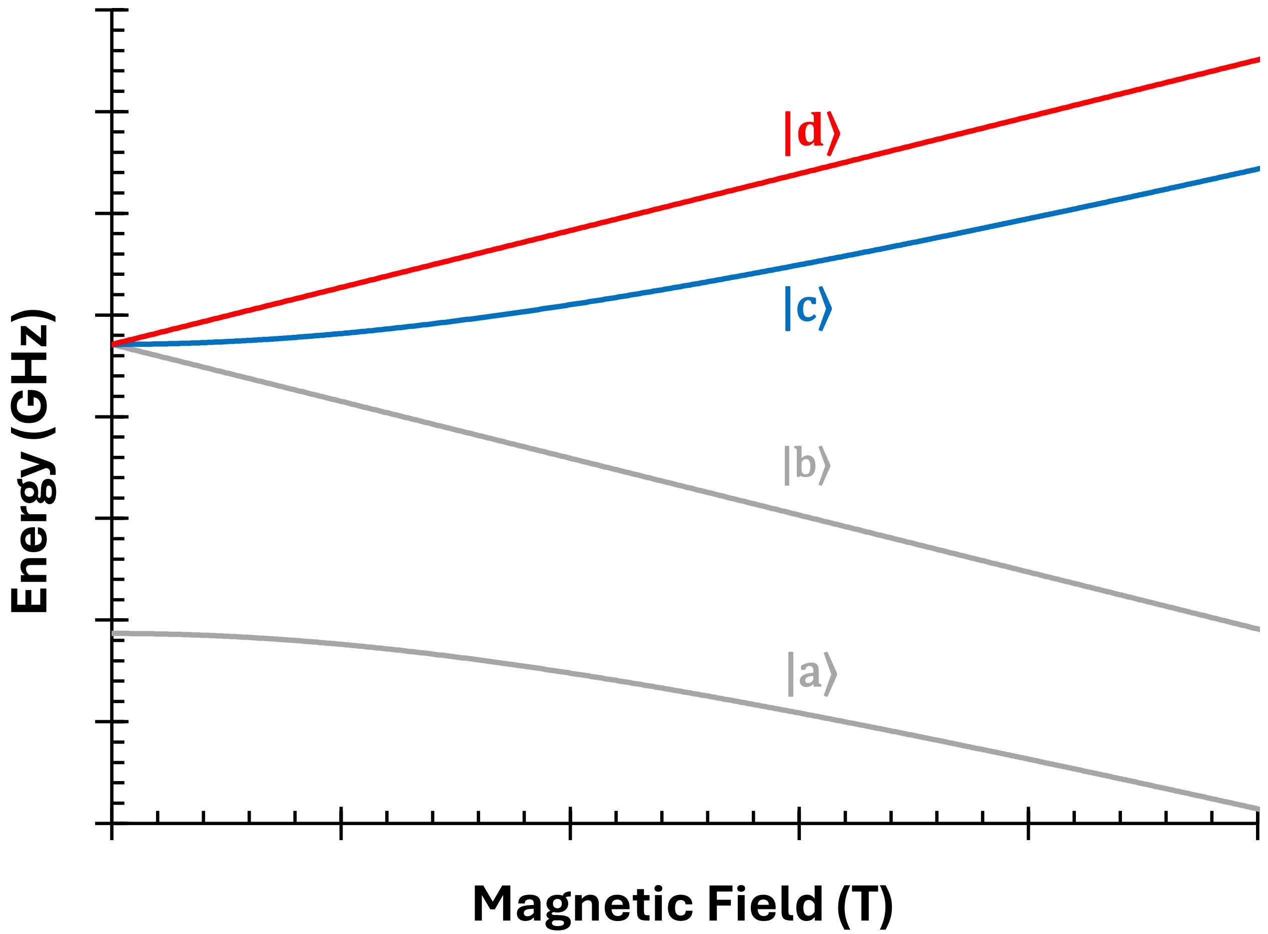


NMR Spectroscopy Experiment

NMR Experiment

We want to perform the
|d⟩ →|c⟩ transition

Transition Freq:
655 MHz



Cutoff Frequency Problem

Trap Radius ≈ 2 cm
Cutoff freq. ≈ 4 GHz

VS.

NMR Transition (655 MHz, $\lambda \approx 46$ cm)

Cutoff Frequency Problem

Trap Radius ≈ 2 cm
Cutoff freq. ≈ 4 GHz

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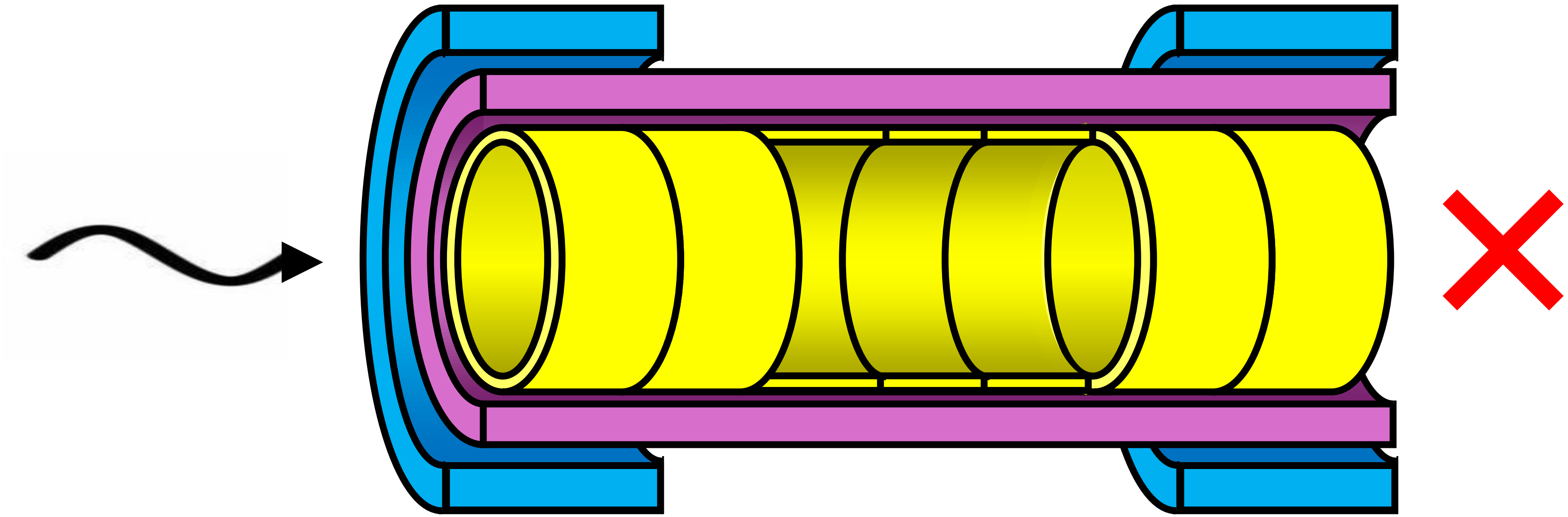
NMR Transition (655 MHz, λ ≈ 46 cm)

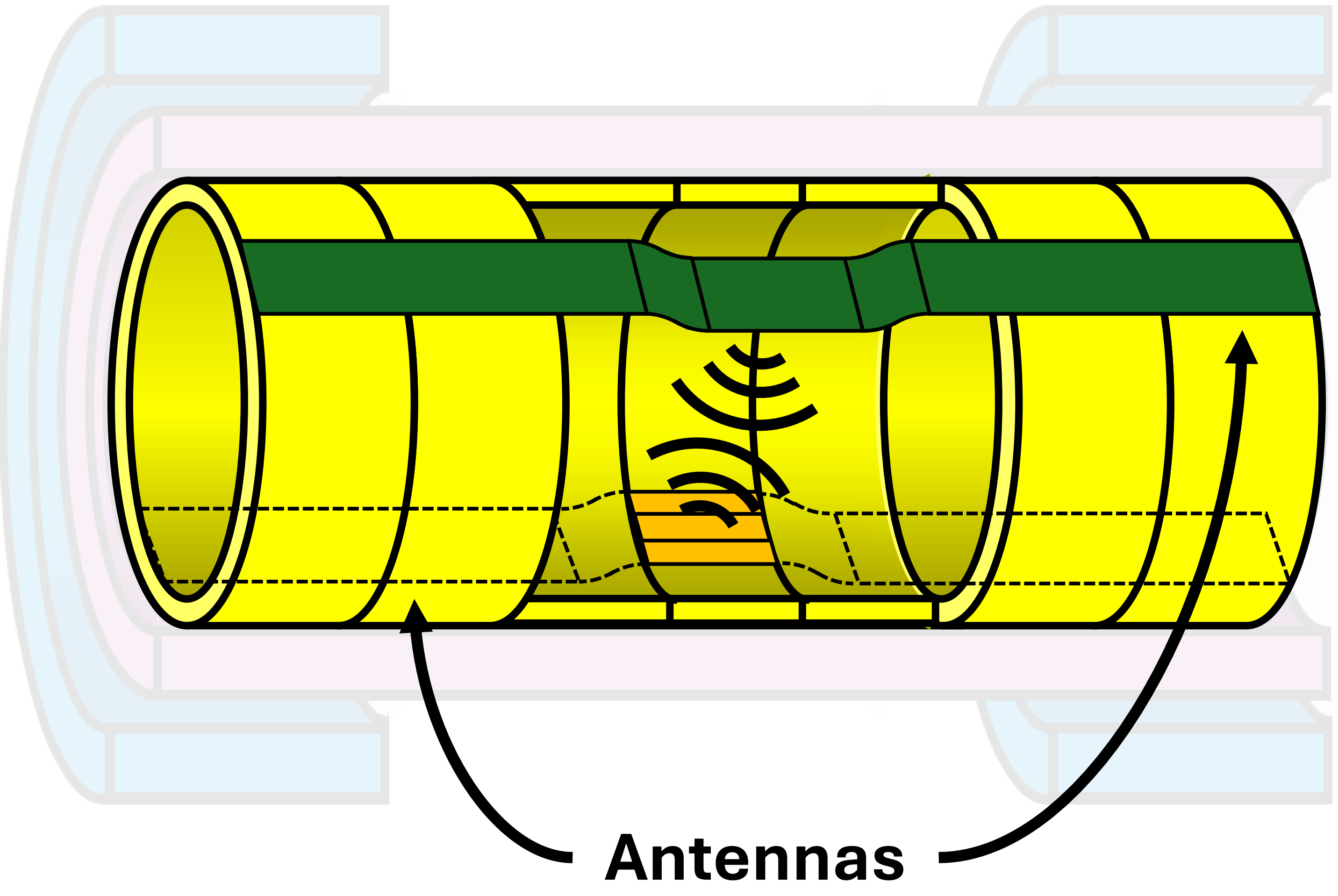
655 MHz



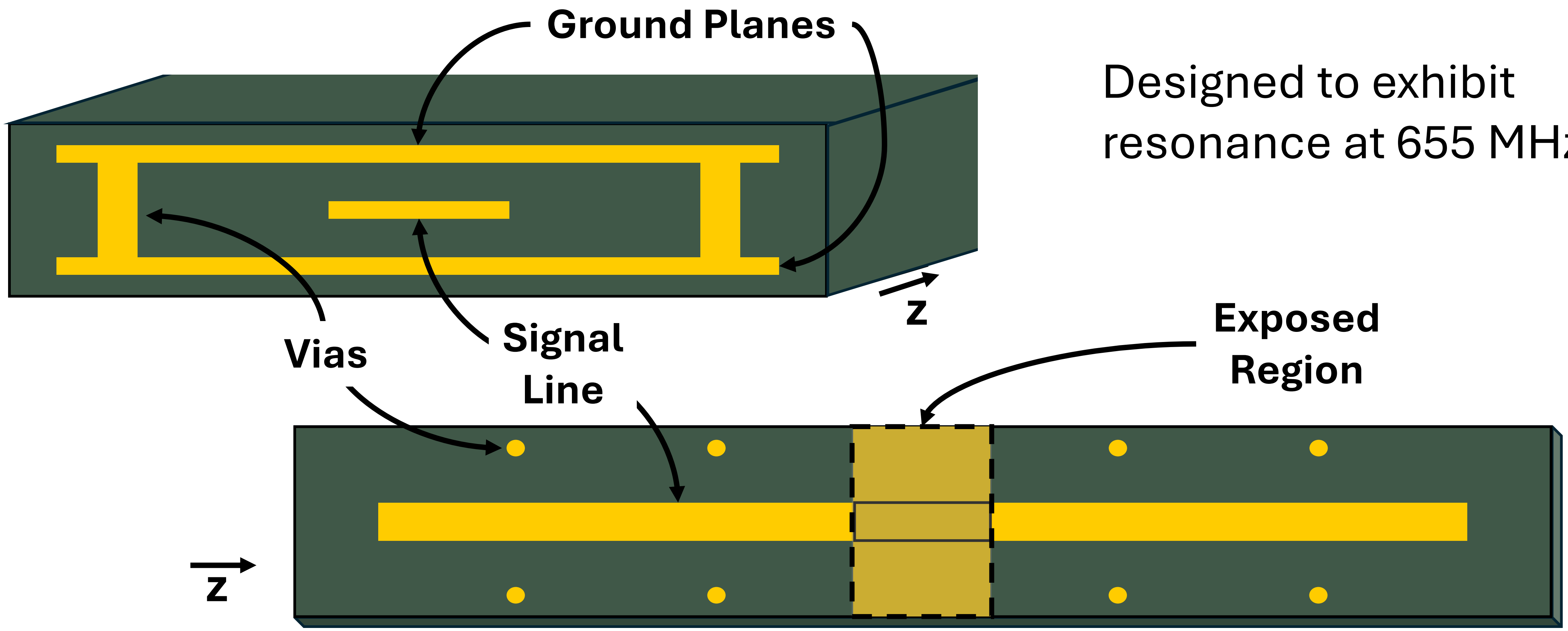
NMR Experiment Design

New System:

- Two resonator antennas to inject 655 MHz waves
- Antennas follow a modified half-wave stripline resonator design
- Weave into trap interior



Stripline Resonator Antenna

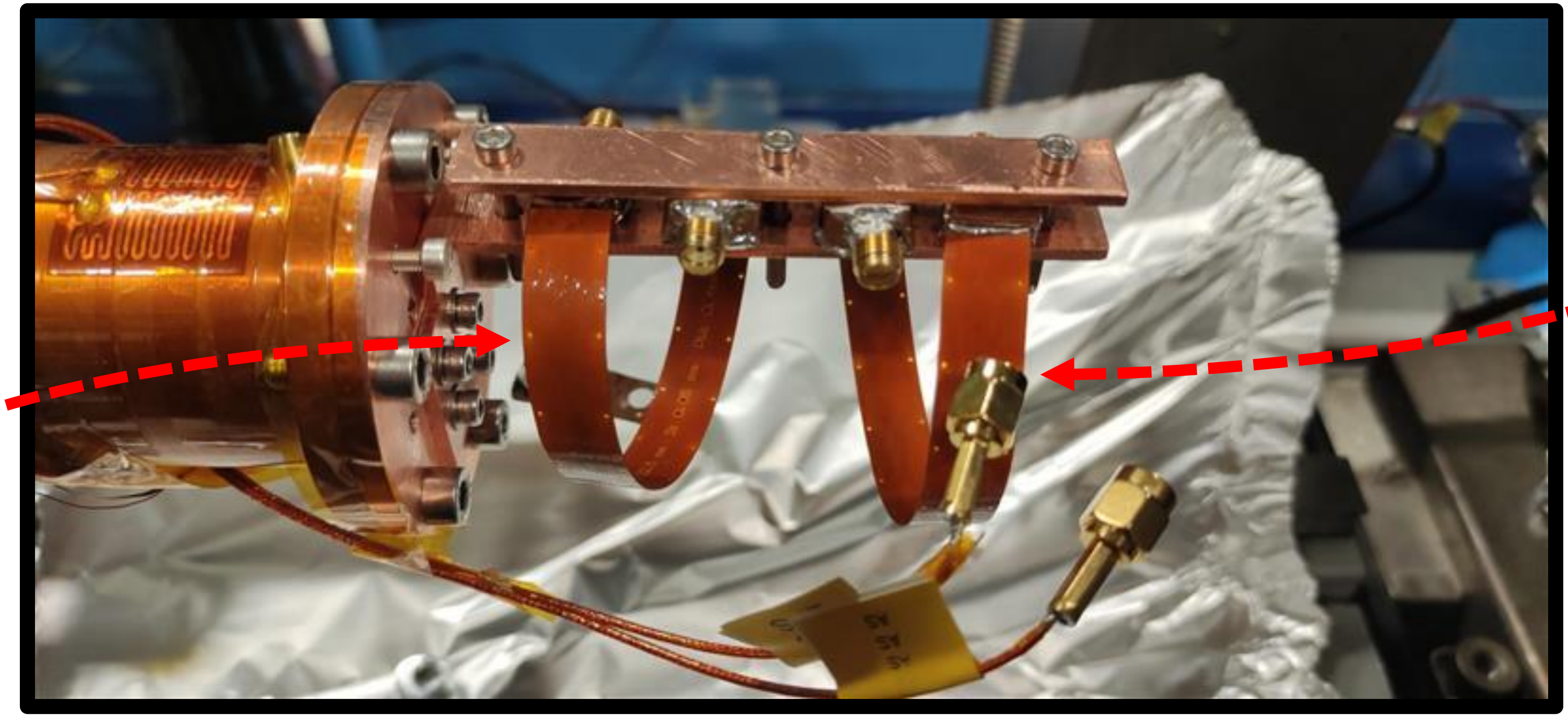


Designed to exhibit resonance at 655 MHz

NMR Test Resonators

Need real data at cryogenic conditions to inform the antenna design

Resonator



Resonator

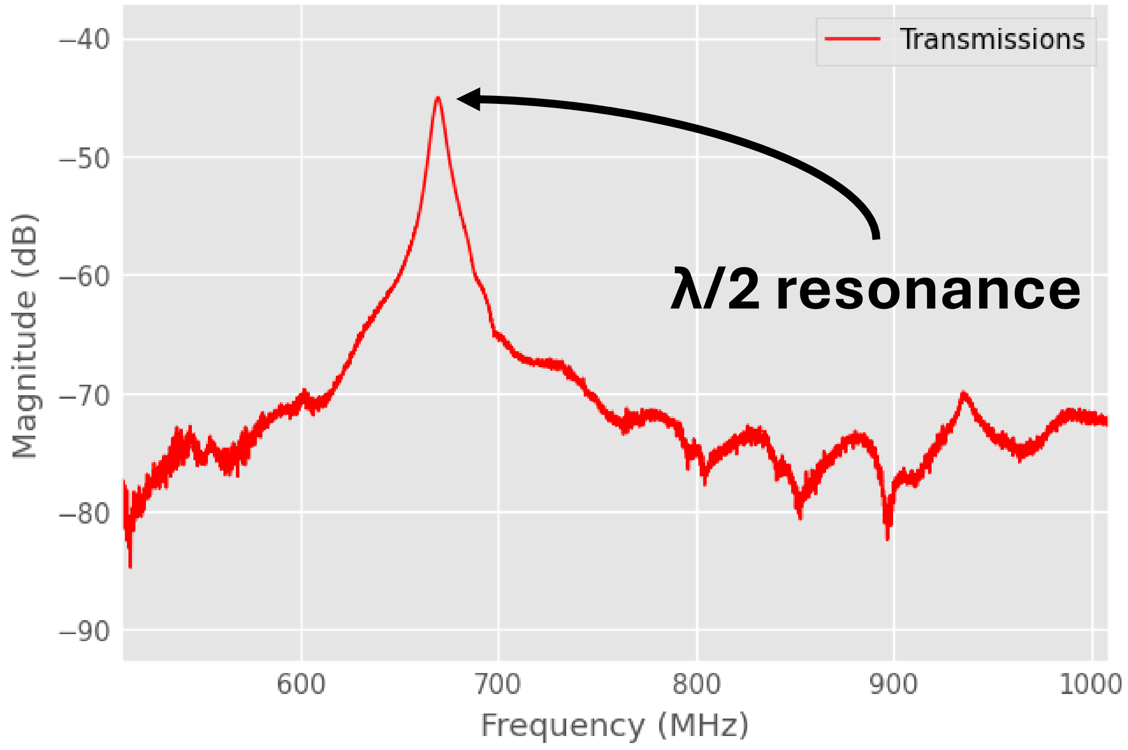
Two Test Resonator Circuits

Courtesy of Alberto Jesus Uribe Jimenez

NMR Test Resonators

Need real data at cryogenic conditions to inform the antenna design

Transmission Spectrum

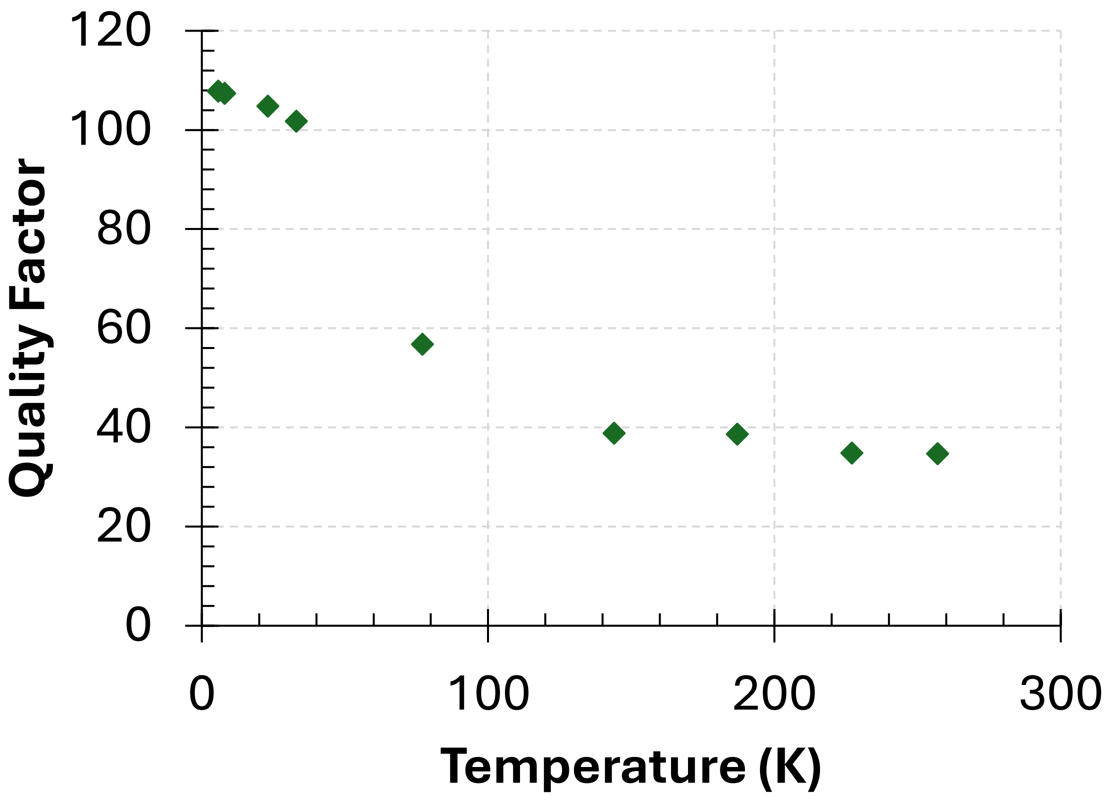


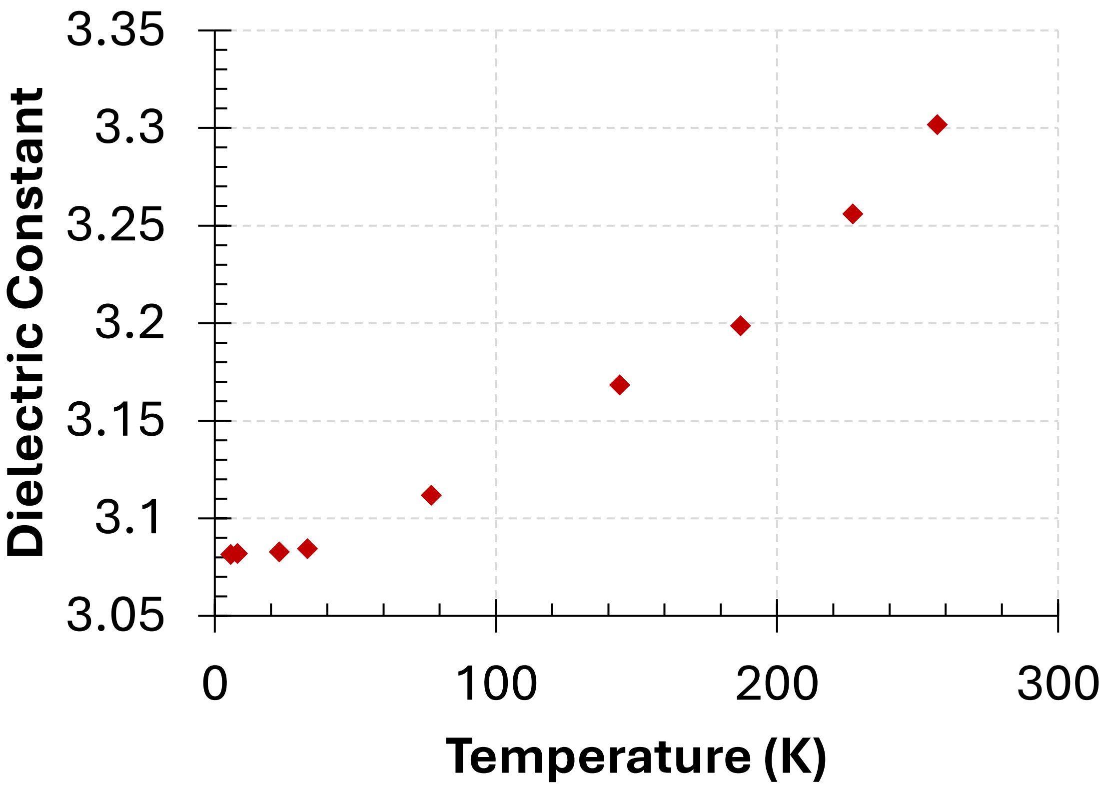
We can obtain:

- **Dielectric** properties
- **Conductor** effects
- Undesired **modes**

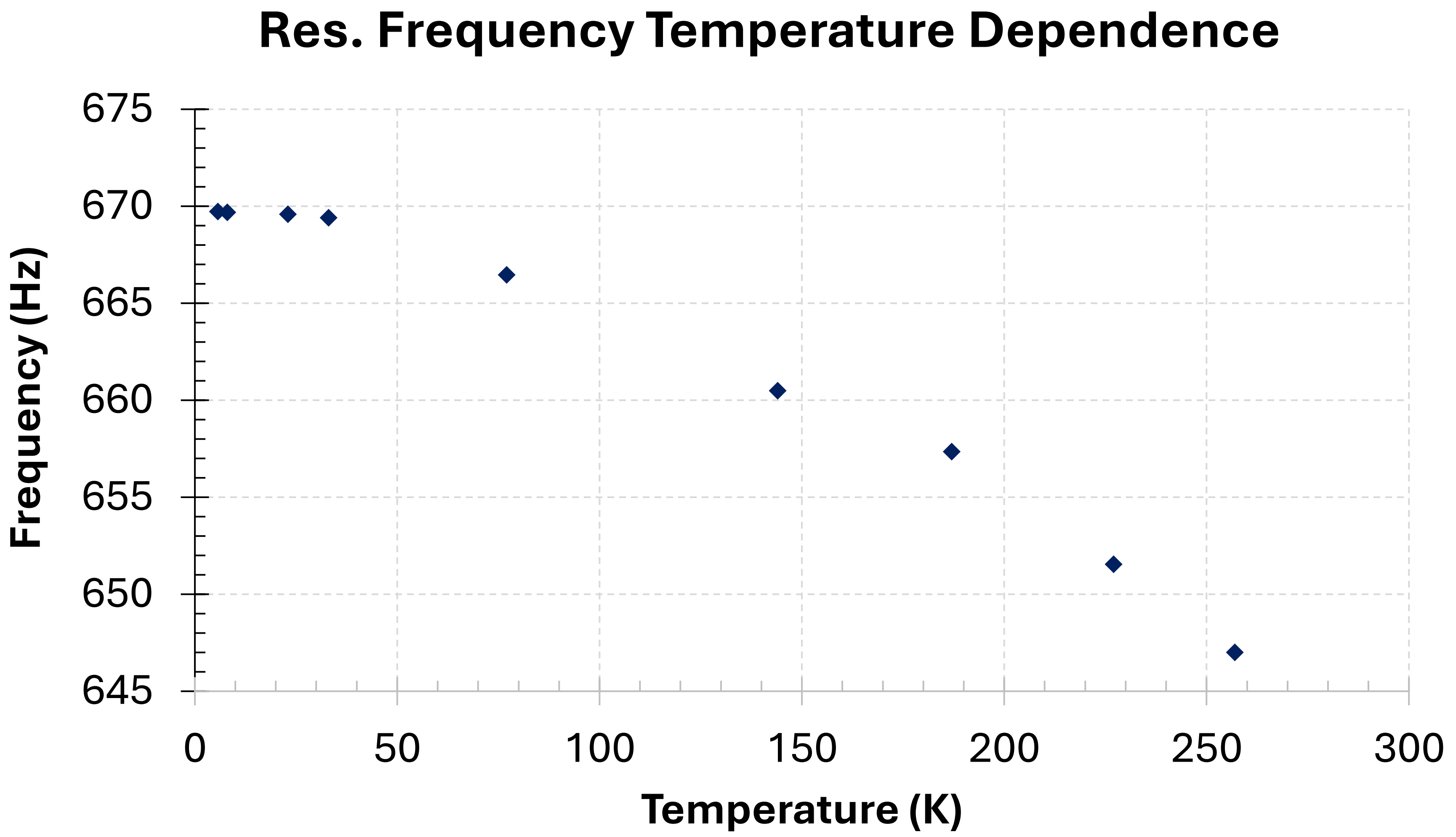
NMR Test Resonators

Temperature Dependence Measurements





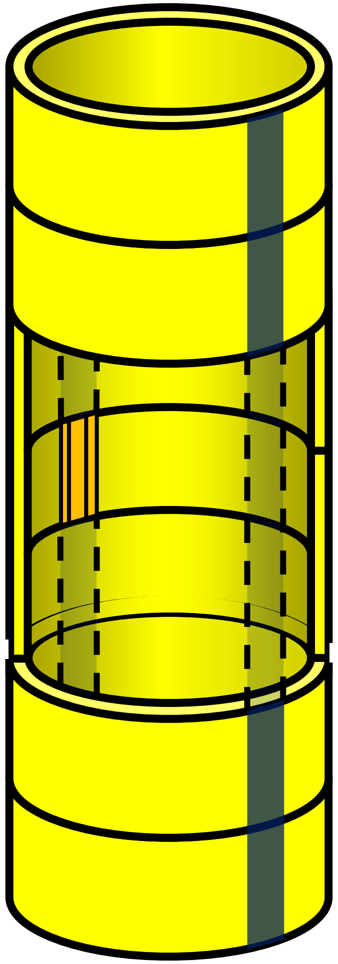
NMR Test Resonators



Summary and Outlook

- **NMR Spectroscopy:** developing a new method to investigate an unprobed feature of antihydrogen, with the potential for high precision.
- **Test Resonators:** performed measurements with 'test' circuits to determine how the system acts in cryogenic conditions
- **Implementation:** manufacture the first antennas, perform the first demonstrations of the NMR transition

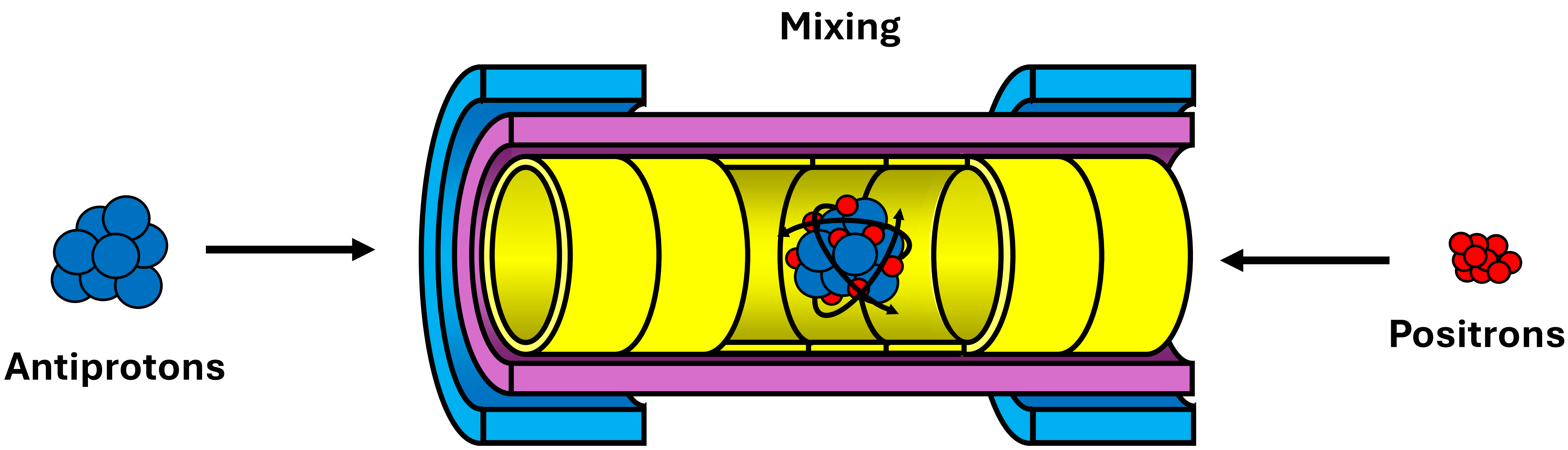
NMR Resonator Antenna



NMR Experiment

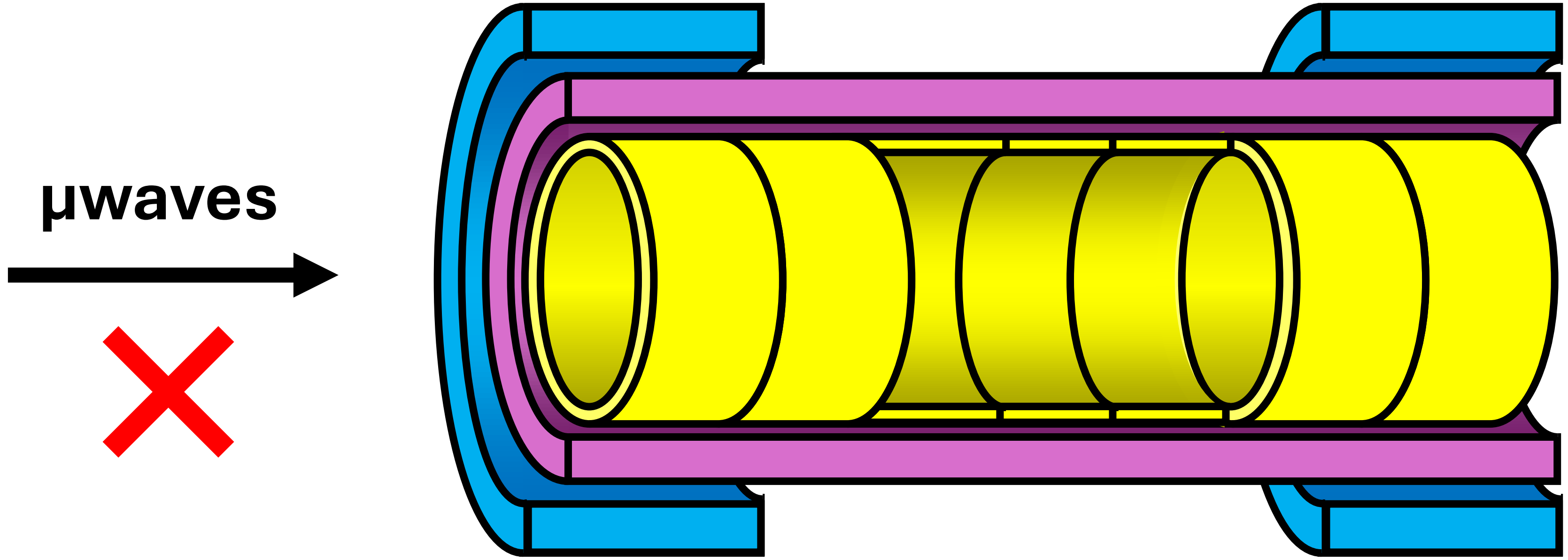
Supplemental Slides

Trapping Antimatter at ALPHA



Antiprotons/positrons are cooled and mixed at the centre of the trap

NMR Experiment Design



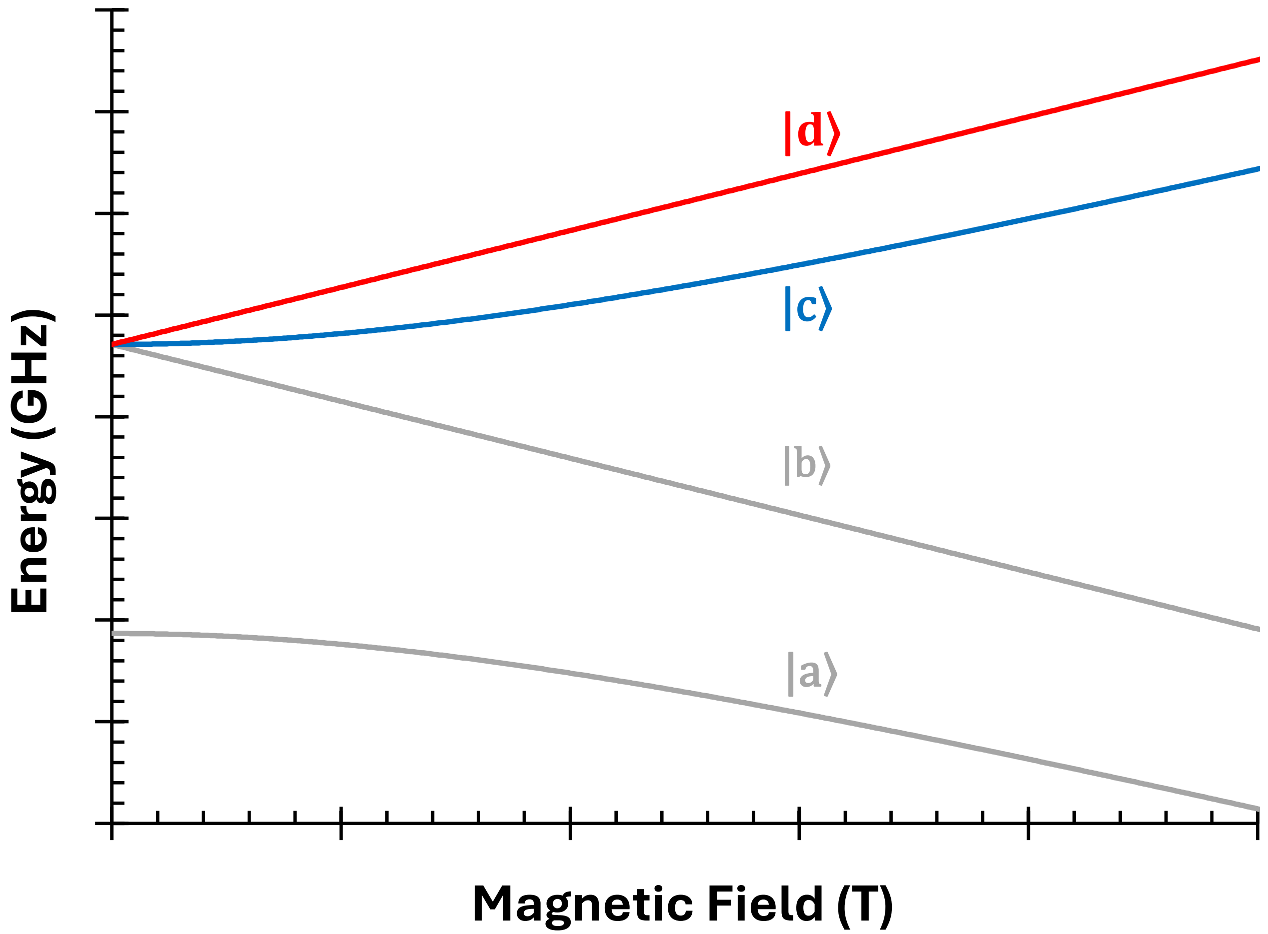
ALPHA Trap

Cannot inject 655 MHz wave axially

Develop a **new microwave injection** system

NMR Experiment Protocol

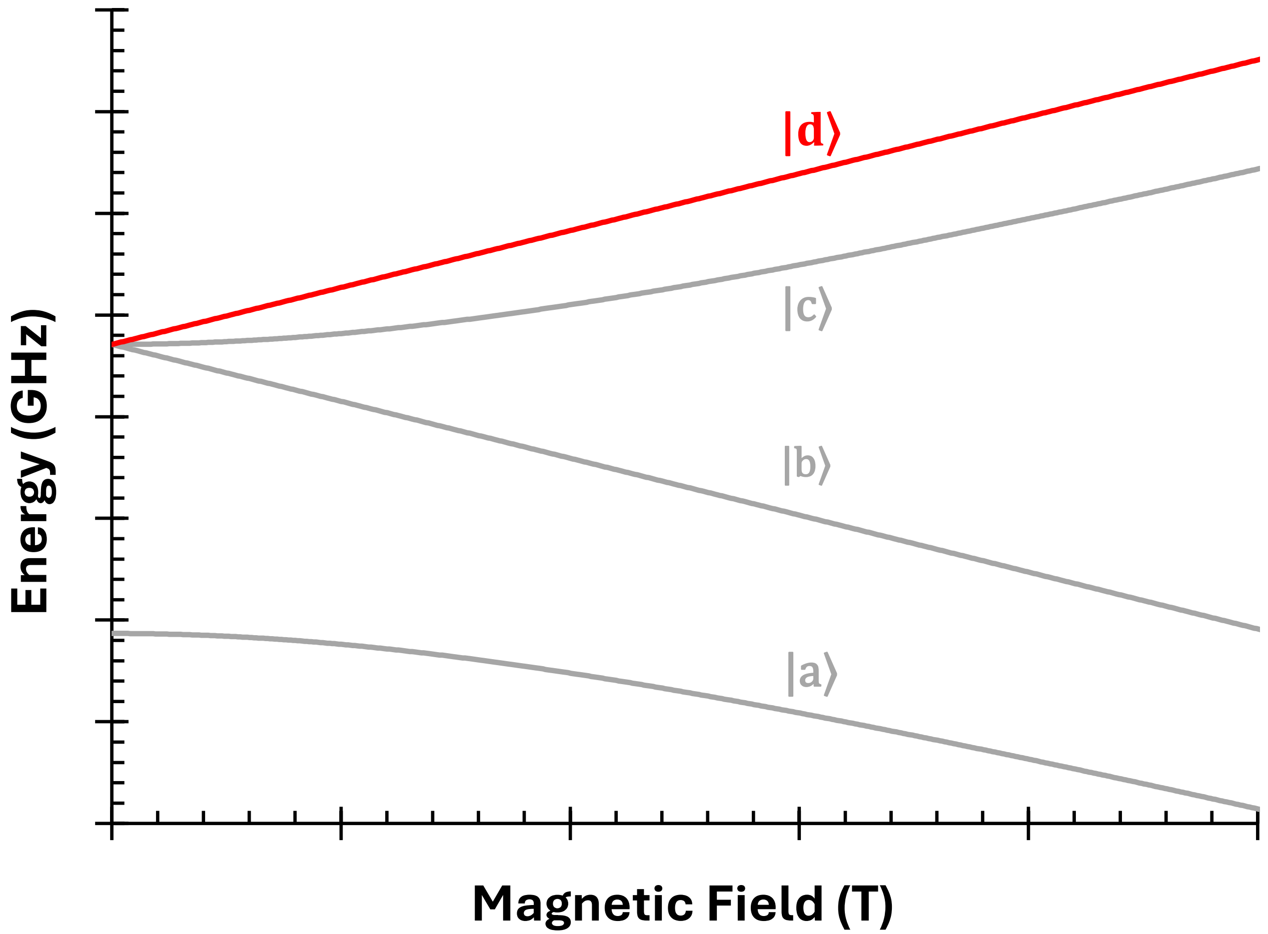
1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states



NMR Experiment Protocol

1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states

2. **Empty the |c⟩ state atoms**



NMR Experiment Protocol

1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states

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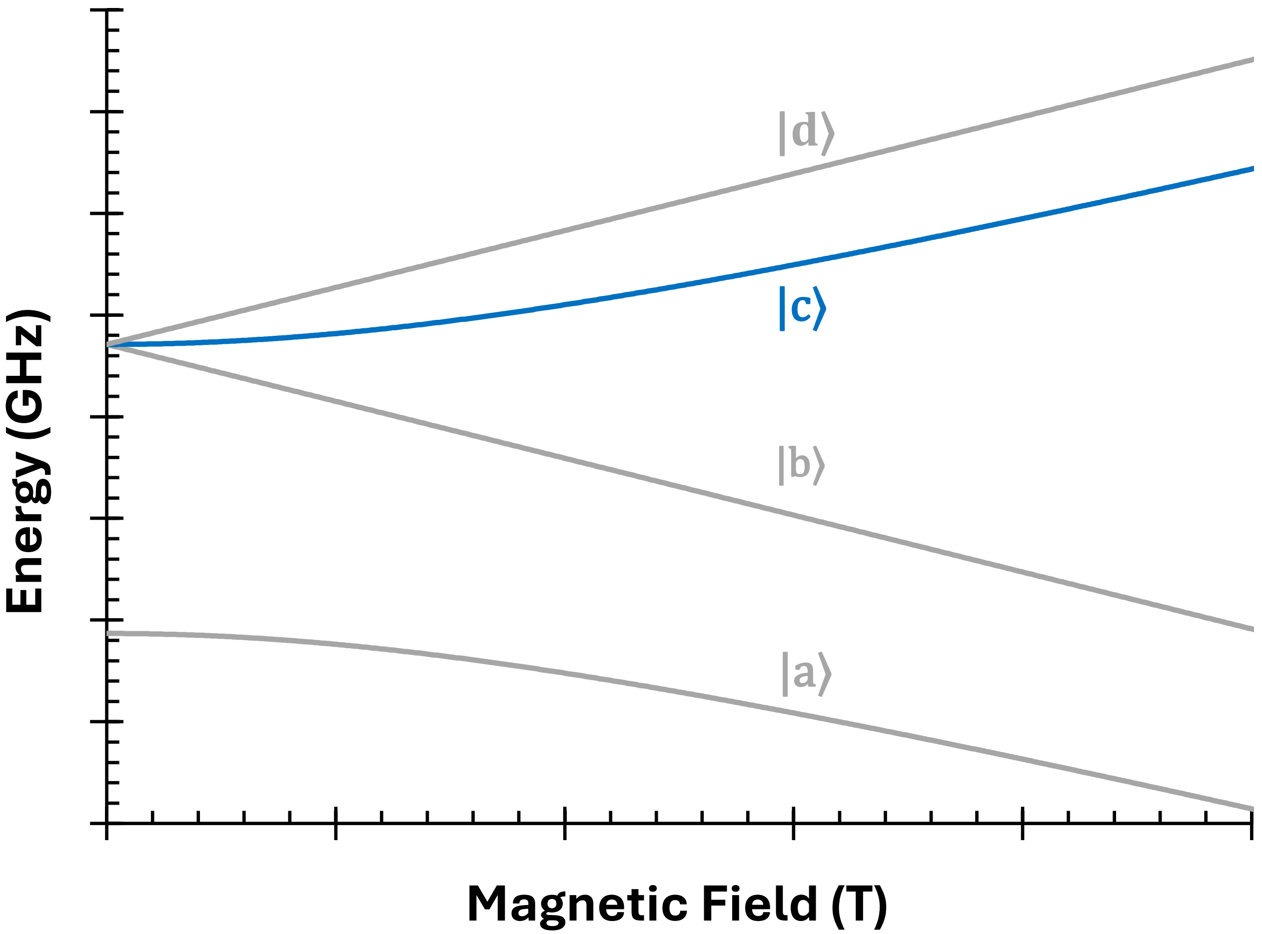
3. **Induce the |d⟩ to |c⟩ (NMR) transition**



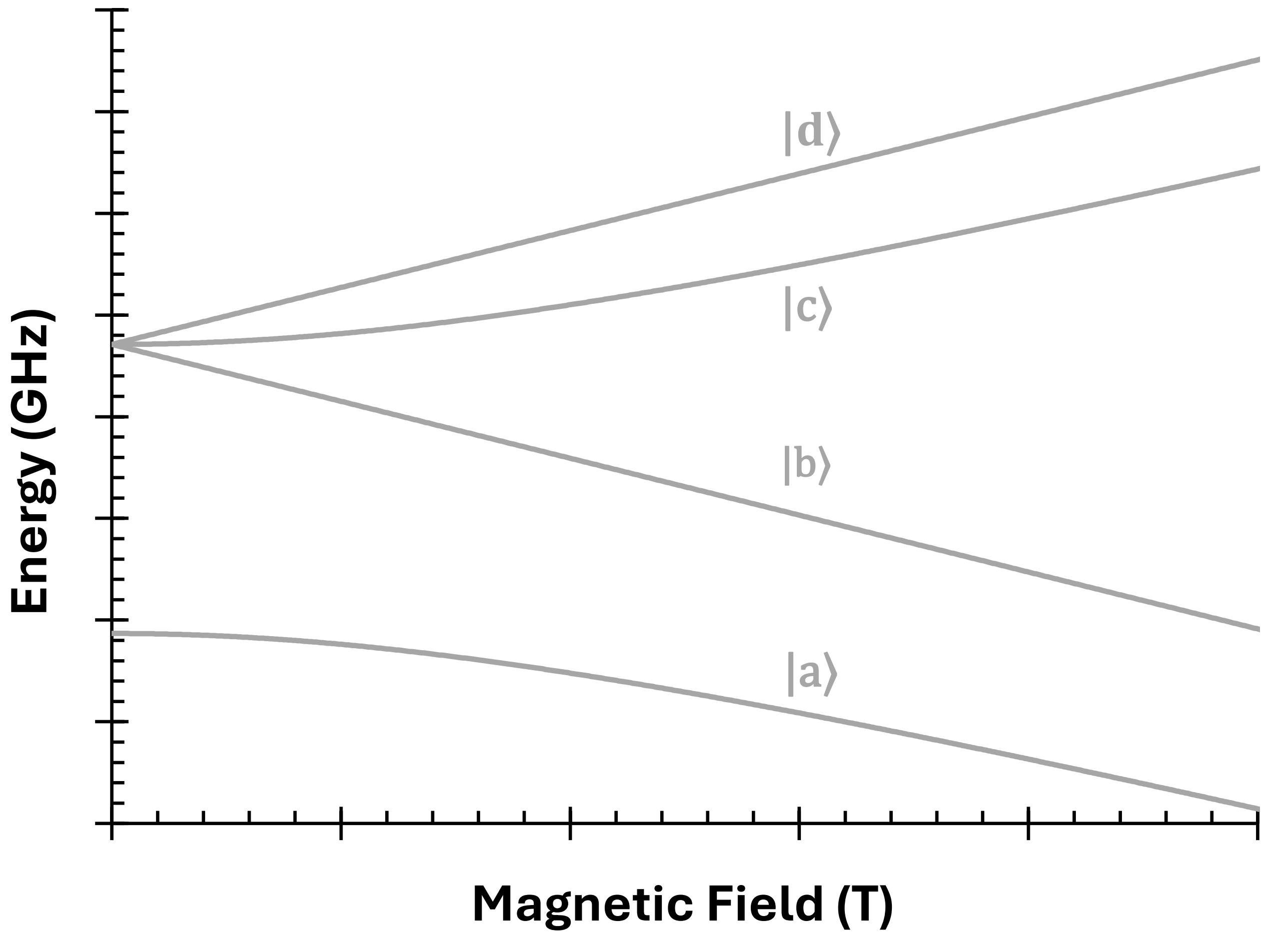
NMR Experiment Protocol

1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states

2. Empty the |c⟩ state atoms

3. Induce the |c⟩ to |d⟩ (NMR) transition

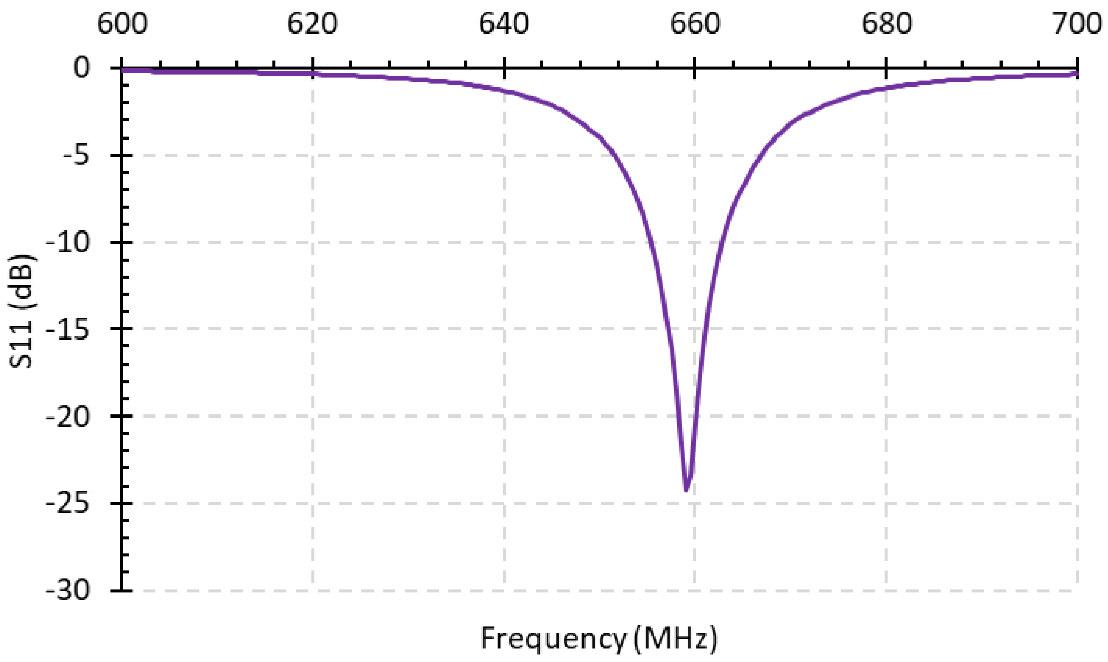
4. **Empty the |c⟩ state atoms again and observe the counts**



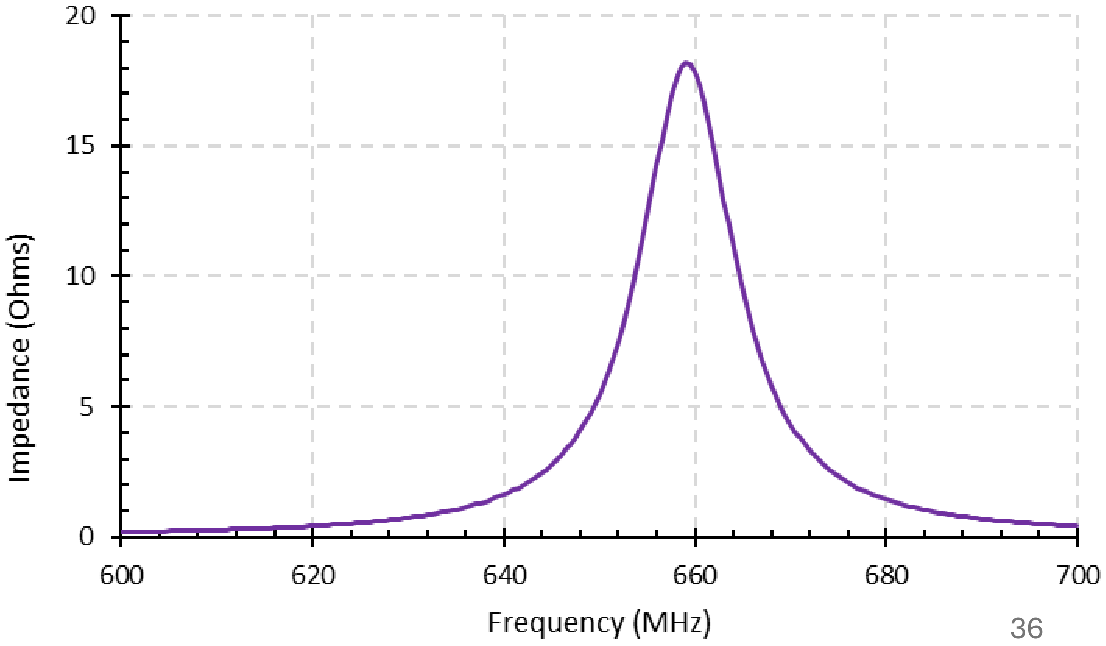
NMR Antenna Simulation Data

Use an electromagnetic modelling software (ANSYS HFSS) to design antennas

Reflections



Real Impedance



Attenuation Factor Calculations

$$\alpha = \alpha_c + \alpha_D$$

$$\alpha_c = \frac{(2.7 \cdot 10^{-3}) R_S \varepsilon_r Z_0}{30\pi(b - T_R)} A$$

$$R_S = \sqrt{\frac{\mu_0 \pi f}{\sigma}}$$

$$\alpha_D = \frac{\pi\sqrt{\varepsilon_r}\tan\delta f}{c}$$

$$\alpha = \frac{\pi}{2LQ_0}$$