Hyperfine Interact
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Progress towards microwave spectroscopy of trapped antihydrogen

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Abstract Precision comparisons of hyperfine intervals in atomic hydrogen and antihydrogen are expected to yield experimental tests of the CPT theorem. The CERN-based ALPHA collaboration has initiated a program of study focused on

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microwave spectroscopy of trapped ground-state antihydrogen atoms. This paper outlines some of the proposed experiments, and summarizes measurements that characterize microwave fields that have been injected into the ALPHA apparatus.

Keywords Antihydrogen · CPT · Hyperfine splitting · Penning-Malmberg trap · Neutral atom trap

1 Introduction

The ultimate goal of Project ALPHA is to study antihydrogen ($\overline{\mathrm{H}}$) atoms and compare their properties with those of hydrogen (H) atoms, to determine whether or not discrepancies exist. One of the most-precisely determined quantities in physics is the zero-field hyperfine splitting of ground state hydrogen; that is, the energy difference between the singlet (F=0) and triplet (F=1) states of the atom in the limit of no externally-applied magnetic field. This quantity is known to an experimental precision of 10^{-12} [1], providing a solid benchmark against which the corresponding splitting in antihydrogen can be compared. No measurement of the ground-state hyperfine splitting for antihydrogen yet exists. Additionally, the gyromagnetic ratio of

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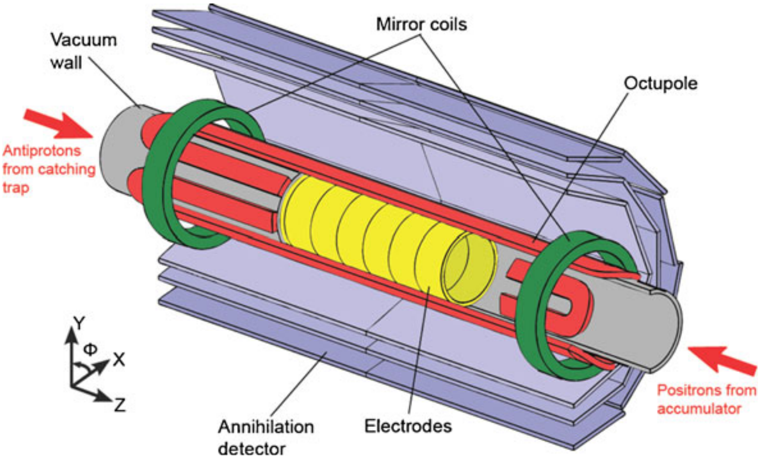


Fig. 1 A schematic 'cut-away' view of the ALPHA apparatus showing the arrangement of superconducting magnets that form the neutral atom trap

the antiproton ($\gamma_{\bar{p}}$) is at present only determined to 3 parts in 10^3 [2]; in principle, the precision to which this quantity is known can also be improved through microwave spectroscopy of ground-state antihydrogen. Two recent reports from the ALPHA collaboration mark substantial progress toward the realization of experiments that will begin to fill in these gaps in knowledge. We have successfully confined neutral antihydrogen atoms in a magnetic trap [3], and have shown that these atoms end up in their ground electronic state where they can be held for time periods of order 15 minutes [4].

2 Neutral atom trap

The synthesis of cold antihydrogen in the ALPHA apparatus is accomplished through careful manipulation and mixing of antiproton and positron plasmas in a Penning-Malberg trap. Electrostatic potentials applied to a series of hollow cylindrical electrodes confine charged particles in the axial direction while a uniform 1 Tesla solenoidal magnetic field provides radial confinement.

Neutral antihydrogen atoms are in turn confined by a sophisticated combination of superconducting magnets arranged as a variation of the Ioffe-Pritchard minimum-magnetic-field geometry [5]. This configuration consists of a pair of solenoidal 'mirror' coils that generates the axial minimum-magnetic-field and a transverse octupole that creates a radial minimum-magnetic-field (Fig. 1). The confinement of neutral atoms is accomplished via interaction of their magnetic dipole moments $\boldsymbol{\mu}$ with the inhomogeneous magnetic field $\mathbf{B}$. The ALPHA trap can confine ground state antihydrogen atoms with kinetic energies less than 0.5 K in temperature units. Note that only atoms with $\boldsymbol{\mu}$ aligned antiparallel with respect to the static magnetic field can be trapped.

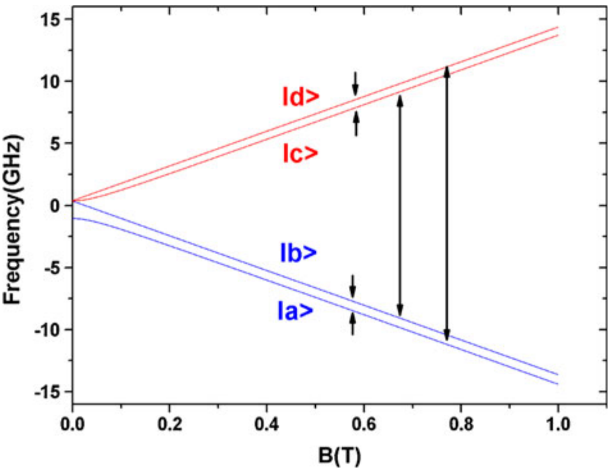


Fig. 2 Relative hyperfine energy levels (in frequency units) and allowed transitions for ground state H (or $\overline{\mathrm{H}}$) when a time-varying magnetic field $\mathbf{B}_1$ is applied perpendicular to the static field

3 Experimental concept

The Breit-Rabi diagram for the ground state of the H (or $\overline{\mathrm{H}}$) atom is shown in Fig. 2. The four eigenstates are labeled $|a\rangle$, $|b\rangle$, $|c\rangle$ and $|d\rangle$ in order of increasing energy in low magnetic fields. The 'low-field seeking' states $|c\rangle$ and $|d\rangle$ have $\boldsymbol{\mu}$ antiparallel to $\mathbf{B}$ and can be trapped. The 'high-field seeking' states $|a\rangle$ and $|b\rangle$ have $\boldsymbol{\mu}$ parallel to $\mathbf{B}$ and cannot be trapped. For H, the relative energies of these states are given by:

$$E_a = -\frac{a}{4} - \frac{a}{2}\sqrt{1 + \left[\frac{\hbar\left(\gamma_e + \gamma_p\right) B}{a}\right]^2} \tag{1}$$

$$E_b = \frac{a}{4} - \frac{\hbar}{2}\left(\gamma_e - \gamma_p\right) B \tag{2}$$

$$E_c = -\frac{a}{4} + \frac{a}{2}\sqrt{1 + \left[\frac{\hbar\left(\gamma_e + \gamma_p\right) B}{a}\right]^2} \tag{3}$$

$$E_d = \frac{a}{4} + \frac{\hbar}{2}\left(\gamma_e - \gamma_p\right) B\,. \tag{4}$$

where a is the zero-field hyperfine splitting constant for the ground state atom and γ_e and γ_p are the gyromagnetic ratios of the electron and proton. Equivalent expressions exist for $\overline{\mathrm{H}}$, involving the gyromagnetic ratios of the positron (γ_{e^+}) and antiproton ($\gamma_{\bar{p}}$).

The essential idea for microwave spectroscopy of trapped antihydrogen atoms is to induce transitions from trapped (low-field seeking) to non-trapped (high-field seeking) states by applying time-varying magnetic fields. The consequence of such transitions would be the ejection of atoms from the trap, followed by their annihilation on nearby electrodes; products of these annihilation events would then be recorded by the ALPHA annihilation detector (Fig. 1). Knowing the frequency at which transitions are induced would enable one to infer the zero-field hyperfine

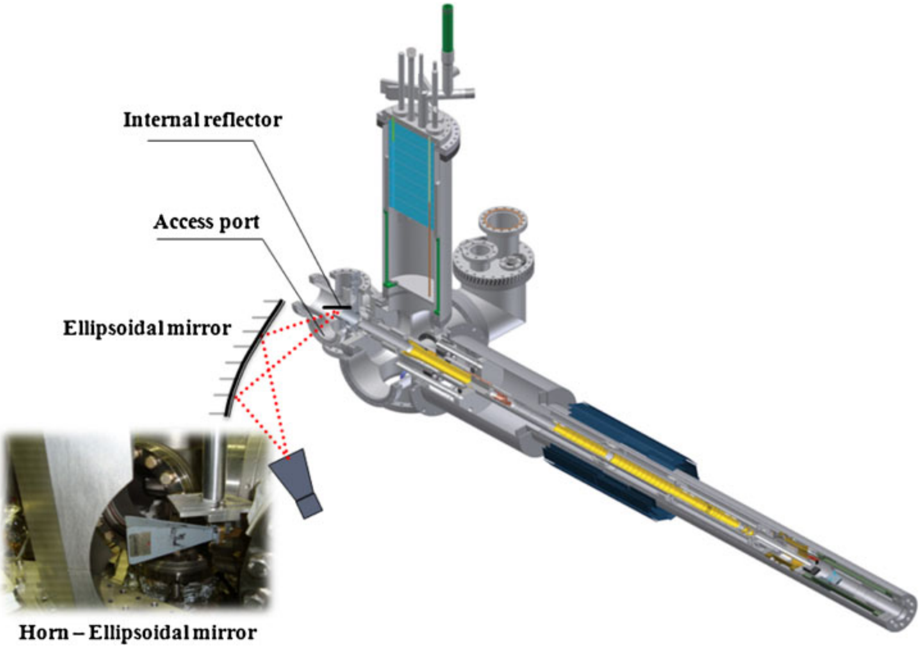


Fig. 3 A schematic view of microwave injection into the ALPHA apparatus using an external ellipsoidal mirror

splitting constant of the antihydrogen atom and the gyromagnetic ratio of the antiproton.

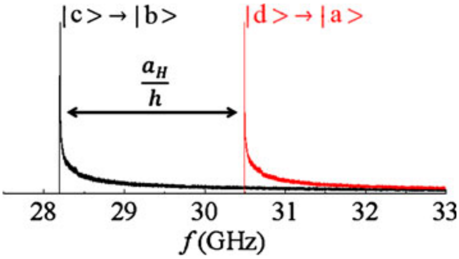
Figure 2 also shows the allowed transitions between hyperfine levels when a time-varying magnetic field is applied perpendicular to the static magnetic field. In the high-field limit, two of these transitions ($|c\rangle \rightarrow |b\rangle$ and $|d\rangle \rightarrow |a\rangle$) amount to a positron spin flip. We refer to these as PSR transitions (cf. ESR transitions for the hydrogen atom). In the same limit, the other two transitions ($|d\rangle \rightarrow |c\rangle$ and $|b\rangle \rightarrow |a\rangle$) amount to an antiproton spin flip, and are thus referred to here as NMR transitions.

4 Injection of microwaves into the ALPHA apparatus

K_a-band microwaves suitable for PSR can be injected using a horn antenna and ellipsoidal mirror, both of which are located outside the trapping apparatus. The beam then passes though a window, strikes a planar metallic reflector inside the apparatus, and enters the electrode stack (Fig. 3).

The ellipsoidal mirror consists of a block of aluminum machined so as to mimic part of the inner surface of an ellipsoid of revolution. Efficient injection of the beam into the heart of the apparatus is accomplished by placing the microwave horn at one focal point of the ellipsoidal mirror and arranging for the other focal point to lie near the midpoint of the internal reflector.

Fig. 4 Distribution of PSR transition frequencies in the trap, as determined from a Monte Carlo simulation of trapped atom dynamics. In this example, atoms were loaded from the low energy tail of a 15 K thermal distribution. The central magnetic field is 1 Tesla



5 Strategies

5.1 PSR transitions

The simplest measurement strategies involve PSR transitions. Low-field seeking atoms ($|c\rangle$ and $|d\rangle$) are first confined in the neutral atom trap. Then, in one scenario, a transverse microwave magnetic field $\mathbf{B}_1$ resonant with the $|c\rangle \rightarrow |b\rangle$ transition is applied to convert $|c\rangle$ state atoms into $|b\rangle$ state atoms. These $|b\rangle$ state atoms are high-field seeking and are thus are ejected from the trap and annihilate when they strike the electrode walls. Once the $|c\rangle$ state population in the trap is depleted, the process could be repeated with the microwave field tuned to the resonant frequency of the $|d\rangle \rightarrow |a\rangle$ transition. If both PSR transition frequencies (f_{bc} and f_{ad}) are measured under precisely the same conditions, their difference yields the hyperfine splitting constant a of ground state antihydrogen without requiring a simultaneous measurement of the magnetic field; that is

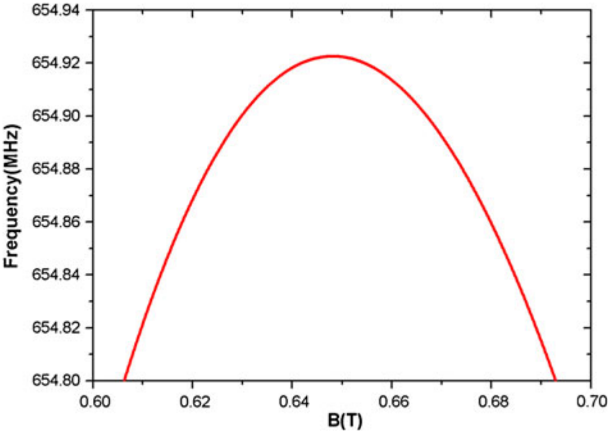
$$(E_d - E_a) - (E_c - E_b) = a\,. \tag{5}$$

Figure 4 shows the distribution of PSR transition frequencies, as determined from a Monte Carlo simulation of atomic trajectories in which the trap is loaded with equal numbers of $|c\rangle$ and $|d\rangle$ state atoms. The abrupt edges in these distributions are associated with the minimum in the static field near the center of the trap and the long tails reflect the fact that everywhere else, the static field is inhomogeneous. Importantly, these edges represent a sharp spectroscopic feature that can be probed by varying the frequency of the microwave fields used to induce transitions. With many cold trapped atoms available for study (and a carefully designed and controlled magnetic field profile near the trap minimum), one might expect measurements of PSR transition frequencies to eventually yield the hyperfine splitting constant a to about 1 part in 10^7.

5.2 NMR and PSR transitions

Another possible measurement involves inducing both NMR and PSR transitions. In this experiment, the first step is to eject all of the atoms in the $|c\rangle$ state by driving the $|c\rangle \rightarrow |b\rangle$ transition, leaving only $|d\rangle$ state atoms in the trap. Then the $|d\rangle \rightarrow |c\rangle$ transition (NMR) and the $|c\rangle \rightarrow |b\rangle$ transition (PSR) are driven sequentially. Again this leads to atoms being ejected from the trap, enabling one to measure both f_{cd} and f_{bc}.

Fig. 5 Frequency of the $|c\rangle \rightarrow |d\rangle$ transition as a function of magnetic field in the vicinity of the maximum that occurs at $B = B' \approx 0.65$ Tesla



There is an important feature of this measurement that can be used to advantage for spectroscopy. The transition frequency f_{cd} passes through a maximum at a magnetic field $B' = 0.65$ Tesla (Fig. 5). In other words, to first order f_{cd} is independent of B at B'. The absolute value of this transition frequency at this particular field is a characteristic of the antihydrogen atom that is of interest in its own right, and one that could be compared to a corresponding measurement for hydrogen. The fact that it is associated with an extremum suggests that in principle one could measure f_{cd} at $B = B'$ more accurately than at other fields. In this context one can show that

$$\frac{a}{h} = \frac{2\xi f'_{cd}}{\xi - 2} \qquad \text{and} \qquad \frac{\gamma_{\bar{p}}}{\gamma_{e^+}} = \frac{\xi}{2}\left(\xi - \sqrt{\xi^2 - 4}\right) - 1 \tag{6}$$

where

$$\xi = \frac{f'_{bc}}{f'_{cd}} - 1\,, \tag{7}$$

and f'_{cd} and f'_{bc} denote f_{cd} and f_{bc} at $B = B'$. Thus, simultaneous measurement of f'_{cd} and f'_{bc} gives the ground state antihydrogen hyperfine splitting constant a and the antiproton gyromagnetic ratio $\gamma_{\bar{p}}$ (since $\gamma_{e^-}/\gamma_{e^+}$ is already known to 8 parts in 10^{13} [6]) without requiring an independent measurement of B. As with a measurement of PSR transition frequencies alone (Section 5.1), there is significant spectroscopic advantage to performing this measurement on atoms as they pass through the turning point in the field near the centre of the trap.

6 Recent microwave measurements

The aim of this section is to briefly report some of the microwave measurements performed recently in the ALPHA apparatus. The primary goals of these experiments are to determine the efficiency of microwave injection into the heart of the ALPHA apparatus, and to calibrate microwave field amplitude in situ. The compatibility of the cryogenic ALPHA trapping apparatus with high power microwave radiation was also confirmed.

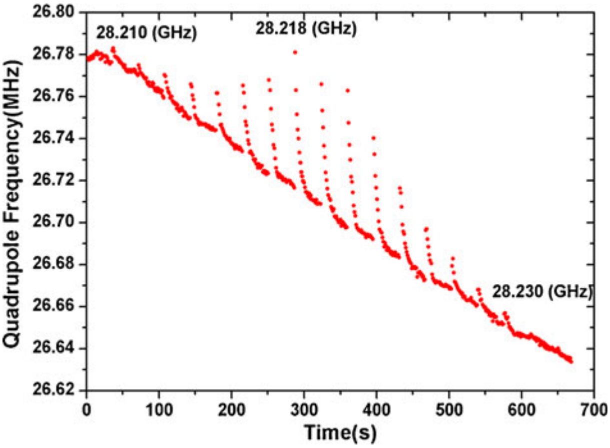


Fig. 6 Quadrupole mode frequency of the plasma in response to a series of microwave pulses, as the microwave frequency is stepped through the cyclotron resonance

6.1 Cyclotron resonance

The cyclotron frequency of trapped electrons is readily measured, and provides a useful diagnostic for probing the static magnetic field inside the apparatus. The measurement is typically conducted as follows: an electron plasma comprising approximately 7×10^7 particles (density: 6.5×10^{14} m^{-3}) is loaded at the center of the apparatus and then a sequence of 4 μs duration microwave pulses is applied at a rate of 33 mHz. The microwave frequency is incremented so as to scan through the cyclotron resonance. Meanwhile, collective modes of the electron plasma are excited (via potentials applied to the trap electrode), and the frequency of the quadrupole mode is determined and recorded. The frequency of this particular mode is a function of aspect ratio and plasma temperature [7]. When the frequency of the applied microwave electric fields matches the cyclotron frequency, the plasma heats up and causes the quadrupole mode frequency to shift (Fig. 6). Cyclotron radiation then provides a mechanism for the plasma to cool back down to equilibrium before the next microwave pulse is applied.

Data such as that shown in Fig. 6 enables one to determine the electron cyclotron frequency and hence the magnetic field inside the apparatus. It also clearly demonstrates that microwave fields are established in the apparatus at both the position and frequency of interest for spectroscopy.

As another application of these methods, we have used cyclotron resonance to heat positron plasmas (Fig. 7). This type of procedure has potential applications to antihydrogen trapping experiments. In particular, it provides a highly selective (i.e. resonant) method for heating positrons in the presence of antiprotons, without influencing the temperature of the latter.

6.2 Microwave field calibration

Precision PSR measurements require some knowledge of the microwave fields that are established inside the ALPHA apparatus. Methods similar to those described above can be used to obtain estimates of these fields. Again one starts by loading an electron plasma in the center of the apparatus. Then a pulse of microwave radiation

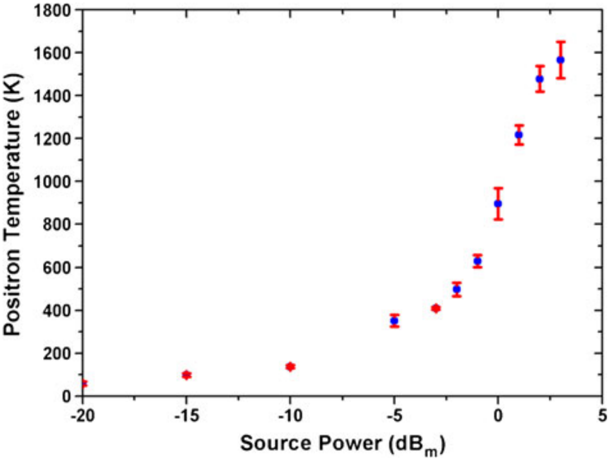


Fig. 7 Positron plasma temperature following a pulse of microwave injected at the cyclotron resonance frequency, as a function of source power. The base temperature of the positron plasma is of order 80 K

Table 1 Estimates of microwave field amplitudes inside the ALPHA trap, as inferred from cyclotron resonance heating experiments (plane wave approximation)

Frequency (GHz)	P_{Source} (dB$_m$)	E (V/m)	B_1(G)
28.233	+25	23	0.77×10^{-3}

at the cyclotron resonance frequency is injected, causing the plasma temperature to increase by ΔT (which is determined by monitoring the quadrupole mode frequency of the trapped plasma). In the limit where the duration τ of a rectangular microwave pulse is short compared to damping/collisional times in the plasma,

$$\Delta T = \frac{q^2 \tau^2 E_+^2}{12 m_e k_B}, \tag{8}$$

where E_+ is the component of the microwave electric field in a reference frame co-rotating with the cyclotron motion, q is the elementary charge, m_e is the electron mass, and k_B is the Boltzmann constant. Thus, by measuring ΔT one can infer the microwave electric field. Estimates of the microwave magnetic field amplitude B_1 and time-average power P propagating down the bore of the apparatus can then be made in various limits. For example, an analogy to plane wave propagation in free space would imply

$$P = \frac{A E^2}{2 Z_0}. \tag{9}$$

where $A \approx 16$ cm^2 is the open cross sectional area of the electrode stack and $Z_0 = 377\ \Omega$. Clearly this is a crude approximation, and the interpretation of the electric field E in this expression in relation to E_+ depends on factors such as the standing wave ratio. Nevertheless, such estimates provide useful insight. Table 1 lists estimates of microwave field amplitudes generated in the center of the ALPHA trap under typical operating conditions, as inferred from a microwave heating experiment at the cyclotron resonance frequency involving 80 ns pulses. The microwave injection efficiency for this particular measurement (including losses outside of the trapping apparatus) is of order 1%.

7 Conclusion

The hyperfine splitting constant of ground state atomic hydrogen is one of the most precisely measured quantities in physics. It represents an excellent benchmark against which the results of hyperfine microwave spectroscopy experiments performed on antihydrogen can be compared. The ALPHA collaboration has made progress towards the realization of an antihydrogen microwave spectroscopy program.

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