In 2005, the Division of Nuclear Physics (DNP) created a PhD Thesis Prize competition for best thesis in Experimental or Theoretical Nuclear Physics by any student receiving their PhD degree from a Canadian University in the current or prior calendar year (see http://dnp.phys.uregina.ca/articles/Thesis%20Prize). The DNP is pleased to announce that the recipient of the 2014-15 DNP Thesis Prize is Timothy Friesen. Dr. Friesen was awarded his PhD by the University of Calgary in 2014 for the work "Probing Trapped Antihydrogen: In Situ Diagnostics and Observations of Quantum Transitions". A summary of Dr. Friesen's thesis work appears below.

PROBING TRAPPED ANTIHYDROGEN

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SUMMARY

This article describes how the ALPHA experiment measures the magnetic field seen by trapped antihydrogen atoms and how it demonstrated resonant positron spin flip transitions.

The hydrogen atom is one of the most important and best-understood systems in physics. Hydrogen spectroscopy has been invaluable for testing and motivating theory, and the hydrogen spectrum is known to high levels of precision. This makes antihydrogen, the anti-matter counterpart to hydrogen, a natural candidate to test CPT (charge-parity-time) symmetry, the fundamental symmetry between matter and antimatter. In addition, since antihydrogen is electrically neutral, it is an excellent candidate to study whether the gravitational interaction between matter and antimatter is different than that between matter and matter.

The goal of the ALPHA collaboration is to study, and in particular to perform spectroscopy on, antihydrogen atoms trapped in a magnetic neutral atom trap. The ALPHA apparatus consists of a Penning-Malmberg trap for the confinement and manipulation of charged antiprotons and positrons combined with an Ioffe-Pritchard-type neutral atom trap for confinement of antihydrogen (see Fig. 1). The ALPHA apparatus is located in the Antiproton Decelerator (AD) facility at CERN just outside of Geneva, Switzerland. The AD provides low-energy antiprotons (5.3 MeV) to the ALPHA experiment as well as several other experiments dedicated to measurements of antiprotons and antihydrogen. Antihydrogen is formed by mixing antiprotons with a positron plasma produced by a sodium-22-based positron accumulator. The antihydrogen atoms can then be trapped by the magnetic minimum trap, consisting of two superconducting mirror coils and a superconducting octupole magnet, that interacts with antihydrogen's small magnetic dipole moment to create a confining potential of roughly 50 μeV. The trapping of antihydrogen atoms was first demonstrated by ALPHA in 2010 [1] and holding times of 1000 seconds have been achieved [2]. Because the trap depth is low, only 1 or 2 anti-atoms are currently trapped for every 40,000 formed. However, even with few atoms trapped per trial, antihydrogen atoms can be studied by repeating each experiment many times to gather statistics.

One of the biggest challenges facing the spectroscopy of trapped antihydrogen is determining the magnetic field seen by the antihydrogen atoms. Because of the inhomogeneous nature of the magnetic trapping fields, the Zeeman effect will result in a strong spatial dependence of the transition frequencies. External sensors such as Hall probes will only measure the fringe fields of the trapping magnets and internal measurements are complicated by the limited physical access to the antihydrogen trapping volume.

To measure the magnetic field seen by the antihydrogen atoms, ALPHA developed a method for measuring the cyclotron resonance frequency ($f_c = qB/2\pi m$, where q and m are the charge and mass of the electron, respectively, and B is the magnetic field) of an electron plasma [3]. The electron plasma can be positioned along the axis of the Penning trap to measure the magnetic field in different locations in the trap. The most uniform field region, and therefore the region with the most uniform transition frequency for spectroscopy, occurs at the field minimum in the centre of the trap. To maximize the transition probability of a desired transition it is critical to be able to measure this minimum magnetic field to the highest precision possible.

The cyclotron resonance of an electron plasma is determined by monitoring changes in the plasma temperature while a series of microwave pulses are applied at frequencies that scan through the cyclotron resonance. The cyclotron motion of the electrons will be excited by the co-rotating component of the microwave electric field.

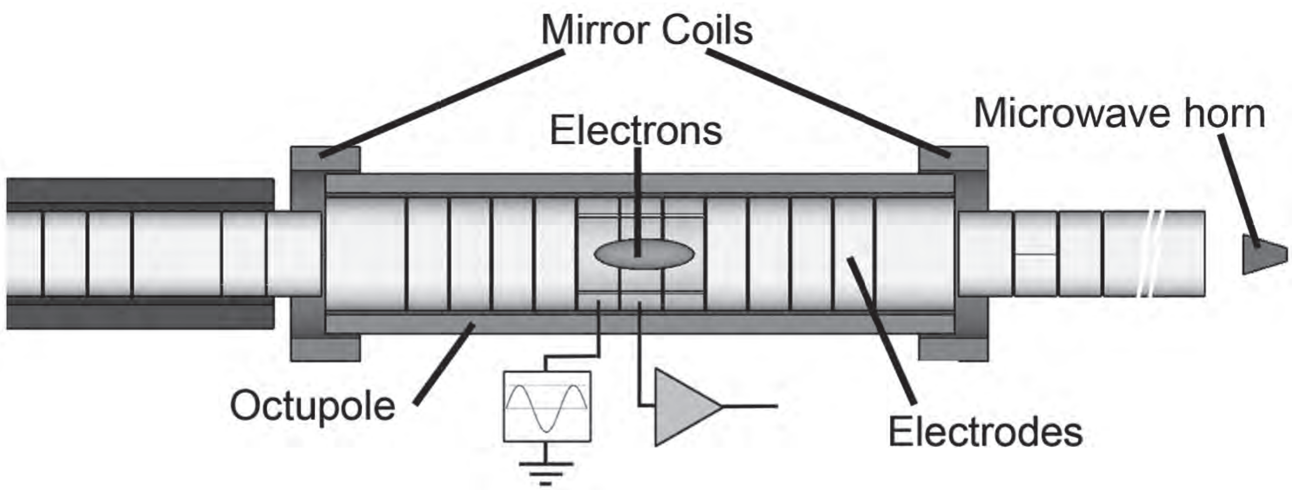

Fig. 1 Sketch of the ALPHA Penning trap and neutral atom trap magnets. A 1 T solenoid (not shown) surrounds the components shown here with the exception of the microwave horn located 1.3 m from the centre of the trap. Also shown is the quadrupole mode excitation drive applied to an electrode on one end of the electron plasma. The subsequent ringing of the plasma is picked up on the centre electrode. The radial extent of the plasma has been exaggerated here for illustrative purposes.

Following each pulse, the energy absorbed by the cyclotron motion will be redistributed by collisions to the remaining degrees of freedom resulting in an increased plasma temperature. To track the plasma temperature changes following each microwave pulse, we monitor the frequency of a normal mode of oscillation of the electron plasma known as the quadrupole mode. This frequency is measured by exciting the motion with a radio-frequency drive applied to one electrode and detecting the image current oscillations on another (see Fig. 1). For small temperature changes the frequency of the quadrupole mode increases linearly with temperature, so by measuring the quadrupole frequency changes as a function of microwave frequency we can find the cyclotron resonance. An example of such a measurement is shown in Fig. 2. With this technique we are able to measure the minimum magnetic field of the antihydrogen trap to roughly 3 parts in 10^4.

Using the electron cyclotron resonance to measure the magnetic field, ALPHA was able to induce and observe the first-ever resonant transitions in antihydrogen by exciting the positron spin resonance transition in antihydrogen's ground state [4]. In a magnetic field, the ground state of antihydrogen is split into two trappable states and two untrappable states. In the high-field limit, the spin of the positron is anti-aligned with the magnetic field in the trappable states and aligned in the untrappable states. Therefore there are two positron spin resonance (PSR) transitions between trappable and untrappable states that can be driven by applying a resonant oscillating magnetic field perpendicular to the magnetic trapping fields. An antihydrogen atom that has undergone this transition will then quickly annihilate on the surrounding electrodes and release charged pions which are detected by a silicon detector as a clear signal of an induced transition.

To establish that resonant PSR transitions were induced, we performed three types of measurements: microwaves on resonance, microwaves off resonance (detuned by -100 MHz), and no microwaves. Each of these measurements had a microwave interrogation time of 180 s which is followed by a quick shutdown of the magnetic trap to detect the annihilation of any remaining atoms. When a PSR transition is induced, the atom should annihilate during the microwave interrogation time rather than when the magnetic trap is shut off. If a transition is not induced, it will not annihilate during the interrogation time (ignoring annihilations on background gas) but when the magnetic trap is shut off.

After performing roughly 100 trials of each experiment (on-resonance, off-resonance, and no microwaves), the overall survival rate of the atoms in the on-resonance set showed a clear decrease compared to the off-resonance experiments. The probability that a statistical fluctuation of the off-resonance survival rate could explain the on-resonance rate is 1×10^{-5} (P-value). In addition, during the interrogation time there was a significant excess of on-resonance events compared to off-resonance events during the first 30 seconds of microwave interaction. This difference corresponds to a P-value of 2.8×10^{-5}. These two data sets combined led ALPHA to conclude that resonant positron spin flip transitions were induced in trapped antihydrogen atoms. This experiment was a proof-of-principle demonstration for antihydrogen spectroscopy rather than a full attempt to accurately measure the transition frequency. However, by demonstrating the difference between on- and off-resonance experiments, the PSR transition frequency has been bounded to within 100 MHz, or 4 parts in 10^3 of the expected hydrogen PSR frequency.

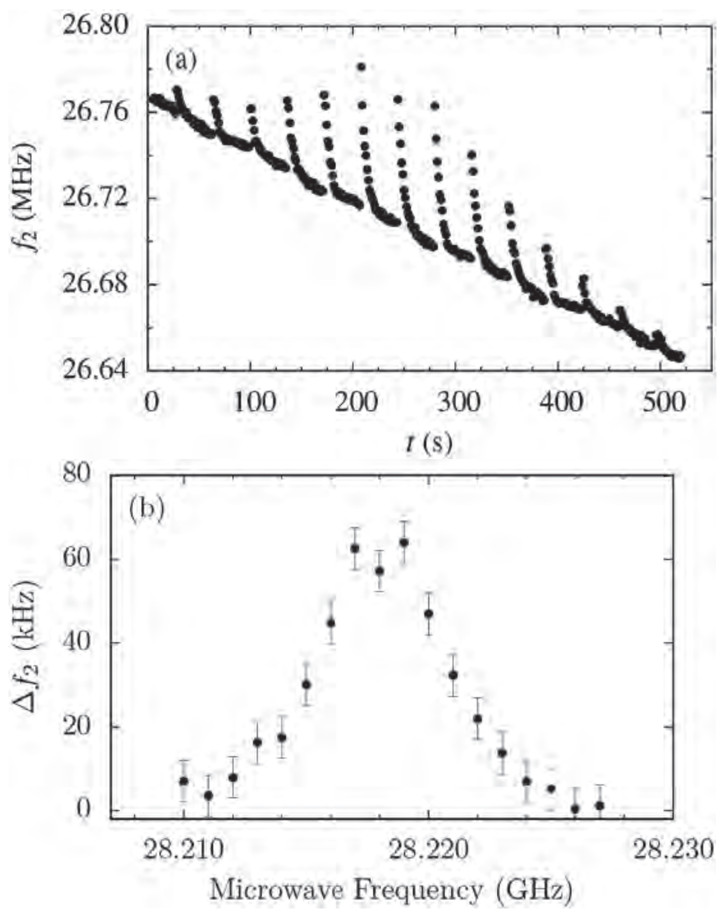

Fig. 2 (a) The quadrupole mode frequency (f_2) evolution of an electron plasma, with a radius of 0.9 mm and consisting of 6.6×10^7 electrons, in a uniform magnetic field while scanning for the cyclotron resonance. The frequency jumps are due to 4 µs microwave pulses at frequencies scanning through the cyclotron resonance frequency. The downward slope of the baseline quadrupole mode frequency is consistent with the slow expansion of the plasma. (b) The cyclotron lineshape is generated by plotting the changes in quadrupole frequency as a function of the frequency of the microwave pulses.

Very recently, the ALPHA collaboration reported another major milestone in antihydrogen research by exciting the two-photon 1S-2S transition for the first time [5], and a similar precision measurement in antihydrogen would provide a stringent test of CPT symmetry.

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