MICROWAVE SPECTROSCOPY OF ANTIHYDROGEN AS A TEST OF CPT SYMMETRY

BY JUSTINE J. MUNICH[1]

J.J. Munich,
<jmunich@sfu.ca>

Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6

This is an exciting time to be in antihydrogen physics. Recent advances in antihydrogen production and trapping have allowed the Antihydrogen Laser Physics Apparatus (ALPHA) Collaboration to produce and trap antihydrogen atoms in record numbers [1]. We are trapping tens of antiatoms per antiproton bunch on average, compared to 1 antiatom every ten bunches in 2010 [2]. The abundance of antiatoms in our trap enables statistical significance for spectroscopic measurements in record times. Antihydrogen is a field worth following for the next few years!

This paper will focus on microwave spectroscopy of ground state antiatoms in a magnetic trap, which probes the interactions of the antiparticle spins with each other and with the external magnetic field. In 2012 we reported on an experiment in which transitions were induced between hyperfine levels of ground state antihydrogen atoms held in a magnetic trap [3]; here I will describe potential avenues for refinement. This area is rich in opportunities for measurements that can be compared with hydrogen to test charge parity time (CPT) symmetry. With hydrogen being one of the simplest and best understood systems in physics, studying antihydrogen provides a rich landscape of possibilities [4]. CPT invariance is a basic tenet of quantum field theories and the Standard Model, and forms a key part of the current understanding of our universe.

The hydrogen atom is one of the few real-world quantum mechanical systems that has a Hamiltonian that can be solved analytically with few approximations. Any graduate student and many undergraduates will find that with paper and pencil, and perhaps a quick refresher on Hamiltonian mechanics, the hydrogen Hamiltonian in an external magnetic field is easily solved. Here, I will show the solutions for antihydrogen, which can be solved using the same techniques while using experimentally derived values for antimatter instead of those of matter. Four eigenstates emerge. Table 1 shows the results of these calculations. Two of these states are product states: $|b\rangle$ and $|d\rangle$. There are two more entangled states of the two spins, $|a\rangle$ and $|c\rangle$, but in high fields the coefficients shift to one of the simple products of single particle states. In our trap, we are well within the high field regime, so we will consider all the eigenstates as products of single particle states. Once we know the eigenstates, we can solve for the energies of each as well.

SUMMARY

Antihydrogen comparisons with hydrogen are promising candidates for charge parity time (CPT) symmetry tests. This paper explores how microwave spectroscopy can help test CPT invariance.

Knowing this, we can plot the Breit-Rabi diagram for ground state antihydrogen, shown in Fig. 1. This calculation assumes CPT invariance of course, so this is what we will be comparing to in order to search for deviations. Notice that I've drawn in some specific transitions in the diagram; these transitions correspond to a spin flip for the positron. Positron spin resonance (PSR) transitions are analogous to electron spin resonance (ESR) transitions. While it is clear that the frequencies of these transitions are dependent on the external magnetic field, the difference between them is not. In fact,

$$\Delta E = (E_d - E_a) - (E_c - E_b) = a, \tag{1}$$

which corresponds to the well known 21 cm spectral line for hydrogen. And if CPT invariance holds, then this splitting should have the same value for antihydrogen. This is what we're after in our tests.

At the European Organisation for Nuclear Research (CERN), we collect antiprotons in bunches of about ninety thousand every two minutes. We use a radioactive sodium source to produce positrons. Through a series of manoeuvres in a stack of electrodes we can collect, cool, and mix the antiprotons with about 1.6 million positrons. They will bind to create antihydrogen, and a fraction of the antiatoms we produce can be trapped in a magnetic potential well. The magnetic minimum is situated in the centre of our apparatus, and is formed through the use of an octupole and various solenoids.

1. Justine Munich tied for 2nd place in the CAP Best Student Oral Presentation competition at the 2017 CAP Congress at Queen's University in Kingston, ON.

TABLE 1

NOTATION: THE MAGNETIC MOMENTS OF THE POSITRON AND ANTIPROTON ARE μ_e+ AND $\mu_{\bar{p}}$, RESPECTIVELY. THE ZERO FIELD SPLITTING IS $\frac{a}{h} \approx 1420$ MHZ AND IS KNOWN TO VERY HIGH PRECISION FOR HYDROGEN. THE FIRST ARROW INDICATES THE POSITRON SPIN (↑ AND ↓). THE SECOND (BOLDED) ARROW DENOTES THE ANTIPROTON SPIN (⇑ AND ⇓).

State	Basis States in Zero Field	Basis States in High Field	Energy
$\vert a\rangle$	$\frac{\vert\downarrow\Uparrow\rangle - \vert\uparrow\Downarrow\rangle}{\sqrt{2}}$	$\vert\uparrow\Downarrow\rangle$	$E_a = -\frac{a}{4}\left[1+2\sqrt{1+\frac{4\left(\mu_e + -\mu_{\bar{p}}\right)^2 B^2}{a^2}}\right]$
$\vert b\rangle$	$\vert\uparrow\Uparrow\rangle$	$\vert\uparrow\Uparrow\rangle$	$E_b = \frac{a}{4} + \left(\mu_{e+} + \mu_{\bar{p}}\right)B$
$\vert c\rangle$	$\frac{\vert\downarrow\Uparrow\rangle + \vert\uparrow\Downarrow\rangle}{\sqrt{2}}$	$\vert\downarrow\Uparrow\rangle$	$E_c = \frac{a}{4}\left[-1+2\sqrt{1+\frac{4\left(\mu_e + -\mu_{\bar{p}}\right)^2 B^2}{a^2}}\right]$
$\vert d\rangle$	$\vert\downarrow\Downarrow\rangle$	$\vert\downarrow\Downarrow\rangle$	$E_d = \frac{a}{4} - \left(\mu_{e+} + \mu_{\bar{p}}\right)B$

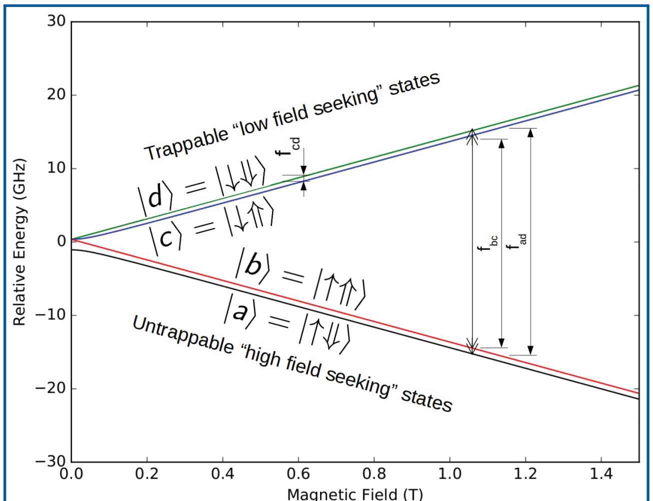

Fig. 1 The Breit-Rabi diagram for ground state antihydrogen, assuming CPT invariance, shows four states and their energies as a function of external magnetic field. We label the states in alphabetical order from the lowest energy states to the highest. The two positron spin flip transitions are labelled as f_{bc} and f_{ad}. f_{bc} is the frequency required to induce a positron's spin to flip from down to up, causing a transition from the $\vert c\rangle$ state to the $\vert b\rangle$ state. f_{ad} indicates the frequency required for the transition from the $\vert d\rangle$ to the $\vert a\rangle$ state. There is also one nuclear magnetic resonance transition labelled, f_{cd}, which refers to the spin flip of an antiproton.

Notice that atoms in only two of the four states, $\vert c\rangle$ and $\vert d\rangle$, are attracted to low magnetic fields. We call these the low field seeking atoms, and they are what we can trap. The atoms in high field seeking states get ejected from our trap and hit the walls of our apparatus where they annihilate. We can detect the products of that annihilation event. So, if we do induce a PSR transition from one of the two trappable states, the antiatom ejects from the trap and we detect an annihilation. This is what we do in our experiment; we scan the frequency of the microwave fields in the trap, from low to high, and count events as atoms are ejected from the trap. We intentionally start low and go up in frequency, so that when we hit the minimum energy needed for the transition, we see a sharp onset; below the onset, the frequency will be too low to be resonant with any atoms in the trap. Once we see a sharp onset in the lower transition and depopulate the $\vert c\rangle$ state antiatoms, we can jump up in frequency to the vicinity of the higher transition and repeat the scan. Here, we aim to measure the difference in the low-frequency onsets, rather than the absolute values, in order to extract a magnetic field independent measure of the hyperfine splitting. We have just completed a measurement of this quantity and find that the splittings in hydrogen and antihydrogen are different by no more than four parts in 10^{-3} [5].

I am going to summarize some future work that we have planned involving a study of nuclear magnetic resonance (NMR) transitions in antihydrogen.

Looking back at the Breit-Rabi diagram for ground state antihydrogen, I want to emphasize a different transition. In Fig. 1, we can see the transition frequency between $|c\rangle$ and $|d\rangle$ states. Since this involves a spin flip for the antiproton, we call this a nuclear magnetic resonance (NMR) transition. This transition will not cause an annihilation event; the atom would remain in a trappable state. Studying this transition is possible given that we are now confident that we can kick out all of one of the states; we could, for example, kick out all $|c\rangle$ state antiatoms, then irradiate the remaining $|d\rangle$ state antiatoms to try to induce NMR transitions to the $|c\rangle$ state. Then, we can clear the $|c\rangle$ state antiatoms again, and see if we succeeded in inducing any $|d\rangle$ to $|c\rangle$ transitions. This measurement is very promising, and could potentially provide one of the most stringent tests of CPT invariance.

The main reason it could bode so well for CPT invariance testing is due to its first order insensitivity to magnetic field. In order to explain this, I draw your attention to Fig. 2, where I plot the energy difference between the $|c\rangle$ and $|d\rangle$ states. Notice that there is a maximum at about 0.65 T. This zero derivative is what gives us a first order insensitivity to magnetic field, and is an ideal place to do the experiment. This coupled with the first order insensitivity to position that we get due to the trap being a magnetic minimum, should give us the ability to do precise measurements of the frequency of the transition as atoms pass through the centre of the trap. We anticipate being able to gain several orders of magnitude more precision compared to PSR transition measurements. At this level, we can start to probe the internal and magnetic structure of an antiproton.

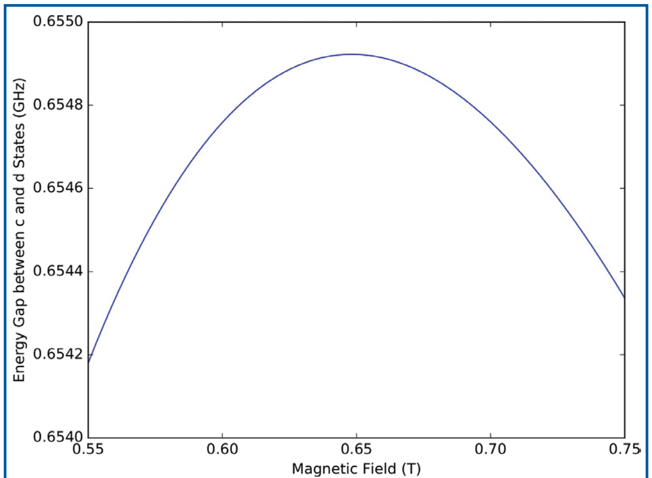

Fig. 2 The energy difference between the $|d\rangle$ and $|c\rangle$ states plotted as a function of external magnetic field. Notice the turning point at 0.65 T where the energy difference passes through a maximum. This is expected to give rise to a sharp spectroscopic feature in the transition frequency due to the first order insensitivity to external magnetic field.

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