WP8: Fundamental physics from precision studies of exotic atoms

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1. Introduction

Exotic atoms, specifically antihydrogen, and positronium, offer new and unique portals through which to search for new physics and perform stringent tests of fundamental symmetries and bound state QED theory. Experiments using AMO techniques, including precision spectroscopy, that are expected to be sensitive to new physics are of increasing interest [1], and this proposal seeks to capitalize on such work, with the additional advantages offered by using exotic atomic systems.

In a recent land-mark experiment at CERN's Antiproton Decelerator (AD) facility, the ALPHA-collaboration has performed spectroscopy of the 1S-2S interval of antihydrogen held in a magnetic minimum trap. The result is consistent with CPT-invariance to a precision of 2 x 10^{-12} [2]. The roadmap for future antihydrogen physics points towards increasing precision in spectroscopic tests of fundamental symmetry, unravelling further structure such as the antiproton charge radius and tests of the Weak Equivalence Principle.

Positronium (Ps) is a metastable matter-antimatter atom. As a pure QED system, with maximal recoil contributions and no hadronic components, it is an exquisitely sensitive probe of bound state QED [3] that is also potentially sensitive to new particles or interactions. Sufficiently precise measurements of Ps energy levels, in conjunction with advanced theory, can therefore be used to test bound state QED, measure the Rydberg constant (without proton radius complications [4]), and conduct searches for new particles or interactions [5], including gravitational effects [6].

2. Antihydrogen

The UK contributes to antihydrogen physics predominantly via the ALPHA collaboration (http://alpha.web.cern.ch) in which Bertsche, Charlton, Eriksson, Isaac, Madsen and van der Werf have leadership roles. Precision measurements on antihydrogen have been enabled by several recent breakthroughs in the ALPHA experiment such as enhanced control of antiparticle plasmas [7] and antihydrogen accumulation [8]. Trapping antihydrogen can now occur on time-scales of order 1 day. In addition to the first observation [9] and characterisation of the 1S-2S interval, the hyperfine spectrum and the Lyman-alpha line have been observed [10,11] with results also consistent with CPT-invariance. The Lyman-alpha line is pertinent in considerations for future improvement in precision due to the possibility of laser cooling antihydrogen on this transition. The spectroscopy results are summarised in Table 1.

Transition	Frequency (GHz)	Relative precision	Reference
1s $^2S_{1/2}$-2s $^2S_{1/2}$ (0 T centroid)	2,466,061.413,187,035(10)	4.5 10^{-15}	[18]
1s $^2S_{1/2}$-2s $^2S_{1/2}$ H (1T, d-d calculated)	2,466,061.103,080,3(6)	2.4 10^{-13}	[18, 2]
1s $^2S_{1/2}$-2s $^2S_{1/2}$ $\overline{\mathrm{H}}$ (1T, d-d observed)	2,466,061.103,079,4(54)	2.2 10^{-12}	[2]
1s $^2S_{1/2}$-2s $^2S_{1/2}$ H (1T, c-c calc.)	2,466,061.707,104(2)	8 10^{-13}	[9]
1s $^2S_{1/2}$-2s $^2S_{1/2}$ $\overline{\mathrm{H}}$ (1T, c-c obs.)	2,466,061.707,1(2)	2 10^{-10}	[9]
1s $^2S_{1/2}$-2p $^2P_{3/2}$ H (1T centroid calc.)	2,466,051.625		[11]
1s $^2S_{1/2}$-2p $^2P_{3/2}$ $\overline{\mathrm{H}}$ (1T obs.)	2,466,051.7(0.12)	4.9 10^{-8}	[11]
1s $^2S_{1/2}$-1s $^2S_{1/2}$ H (F=1, F'=0 obs.)	1.420,405,751,768(1)	1 10^{-12}	[12, 13]
1s $^2S_{1/2}$-1s $^2S_{1/2}$ $\overline{\mathrm{H}}$ (1T c-b, d-a obs.)	1.4204(5)	4 10^{-4}	[10]

Table 1. Transitions in trapped antihydrogen and the observed frequency with results in hydrogen for reference. At 1 T, the hyperfine states in the 1S and 2S manifolds are labelled a, b, c and d with increasing energy.

ALPHA has further measured the charge of the antihydrogen atom [14,15] and developed a method for measuring the ratio of gravitational and inertial mass, *F*, yielding a first crude constraint [16]. During 2018 the collaboration has completed a new instrument, ALPHA-g, for more precise measurements of *F* with precisions up to 1% envisaged long-term.

The current level of precision of laser spectroscopy of the 1S-2S line is already enough to allow a measurement of the Lamb shift in antihydrogen. The antiproton charge radius contributes with 1.2 MHz to the ground state Lamb shift and a unique determination requires probing another line at this precision [17]. This requires an upgrade (ALPHA-3) of the current apparatus (during CERN's LS-2 shutdown period), which will further provide improved charged particle trapping and photon detection as integral parts of the cryogenic apparatus as well as provision to work with normal hydrogen. A significant increase in laser power at all required wavelengths is required together with a major upgrade to our current frequency metrology which relies on thermal atomic clocks and GPS. Requirements at or beyond the state-of-the art are anticipated in frequency metrology, magnetometry and photon detection in extreme environments (e.g., cryogenic and XHV). These upgrades, together with work towards laser cooling on the Lyman-alpha line, will pave the way towards testing hydrogen and antihydrogen in the same environment with the highest precision possible when antiprotons return in 2021-2023, with the ultimate long-term aim to reach the precision in laser spectroscopy of hydrogen [18]. In parallel, ALPHA-g will develop and perform magnetometry to systematically characterise the dynamics of its trapping field manipulations in anticipation of performing a first measurement with antiprotons in 2021 [19]. Incorporation of laser cooling and a hydrogen control sample based on work carried out for the ALPHA-3 upgrade is anticipated in the 2021-2023 time frame.

The AD is currently being significantly upgraded with the addition of the ELENA ring. This device will decelerate the antiprotons from the AD kinetic energy of 5.3 MeV down to around 100 keV, which will enhance captured yields for antihydrogen production by nearly two orders of magnitude and allow rapid switching of the beam between experiments. The improved antiproton flux will underpin significant improvement in statistical sensitivity and will further allow probing symmetry in measurements that require long campaigns, such as tests of Lorentz invariance.

3. Positronium

Positronium work will be performed at UCL and Swansea, which both currently house pulsed positron beam facilities suitable for the production of a dilute Ps gas in vacuum, which is a pre-requisite for most spectroscopic investigations. The primary goals of the Ps work package are (1) to advance Ps precision spectroscopy far beyond the current levels, (2) perform gravity measurements, either by free-fall of a long-lived Ps beam or by interferometry, and (3) construction of a calorimeter-type detector suitable for probing forbidden and invisible Ps annihilation modes.

Ps spectroscopy has been carried out before, but this research has not progressed in decades, as indicated in table 2. The proposed new experiments will advance the state-of-the-art by taking full advantage of recently developed techniques that have already changed the landscape of Ps physics in a significant way [20], and by developing additional new methods.

Transition	Experimental Result (MHz)	Theory (MHz) [25]	Uncertainty ratio (exp/theory)	Year (exp)	Comment
$1^3S_1 \rightarrow 2^3S_1$	1233607216.4±3.2 [21]	1233607222.18 ± 0.58	5.5	1993	Two photon (λ=486 nm) Doppler-free
$1^3S_1 \rightarrow 1^1S_0$	203389.10 ± 0.74 [22] 203394.2 ± 2.9 [28]	203392.01 ± 0.46	1.6 6.3	1984 2014	10 GHz μ-wave between Zeeman-split states
$2^3S_1 \rightarrow 2^3P_0$	18499.65 ± 5.2 [23]	18498.25 ± 0.08	65	1993	Direct μ-wave
$2^3S_1 \rightarrow 2^3P_1$	13012.42 ± 2.21 [23]	13012.41± 0.08	28	1993	Direct μ-wave
$2^3S_1 \rightarrow 2^3P_2$	8624.38 ± 1.94 [23]	8626.71 ± 0.08	12	1993	Direct μ-wave
$2^3S_1 \rightarrow 2^1P_1$	11180 ± 9 [24]	11185.37 ± 0.08	113	1994	Direct μ-wave in magnetic field

Table 2: State of the art precision optical and microwave spectroscopic Ps measurements. The ratio of the theoretical and experimental uncertainties (combined statistical and systematic) is shown for each transition. The theoretical uncertainties are all from reference [25]. The quoted years refer to the experimental measurements.

The field of Ps spectroscopy has been dormant for decades, partly because it is difficult to obtain large numbers of low-energy positrons. This situation has changed in recent years due to the development of positron buffer gas traps [26]; however, this progress has not yet been fully applied to Ps spectroscopy, which largely remains at the same level it was in 1993 [27]. We intend to advance the field initially by re-measuring all but the ground state hyperfine interval (which is presently being re-measured in Japan, using a new energy-selection technique [28]). QED is, at least in relation to leptons and photons, a complete theory; calculations can in principle be performed to any arbitrary precision. In reality this precision is not arbitrary, as it depends on generating very complex high-order expansions with thousands of terms [29]. Hence it is essential to maintain a close connection between theory and experiment in order to advance this field. Hence, the Ps project also includes theoretical input (led by Frank Deppisch form UCL).

The main deliverables for this work will be (1) development of slow Ps beams using Stark manipulation methods (2) new measurements of the 1^3S_1-2^3S_1 interval, and various 2S-nD and nD-(n+2)D intervals, and (3) new measurements of the n = 2 fine structure. The generation of slow and focussed Ps beams will enable gravity measurements by free-fall, and allow the evaluation of possible interferometric measurements. In addition to spectroscopic QED tests, our experiments will allow us to measure the Rydberg constant (without proton radius complications) and to test for the existence of some light dark matter candidates, whose presence could lead to shifts from the QED predictions. This will depend on the precision achievable: the 3 year goals will be to improve existing measurements by at least 1 order of magnitude (see table 2). The Ps interferometry measurements will be coordinated by Hendrik Ulbricht (Southampton), an expert in matter-wave interferometry [30].

The third phase is distinct from the spectroscopic work and involves the construction of a Ps annihilation calorimeter detector. The positron annihilation process can be used to test for symmetry violations (C, P, and CP) and to search for Ps coupling to dark-matter, mirror universes or hidden dimensions. CP violations in the lepton sector are of particular interest in the context of neutrino mass measurements, meaning that it is useful to set limits on these types of processes. The main deliverable for this is the detector construction and full simulation validation, to be completed after year 2, with main physics data available after year 3, and improved data with stricter limits on several processes thereafter. The science goals for this work are improvements on current limits for forbidden decays, with an emphasis on CP violation measurements (e.g., [31]). This work will be conducted at UCL and will involve input from detector specialists in the UCL HEP group (led by Andreas Korn) who have a strong background in this area (including long term members of the

ATLAS collaboration). This work involves a significant component of data acquisition and analysis that is similar to current HEP methodologies.

4. Funding

4.1: ANTIHYDROGEN: Costs of the envisaged project as follows. Equipment: ALPHA-3 antihydrogen lamb shift spectroscopy (500k); metrology upgrade (1500k); normal hydrogen source and detector (£500k); ALPHA-g magnetometry system (500k). Total = **3000k**. Personnel costs, including cost adjustment for operating at CERN, years 1 & 2 (200k, PIs, 500k, 2 RAs, 200k, 2 students); year 3 (100k, PIs, 250k, 2 RAs). Total = **1250k [2 + 1 year]**
Total 2+1 costs = 4250k
Additional 3 years = 1750k
Total 2+1+3 = 6000k

4.2: POSITRONIUM: The Ps spectroscopy work involves construction of new laser and microwave systems (350k), development of new Ps sources (100k) and precision Rydberg manipulation systems (including time varying pulsed HV systems) designed to produce slow controlled beams (150k). Total equipment = **600k**
Personnel costs in years 1 & 2 are (200k PI time, 140k RA). +170k for year 3 = **410k [2+1 year]**
The Calorimeter detector and DAQ systems have a total construction cost of **450k,**
Personnel costs in years 1 & 2 are (200k PI time, 140k RA). +170k for year 3 = **410k [2+1 year]**
Students must be at least 3 rears so (2+1) x 2 students = **200k**
Total 2+1 costs = 2070k
Additional 3 years = 1020k
Total 2+1+3 = 3090k

5. Management

The antihydrogen work will be conducted under the already existing management structure of the ALPHA collaboration, with the Swansea and Manchester PIs overseeing the described work above. The Ps work will be locally managed at Swansea and UCL according to the individual projects. However, there will be oversight and coordination between the work to maximize impact (for example, new Ps sources developed at UCL and the adjacent London Centre for Nanotechnology can be utilized in Swansea projects). Newly developed techniques can be shared immediately under this structure, and duplication of efforts can be avoided, streamlining the overall programme.

Contacts for the project are Michael Charlton (Swansea, m.charlton@swansea.ac.uk) and David Cassidy (UCL, d.cassidy@ucl.ac.uk)

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