Searches for a Fifth Force and Dark Matter using Precision Atomic Spectroscopy

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Tests of the standard model and its possible extensions using precision spectroscopy have a distinguished history, and include tests of electroweak theory, parity violation and searches for the electric dipole moments. In the last fifteen years there has been a step change in the precision of atomic spectroscopic measurements, due to the application of techniques such as laser cooling and optical frequency combs. The current state of the art is a spectroscopic precision of $\approx 3 \times 10^{-19}$ achieved for an optical clock transition in neutral strontium [1]. This is the most precisely measured quantity in any physical system.

Here we propose to fully exploit high precision spectroscopy to test various aspects of fundamental physics. A major advantage of this approach is that the UK is already internationally competitive in this area, with relevant research groups including (but not limited to) Durham University (Rydberg atoms), Imperial (electron EDM), NPL (optical atomic clocks) RAL (ISIS muon source), UCL (positronium, helium atoms), Swansea (antihydrogen). The programme of research we envision includes:

Spectroscopic searches for a fifth force

A very light, new boson ϕ can induce a fifth force which leads to a modification of the Coulomb potential in atoms for the force between two particles i, j,

$$Z\frac{\alpha}{r} \longrightarrow Z\frac{\alpha}{r} + \frac{y_i y_j}{4\pi}\frac{e^{-m_\phi r}}{r}\,. \tag{1}$$

Precision measurements of atomic transition frequencies can in principle be used to set stringent bounds on whether such a deviation exists. The main difficulty with this approach is the many-body nature of the electronic wavefunction for most atoms, which mean that an exact standard model prediction for the transition frequency is not possible. A number of approaches have been proposed, such as using isotope shifts [2, 3] to reduce the sensitivity to electronic structure. An exciting alternative is to exploit Rydberg states with principal quantum number of $n \gtrapprox 100$. Advantages of Rydberg states include the ability to tune the size of the atomic wavefunction $\propto n^2 a_0$ relative to the range of the fifth force, and the availability of a great number of transitions for each isotope and element, enabling more complex searches for systematic deviations. Furthermore, Rydberg electrons only weakly interact with the nucleus and the remaining core electrons, raising the possibility of precise *ab initio* calculations with developments in existing theory.

In the short term (2 years) we propose to set improved constraints using optical spectrocopy of Rydberg states in heavier atoms such as Rb, Cs and Sr that are easily laser cooled and trapped. For example the Durham group is already able to perform such measurements with ∼kHz absolute precision in Sr. In parallel we recommend funding the theoretical development of the required atomic physics “phenomenology”.

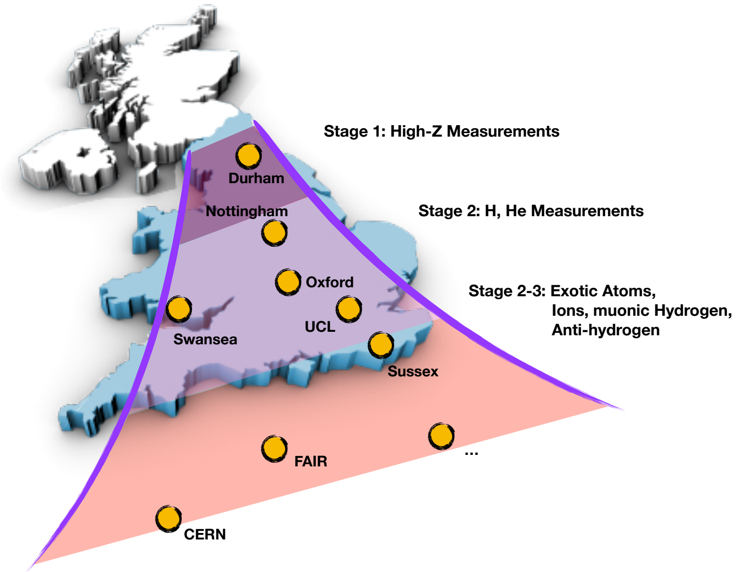

Figure 1: Network and proposed phases of this proposal.

Precision tests using few-body systems

The problem of direct comparison with theoretical calculations can be solved by using light atoms such as the isotopes of hydrogen and helium, where highly accurate standard-model calculations of the atomic wavefunction are possible. An example is provided by the well-known spectroscopy of the $1S \to 2S$ transition in hydrogen that is at the heart of the proton radius puzzle. During the next three years (+3 years) we propose to build dedicated experiments for precision spectroscopy in these light atomic species, using both laser cooling and alternative cooling methods based on Stark and Zeeman deceleration [4] to produce cold samples suitable for precision spectroscopy. As well as contributing to improved measurements of the proton radius, precision measurements of Rydberg states in these atoms would improve the constraints on fifth forces considerably. For example comparing the Rydberg constant measured from low Hydrogen states with $r = a_0$ with the Rydberg constant measured in Rydberg states with $n \approx 30$ corresponding to $r \approx 10^3 a_0$, allows to derive limits on new bosons with $\mathrm{eV} < m_\phi < \mathrm{keV}$. Existing searches achieve a precision of $\delta R_\infty = \mathcal{O}(10^{-6})$, which translates in limits on the product of couplings to electrons and protons of $y_P y_e \lesssim 10^{-12}$ for these masses [5]. We propose that an improvement of between 3-6 orders of magnitude is possible, by creating for example an atomic fountain of hydrogen atoms. Such measurements would also contribute to searches for CPT violation by providing reference measurements to compare with antihydrogen.

We note that the few and many-body approaches are complementary; in H and He theory predictions are very precise but high-precision measurements are hard, whereas in atoms with higher Z such as ^{88}Sr or ^{174}Yb, very high experimental precision can be achieved, but theoretical calculations are challenging. As well as increasing the discovery potential for new physics, comparing measurements in heavy and light Rydberg atoms will help to advance both the experimental state-of-the-art for light atoms and atomic structure calculations in high-Z Rydberg atoms.

Precision tests using exotic atoms

In the final stage of our proposal we plan to search for new forces in the leptonic sector. We note that the UCL group is world leading in the creation and spectroscopy of low-energy positronium atoms. The possibility of precision spectroscopy in muonium is particularly interesting, since a number of observables involving muons have shown deviations from SM predictions, such as the anomalous magnetic moment $(g-2)_\mu$ [6] and hints of lepton non-universality in rare $b \to s\ell^+\ell^-$ transitions [7]. Spectroscopy in muonium of muonic Hydrogen would provide a unique and timely probe of light new physics that could be responsible for these effects. Beyond searches for new forces coupling to muons, we intend to perform an independent, improved determination of the proton radius. Here the UK gains a competitive edge from hosting muon user facility at the ISIS facility (RAL) (one of only two in Europe), opening the possibility of a longer-term medium scale project to develop an instrumental station for precision measurements in muonic systems.

	Stage 1 (2 years)	Stage 2 (+3 years)	Stage 3 (future)
Experiment	High-Z Measurements	H,He Measurements	Muonic H Measurements
Results	2019-2020	2022-2024	2023-2027
Cost	£0.5 million	£3 million	£5-10 million

Table 1: Timeline of the proposed experiments.

Questions

What are the science goals? What are the deliverables?
The goals/deliverables are to achieve considerably improved sensitivity to fifth forces and light dark matter, addressing the proton radius puzzle, and providing a new, important tool to understand the theory of the atomic structure of high-Z atoms.

What is the plan of work for two years? See Table 1.

Where is the work happening?
Experiments would be carried out within the Quantum Light and Matter group at Durham University, and at Sussex University. Theoretical work would be carried out at Durham, Nottingham and Sussex. We are working on consortium building with UCL, Swansea, NPL, RAL and Imperial.

What internal infrastructure to support the work exists?
Durham has internationally unique facilities for precision spectroscopy of Rydberg states (Stage 1) [8, 9], including an optical frequency comb facility [10]. Durham also has extensive expertise and infrastructure dedicated to non-laser based cooling techniques (Stage 2), that can be extended to atoms like H and He.

Who is the team?

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What is the approximate budget fully burdened? See Table 1.

How is this work competitive with, distinct from and complementary to the international landscape in this general area?
We exploit and build on the world-leading atomic spectroscopy community in the UK. The

newly triggered, close collaboration with particle physicists will shape a new community specialised in atomic experiments for fundamental physics.

Who is coordinating?

This workpackage is jointly coordinated by Matthew Jones (Durham, experiment) and Martin Bauer (Durham, theory)

What is the internal work package governance going to be (since it is a multi-institution work package)?

We envisage that the workpackage would be coordinated via the IPPP at Durham University, which has a track record of managing large-scale collaborative projects, strong support for administration and outreach, and excellent facilities for collaboration. Support would be provided by the Durham experimental team. Strategic leadership would be provided by a steering committee consisting of a representative from each node, plus one or two external experts.

What would be the follow on plan for a second three years? See Table 1.

If you are organizing a dedicated work package workshop what support is requested from QSFP?

Budget for travel and accomodation of $£5k$.

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