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A status report on experimental tests of QED in medium-Z systems

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Abstract

The electron beam ion trap has opened the door for experimental physics to perform critical tests of bound state QED in the medium-Z regime. The relatively small uncertainties associated with the theoretical predictions necessitate highly accurate experimental measurements of atomic transition energies. This work presents an overview of the issues and key concepts involved in the field. It also demonstrates several major steps taken to suppress systematic uncertainties that have limited past work and presents an error budget for current and future work.

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1. Introduction

Second quantisation, the quantisation of the radiation field, was one of the key developments in modern physics during the 20th century. The subject of quantum field theory quickly followed, the application of which to systems of charged particles led to the formulation of the theory of quantum electrodynamics (QED). This fully quantised theory describes the force in terms of particle exchange and, in the case of electromagnetic fields, these particles are virtual photons.

The application of QED to the calculation of energy levels of charged particles in bound systems is usually presented in terms of "bound state" QED. One of the first successful applications of bound state QED was the explanation of the Lamb Shift, the separation of the $2s_{1/2}$ and $2p_{1/2}$ level energies in neutral hydrogen as compared to the degenerate energies predicted by the relativistic Dirac equation.

A problem with free particle QED lies in the difficulty in obtaining exact solutions to the calculations involved and thus in obtaining predictions for measurable quantities such as energy (Karshenboim, 2004; Eides et al., 2001). Calculations such as those involved in scattering or decay problems present a particular challenge due to the number and complexity of the interactions (virtual particle exchanges) between the field and the bodies of interest that must be considered. Bound state QED calculations on the other hand generally consider a more efficient parametrisation. However, the presence of the nucleus and the corresponding static nuclear field requires the consideration of many body and strong coulombic effects. Divergent integrals commonly appear in the calculations requiring regularisation and renormalisations of mass and charge. Further, the selection of a finite number of terms from

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the infinite perturbative expansions involved, affects the final result. To date high-accuracy results have only been achieved for one or two electron systems due to the difficulty associated with many-body effects.

Developments in computational speed and in mathematical techniques have progressed to the point that calculations now result in predictions for measurable quantities with quoted accuracies on the parts per million level or less. However, the problems mentioned above and how they are treated yield results for different methods often varying by amounts significantly larger than the quoted uncertainties.

Recent developments in experimental techniques make first order bound state QED theory one of the best tested theories of modern physics (Niering et al., 2000). However, these tests primarily probe the lowest order bound state QED contributions. Testing higher order bound state QED calculations and correlated QED can challenge and drive the development of theory.

QED contributions are experimentally tested by measuring the Lamb Shift. The effect was first observed by Lamb and Retherford in experiments performed on the hydrogen atom and has been defined as the difference between the electron energy level predicted by the Dirac theory and that which is observed experimentally (Drake, 1988). The shift is dominated by finite nuclear size contributions (the Dirac theory treats the nuclear potential as a point source) and bound state QED effects. If we accept that, to first order, effects other than the higher order bound state QED contributions are known to a sufficiently high level of accuracy, then any high-accuracy measurement of the X-ray transition energies can probe the higher order predictions (Fig. 1).

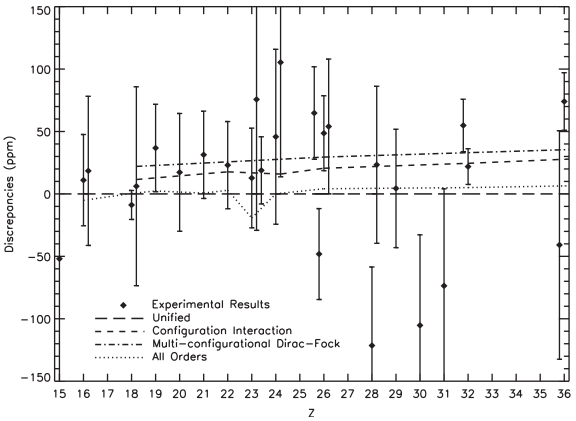

Fig. 1. Theoretical discrepancies relative to Drake (1988) in the medium-Z regime for transition energies in helium-like systems (Chen et al., 1993; Indelicato, 1988; Plante et al., 1994). The experimental uncertainties cover the variation between calculations.

2. Experimental conditions and source

Investigation of bound state QED and the Lamb Shift require few electron atomic systems. Theory is best formulated for one and two electron systems. However, the differences between theoretical calculations for $2p_x$–$1s_x$ transition energies of highly charged ions (HCI) in the medium-Z regime are of order 30 ppm of the total transition energy. Therefore, experimental tests require uncertainties less than this for a critical comment on the computations.

Thermal effects on the resulting X-ray spectral lines contribute to broadenings on the observed peaks that can cause problems especially when observing transitions nearby. The observed ions must be relatively cold.

Medium-Z ions are ideal as the higher order QED contributions scale as $(Z\alpha)^4$. The higher the atomic number, the lower the precision of measurement required to critically measure the higher orders or correction. However, if the ion used has a very large Z then non-QED effects such as those due to the finite nuclear size dominate the shift, making it difficult to extract the bound state QED contribution.

Fast-beam experiments, involving the creation of HCI via beam-foil stripping, and plasma techniques, such as those performed at Tokamak sources, have been limited by bulk motion Doppler shifts and spectral contamination due to the number of competing ion species, making calibration of the system difficult. Uncertainties of order 100–1000 ppm in results from these techniques are not uncommon. Promising techniques include laser resonance spectroscopy (Myers et al., 1996; Silver et al., 1994) and recoil ion spectroscopy to observe transition energies in highly charged argon (Deslattes et al., 1984). However, further work is required in these areas.

The work presented here makes use of an electron beam ion trap (EBIT) for the production of highly charged titanium ions (Ti^{20+}). This device allows the creation, trapping and cooling of highly charged medium to high Z ions and has made significant improvements in the experimental testing of bound state QED. The advantages of the EBIT over other sources are the suppression of the Doppler shift (there is no bulk motion of the ions), a suppression of Doppler broadening (the ions are cooled and confined spatially to a small region), and low satellite contamination (charge state selection is well determined by the kinetic energy of the electron beam used to create the trap potentials).

Fig. 2 shows one of the Ti^{20+} spectra recorded at the NIST EBIT. The relative intensities in this raw data are affected by the (known) response function of the detector system. The w, x, y and z transition lines are clearly visible as well as two lithium-like titanium transition lines, indicating some minor and well separated contamination of the trap with other ionic species.