# Towards One-electron Ions in Rydberg States for Laser Spectroscopy

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***Abstract* — Simple quantum systems play important roles in the determination of fundamental constants. Very recently at NIST, bare nuclei created in an EBIT were extracted and captured in a novel compact Penning trap. This is a step towards production of one-electron ions isolated in an ion trap designed to facilitate recombination experiments and laser spectroscopy. Our goal is to form Rydberg states that can be probed accurately using optical frequency metrology, which could provide a new determination of the Rydberg constant that is independent of the proton radius.**

***Index Terms* — QED, Rydberg constant, one-electron ions, fundamental constants, precision measurements.**

## I. INTRODUCTION

One-electron systems provide some of the most stringent tests of physical laws and yield very precise measurements of the constants of nature. The Rydberg constant, for example, is determined from precise measurements of various transitions in hydrogen and deuterium [1]. At NIST, we have been considering the possibility of testing theory with one-electron ions in high angular momentum states [2][3]. The energy levels for high-angular momentum states can be calculated much more accurately than for low-angular momentum states because problematic aspects associated with the nuclear size correction are vanishingly small. In fact, theoretical uncertainties are smaller than the uncertainties of fundamental constants [2]. The Rydberg constant is the leading source of uncertainty in this regime—about a factor of 100 larger than the uncertainty due to other constants. Hence, one-electron ions in Rydberg states can provide a determination of the Rydberg constant that is independent of the proton radius if sufficiently precise measurements can be realized for comparison with theory. This is potentially useful in efforts to resolve the proton radius puzzle following the measurement of the Lamb shift in muonic hydrogen [4]—[6].

## II. EXPERIMENT

We plan to produce one-electron ions in circular Rydberg states, via electron transfer from an excited atom to a bare nucleus stored in an ion trap. Using nuclear charge in the range $1 < Z < 11$, it is possible to find many E1 transitions between circular Rydberg states in the optical domain accessible to an optical frequency comb synthesizer [2][7]. Other useful features of circular Rydberg states include (1) the narrowest linewidth in a given shell $n$, and (2) suppression of Stark effects.

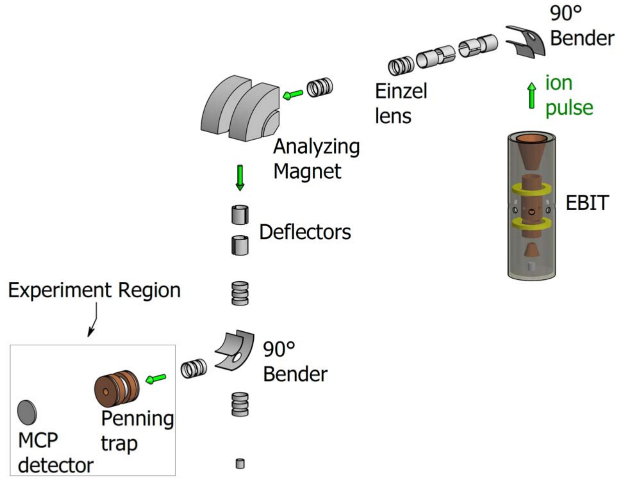

Fig. 1. Simplified schematic diagram of the set-up (not to scale). Ions created in an EBIT are transported to the experiment region via an extraction beam line that includes an analyzing magnet for charge state selection.

An electron beam ion trap (EBIT) is used to create bare nuclei by electron impact ionization of an injected gas. The NIST EBIT facility is equipped with an ion extraction beamline [8], as illustrated in Figure 1. The bare nuclei are extracted in pulses and transported 7.2 m to the experimental apparatus, which houses a compact Penning trap and detectors for counting photons and ions. A cross-sectional view of the apparatus is shown in Figure 2. The novel compact Penning trap for capturing extracted ions is built from two axially-oriented NdFeB magnets that are naturally integrated into the electrode structure [9]. This unitary architecture facilitates radial access for atomic and laser beams, as well as collection of light emitted by stored ions on a photomultiplier tube (PMT).

To capture ions extracted from the EBIT, the front endcap bias is lowered relative to the central ring electrode to allow ion entry. Synchronized with the ejection of an ion pulse from the EBIT, the potential of the front endcap is rapidly raised as ions arrive in the trap. After some storage time, the back

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endcap potential is rapidly lowered to eject the stored ions towards a time-of-flight detector (far left in Fig. 2) to analyze the charge state composition. Figure 3 is an illustration for stored $Ne^{10+}$ nuclei. For short storage times (Fig. 3a), only bare nuclei are observed. For long storage times (Fig. 3b), lower charge states (H-like, He-like, etc.) are formed by electron capture from the residual background gas.

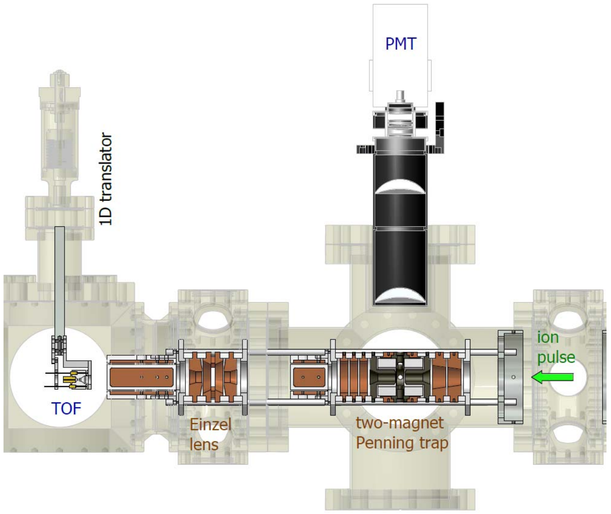

Fig. 2. Cross-sectional CAD drawing to illustrate major components in the experiment region near the ion trap. A two-magnet compact Penning trap is centered in the six-way cross, aligned with the horizontal beamline to capture an ion pulse injected from the right. Stored ions can be counted by ejection to a time-of-flight (TOF) microchannel plate detector (left).

## III. Summary

Slowing and capture of highly-charged ions have been demonstrated in a novel compact Penning trap that is designed to facilitate experiments to produce one-electron ions in Rydberg states, and perform laser spectroscopy. Captured ions have storage lifetimes of order 1 second in this room-temperature apparatus (limited by the residual gas pressure) which is useful for many studies. The theory of one-electron ions in Rydberg states is very precise, offering the possibility that laser spectroscopy in this regime using an optical frequency synthesizer could provide a new determination of the Rydberg constant that is independent of the proton size—a measurement which could be useful in efforts to resolve the proton size puzzle [4]—[6]. Possible applications also include spectroscopic studies of highly-charged ions of special interest in atomic physics, astrophysics and metrology; very recently we have also observed fluorescence from metastable states of captured ions.

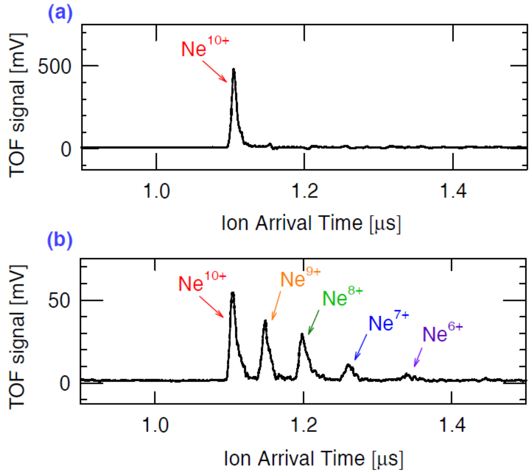

Fig. 3. Time-of-flight signal of ions ejected from the two-magnet compact Penning trap for two storage times after capture of bare neon nuclei: (a) 1 ms storage time; and (b) 2 s storage time, showing production of lower charge states by electron capture from residual gas (1.7 x $10^{-7}$ Pa) in the room-temperature apparatus..

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