A miniature electron-beam ion source for in-trap creation of highly charged ions

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Measurements of the anomalous magnetic moment of the electron bound in hydrogen-like ions with spinless nuclei have proven to be highly sensitive tests of corresponding calculations based on bound-state quantum electrodynamics. Currently, an experiment on hydrogen-like calcium $^{40}$Ca$^{19+}$ is being prepared, which is expected to yield a precision in the $10^{-9}$ level for the electronic $g$ factor. This experiment makes use of an in-trap electron-beam ion source with which the charge breeding of the ions is performed by electron-impact ionization. © 2006 American Institute of Physics.

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I. INTRODUCTION AND THEORY

Penning traps are ideal tools to perform high-precision atomic and nuclear physics experiments on charged particles, such as mass spectrometry and $g$-factor measurements. Highly charged ions are particularly advantageous regarding resolving power and accuracy, since observables like the cyclotron frequency scale with the charge state. Here, the application for precise determinations of electronic magnetic moments will be discussed.

The $g$ factor of an atomic system, defined as the dimensionless proportionality factor between the magnetic moment $\mathbf{\mu}$ and the angular momentum $\mathbf{J}$ by

$$ \mathbf{\mu} = -g\frac{q}{2m} \mathbf{J}, $$

with $q$ and $m$ being the particle’s charge and mass, respectively, contains information on relativistic and quantum-electrodynamic effects on the bound electron. Experimentally, precise measurements on highly charged ions have been performed on $^{12}$C$^{5+}$ (Ref. 1) and $^{16}$O$^{7+}$ (Ref. 2) with fractional uncertainties of a few parts in $10^{-9}$. The results of these measurements agree with the theoretical values and are considered presently as one of the best tests of bound-state quantum-electrodynamics (BS-QED) calculations. Since BS-QED contributions scale with the square of the nuclear charge, $Z^2$, tests become more stringent as experiments are performed on heavier ions. Therefore, an experiment is presently being prepared to determine the $g$ factor of the electron bound in $^{40}$Ca$^{19+}$.3

In order to successfully perform such high-precision experiments, extreme vacuum and temperature conditions have to be achieved ($p \leq 10^{-16}$ mbar, $T \leq 4$ K). This environment requires a completely sealed vacuum setup, which translates into the need for in-trap ion production. For this reason, the setup3 is equipped with a miniature electron-beam ion source (EBIS). It is attached to a cylindrical Penning trap in order to perform ion charge breeding by consecutive electron-impact ionization. The ionization process is complex and many theoretical and semiempirical models have been conceived from which the involved cross sections can be derived. The evolution of the ion densities in the EBIS is described by

$$ \frac{dN_i}{dt} = R_{\text{i}+1-i}^{\text{ioniz}} - R_{\text{i}+1-i}^{\text{recomb}} - R_{\text{i}+1-i}^{\text{radesc}} + R_{\text{i}+1-i}^{\text{source}}, $$

where $i$ defines the charge state, $R_{\text{i}+1-i}^{\text{ioniz}}$ is the ionization rate, $R_{\text{i}+1-i}^{\text{recomb}}$ is the radiative recombination rate, $R_{\text{i}+1-i}^{\text{radesc}}$ is the charge exchange rate, and $R_{\text{i}+1-i}^{\text{source}}$ accounts for the ions that escape from the trap axially, $R_{\text{i}+1-i}^{\text{source}}$ for those which leave radially, and $R_{\text{i}+1-i}^{\text{source}}$ for the injection of ions or neutrals. The radiative recombination cross section is given by Kim and Pratt,5 the one for charge exchange is due to Müller and Salzborn,6 the ion escape from the trap is calculated in Ref. 4, and the injection rate of ions can be found out experimentally.

II. EXPERIMENTAL SETUP

Figure 1 shows a sketch of the in-trap EBIS setup used for ion production and charge breeding. Electrons are extracted from a field emission point and are accelerated to an energy of up to 10 kV. The electron beam follows the magnetic field lines and goes past the anode, which is made out of graphite and upon which a calcium layer of $\sim 10 \, \mu m$ was
deposited. Once it reaches the high voltage of the hyperbolic electrode, it is reflected. After a short time during which the extraction of electrons is continued, due to space-charge effects, the beam becomes wide enough to hit the anode and to evaporate atoms and ions into the Penning trap, where the stepwise ionization takes place.

A highly sensitive charge amplifier is attached to the splitted ring electrode of the trap, enabling the detection of the signal of the image currents induced by the ions’ motion in the radial plane. The evolution of up to eight charge states can be followed simultaneously in real time with a multi-channel fast Fourier transform (FFT) analyzer, since each charge state induces voltages at a specific frequency. These data can be inserted into Eq. (2) to obtain information about the ionization cross sections by electron impact.

### III. STATUS AND OUTLOOK

The setup is in its last construction stage. Meanwhile, a computer code based on the work of Becker has been optimized and used to simulate the in-trap charge breeding process by electron-impact ionization. The strong magnetic field of a superconducting magnet (4 T) compresses the electron beam to typical current densities around 0.5 A/cm². The beam energy can be adjusted in order to optimize for a desired charge state within a given breeding time. At the maximum beam energy of 10 keV, the in-trap EBIS can produce hydrogen-like $^{40}\text{Ca}^{19+}$, whose 1 s electrons are bound with an energy of $5$ keV. Figure 2 shows the results of a simulation of the breeding process for calcium ions as a function of time for the given parameters.

The creation of a hydrogen-like calcium cloud as pure as possible is of extreme importance, since the $g$ factor measurement must be done with one single ion and the difficulty of the isolation process grows with the amount of impurities. Once a single ion is remaining inside the trap, the $g$ factor determination can be started, which is expected to yield a precision of some parts in the $10^{-9}$ level, representing a sensitivity of around 2.5% of the calculated BS-QED contributions.

On the other hand, the only published experimental mea-
measurements of the electron-impact ionization cross sections for calcium were performed in 1967, and the NIST database includes no data for calcium. So our aim is that our measurements, among others which could be performed with the same setup, contribute to slowly fill in the missing knowledge regarding cross sections of electron-impact ionization processes.

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11 http://physics.nist.gov/PhysRefData/Ionization/atom_index.html