# Plans for laser spectroscopy of trapped cold hydrogen-like HCI

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## Abstract

Laser spectroscopy studies are being prepared to measure the 1s ground state hyperfine splitting in trapped cold highly charged ions. The purpose of such experiments is to test quantum electrodynamics in the strong electric field regime. These experiments form part of the HITRAP project at GSI. A brief review of the planned experiments is presented.
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## 1. Introduction

An accurate measurement of the hyperfine splitting (HFS) of the 1s ground state of hydrogen-like highly charged ions (HCI) is a good test of quantum electrodynamics (QED) in the limit of strong electric fields ($10^{15}$ V/cm [1]). Such strong fields cannot be produced using conventional laboratory techniques, but naturally exist close to the stripped nuclei of heavy elements like Pb, Bi or U. By detecting the fluorescence from the laser-excited upper hyperfine state of such a trapped and cold ion, a high-precision measurement of the hyperfine splitting can be made.

HCI with extremely high charge states (e.g. $Pb^{81+}$ or $U^{92+}$) and relativistic energies (400 MeV/u) are created in the heavy ion facility (SIS) at GSI in Darmstadt. These HCI are injected into the experimental storage ring (ESR) and can be decelerated (down to 4 MeV/u) forming 1 μs long bunches containing about $10^5$ ions, arriving every 10 s. In the HITRAP project [2,3] these bunches will be extracted from the ESR, decelerated by linear (IH-LINAC) and radiofrequency (RFQ) stages, trapped and cooled in a Penning trap (cooler trap), and made available for experiments.

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In the ESR at GSI, previous measurements of the HFS were made on bunches of relativistic HCI such as $^{209}\text{Bi}^{82+}$ [4] and $^{207}\text{Pb}^{81+}$ [5]. HFS measurements were also made at the SuperEBIT on $^{165}\text{Ho}^{66+}$ [6], $^{185,187}\text{Re}^{74+}$ [7] and $^{203,205}\text{Tl}^{80+}$ [8]. The resolution obtained in the above experiments is mainly limited by the Doppler effect. A measurement of the 1s ground state HFS of trapped cold HCI using laser spectroscopy should be even more accurate due to a cryogenic UHV environment, high ion cloud density, the absence of a large Doppler shift and virtually unlimited measurement time.

Laser spectroscopy offers the possibility of high-accuracy measurements of transition wavelengths in the visible region [9]. In HCI, electronic transitions are generally in the far UV or X-ray regions of the spectrum. However, since the 1s ground state HFS scales with the atomic number $Z$ as $Z^3$, the ground state HFS of hydrogen-like HCI can move into the visible spectrum for $Z > 70$ [1,10]. The lifetime of this transition falls as $Z^{-9}$ and is of the order of milliseconds for $Z > 70$. A measurement of this transition wavelength gives information on the QED corrections to the HFS or on the spatial distribution of the nuclear magnetisation (Bohr–Weisskopf effect), which is affected by core polarisation and is not completely understood [1]. Its measurement thus allows for critical tests of nuclear models. From a comparison of measurements of the HFS of hydrogen-like and lithium-like HCI the nuclear effects can be eliminated so that an accurate measurement of the QED effects can be made [11,12].

There are several candidate systems that can be studied at HITRAP, including radioactive isotopes. An interesting first challenge would be to measure the HFS of the 1s ground state M1 transition of $^{207}\text{Pb}^{81+}$ ions ($\lambda = 1020$ nm [5]) by means of laser spectroscopy. In order to reach the necessary accuracy, the HCI will be trapped in a cryogenic UHV environment. Once trapped, the ions can be easily stored for long times, therefore the relatively long lifetime $\tau = 50$ ms [5] of the upper hyperfine state is not a problem. Electron capture (neutralisation) by collisions is strongly reduced by operating the trap at cryogenic tempera-

tures (4 K) under UHV conditions (below $10^{-14}$ mbar).

## 2. Zeeman versus hyperfine splitting

The high precision measurements of the HFS will be performed on HCI in a Penning trap, but the strong magnetic field will shift and split the hyperfine levels and thus the natural HFS. This 'Zeeman effect' [13] is schematically illustrated in Fig. 1(a) for the 1s ground state HFS in hydrogen, which has nuclear spin $I = 1/2$. For hydrogen the HFS can be easily calculated using the famous Breit–Rabi formula [14]. The zero-field splitting $A$ is modified by the interaction between the magnetic moment $\mu$ of the ion and the magnetic field strength $B$. In the simple hydrogen case at a field of 1 T, the Zeeman splitting of about $2.8 \times 10^{10}$ Hz is more than one order of magnitude larger than the HFS in hydrogen ($1.4 \times 10^9$ Hz or 21 cm). However, for HCI the HFS dominates the Zeeman splitting by several orders of magnitude. This is indicated in Fig. 1(b) for the 1s ground state HFS of $^{207}\text{Pb}^{81+}$, which also has nuclear spin $I = 1/2$.

In Fig. 2 the calculated wavelengths of the 1s ground state hyperfine transition (neglecting QED and the Bohr–Weisskopf effect) are plotted for HCI with atomic number $Z$ ranging from 50 to 100. Many of these heavier elements have their HFS in the visible region of the spectrum and are
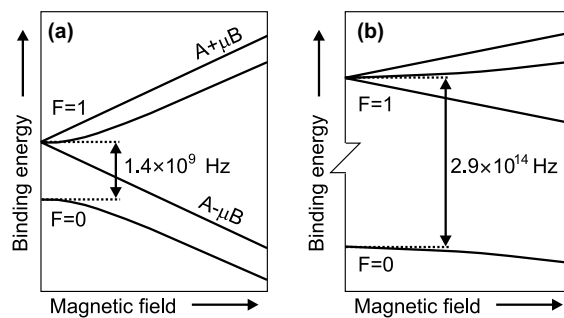


Fig. 1. Zeeman and hyperfine splittings of the 1s ground states of $I = 1/2$ nuclei plotted versus magnetic field: (a) hydrogen atom $^1\text{H}^0$, (b) highly charged lead ion $^{207}\text{Pb}^{81+}$. (The plots are drawn with different scales.)