Improved accuracy of in-ring Laser spectroscopy by in-situ electron cooler voltage measurement*

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Introduction

Laser spectroscopy experiments of highly charged, heavy ions at the experimental storage ring ESR have been performed for more than twenty years by now [1, 2, 3], aiming at tests of fundamental theories. A conclusive test of bound-state quantum electrodynamics (BS-QED) in strong fields, however, has not been reached so far, because of the large uncertainty arising from the unknown spatial distribution of the nuclear magnetization (Bohr-Weisskopf effect). The method formulated by Shabaev and coworkers [4], defining a specific difference between the hyperfine splittings in hydrogen- and lithium-like ions of the same species removes these uncertainties and provides the possibility to test BS-QED without nuclear uncertainties. Although the attempt in 2011 to measure the hyperfine splitting energies of the ground states in hydrogen- and lithium-like bismuth ions was for the first time successful in detecting both resonances, it yielded a large uncertainty caused by an inaccurate knowledge of the ion velocity [5]. Hence, a second attempt was performed in March 2014 with an improved setup.

Setup

The setup was similar to previous experiment in 2011 and is shown in fig. 1. Ions injected into the ESR were cooled with the electron cooler and confined into two bunches using a radio frequency (RF)-cavity, driven with the second harmonic of the revolution frequency. With a bunched beam, the fluorescence signal-to-background ratio could be improved by 50% compared to coasting beam operation. The bunching frequency was used for tagging the arrival times of single photon counts on the photomultiplier tubes by the data acquisition system with 3.3-ns resolution. This was realized using time-to-digital converters implemented on a VUPROM-device[1]. The fluorescence light detection efficiency was optimized in the two cases using two mirror systems adapted to the specific needs of the respective transition and shown on the right side of 1: For the hydrogen-like ions the detection chamber developed for [2] (upper part) and for the lithium-like species the system developed at the University of Münster [6] were used. The excitation of the hyperfine transition was performed by a dye laser system consisting of a Nd:YAG pump laser and a Sirah COBRA dye-laser that provided pulses with energies of 150 mJ. The target laboratory frame wavelengths of 591 nm and 641 nm were produced by Pyrromethene 597 dye and DCM Special dye, respectively, and the light was delivered to the ESR experimental hall using mirrors with a high-reflectivity coating.

A major improvement of the setup was the in situ measurement of the electron cooler voltage, which is used to determine the ions' velocity for Doppler shift compensation. The data analysis of the previous attempt in 2011 revealed that the calibration of the electron cooler voltage display was insufficient, leading to large uncertainties [7]. To circumvent this, an accurate high-voltage divider was installed. A newly established collaboration with the high-voltage metrology working group of PTB[2] enabled us to use a reference voltage divider featuring a relative accuracy of 10^{-5} [8]. An additional measurement of residual frequencies in the d.c. high voltage using a ripple probe developed at PTB revealed a very clean high voltage signal. Besides the anticipated leap in accuracy, the voltage measurement turned out to be a invaluable diagnostic tool. Energy fluctuations of the ion beam that emerged during beamtime could be identified to originate from a floating drift tube inside the electron cooler, and could be clearly distinguished from fluctuation of the high-voltage power supply that also arose during beamtime. The in-situ measurement allowed us to take all voltage fluctuations into account during the analysis.

First Results

The analysis of the fluorescence data was performed using GO4 and SciPy. A typical resonance for hydrogen-like bismuth recorded in one single scan of the laser wavelength with coasting ion beam is shown in the left part of fig. 2. The resonance wavelength in the laboratory frame was determined by fitting a Gaussian profile to the fluorescence data using the orthogonal distance regression algorithm [10] to take the uncertainty of the laser wavelength determination into account. Although the analysis is still ongoing, first results of the rest-frame wavelength of the ground state hyperfine transition in hydrogen-like bismuth could be obtained [9] demonstrating the advantage of the high-voltage measurements. The analysis of the resonances taken without bunching the ion beam ("coasting beam") resulted in a value roughly 10 times more accurate compared

* Work supported by HIC4FAIR, HGS-HIRe, BMBF contract Nos. 05P12PMFAE and 05P12RDFA4.

[1]**V**ME **U**niversal **Pro**cessing **M**odule, an FPGA-based module for VMEbus-systems developed at GSI's experiment electronics department

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DOI:10.15120/GR-2015-1-APPA-MML-AP-11

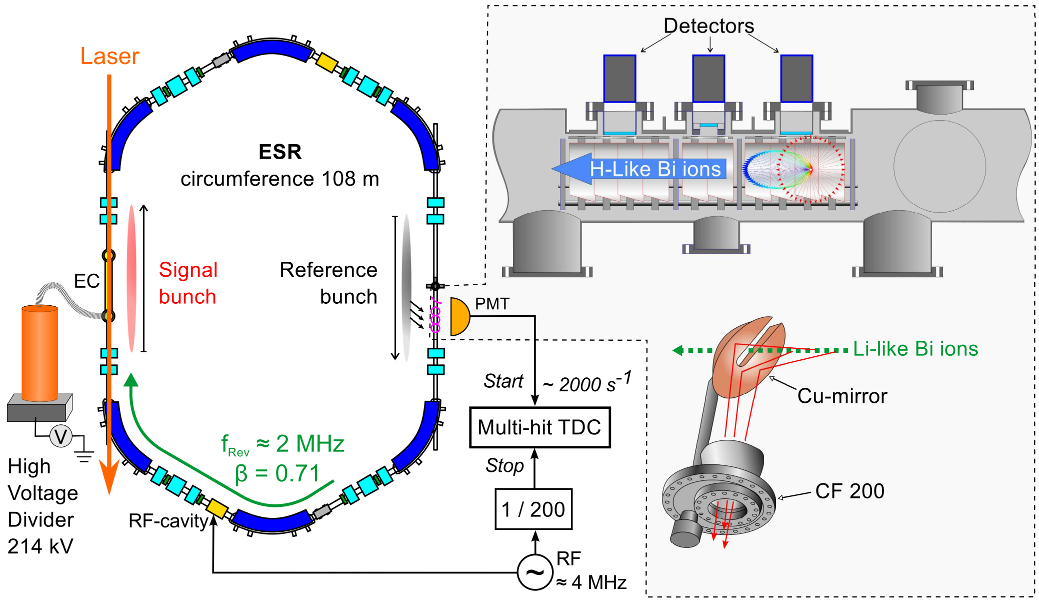

Figure 1: Experimental setup:The voltage of the electron cooler (EC) gun determines the ion velocity in the ESR and is measured with a precise high-voltage divider (HVDC2.1 from PTB). The upper part of the inset shows the detection section used for the hydrogen-like charge state which was reused from [2], the lower part shows the retractable parabolic mirror system [6] for detection of the forward cone-shaped emission characteristic of lithium-like bismuth. All photons detected at one of the two mirror systems are tagged on a VUPROM multi-hit TDC with an absolute time stamp as well as relative to the phase of the revolution frequency.

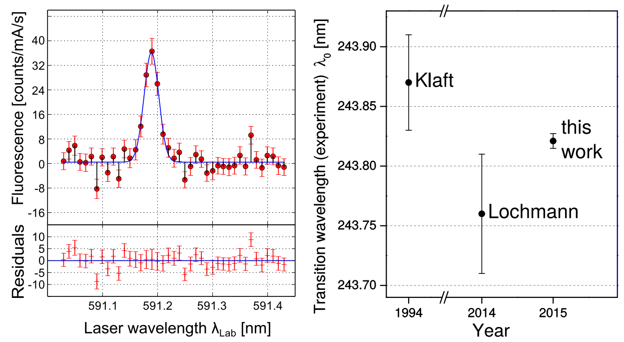

Figure 2: Left: Single resonance signal of hydrogen-like bismuth taken with a coasting ion beam. The fluorescence counts are normalized to ion current and live time of the data acquisition. A fit of a Gaussian profile and the corresponding residuals are also shown. Right: Result of the rest-frame wavelength of the ground state hyperfine transition in hydrogen-like bismuth, compared to previous attempts. The result is compatible with the prior values and its accuracy has been improved by a factor of 10 [9].

to the previous attempts, as shown in the right part of fig. 2.

Conclusion

According to the first results of the LIBELLE 2014 beam time, a QED test using the hyperfine splittings in bismuth ions is in reach now. The accuracy of the obtained hydrogen-like bismuth wavelength is an order of magnitude higher than in all previous attempts and promises a similar leap in accuracy for the lithium-like charge state and, consequently, also for the specific difference. Lifetime measurements for both transitions have been performed as well and are currently under evaluation at the University of Münster. Furthermore, it has been pointed out, that an accurate *in-situ* voltage measurement is vital for laser spectroscopy measurements at the ESR and a valuable diagnostic tool for other experiments using the electron cooler. Hence, a dedicated high voltage divider is currently commissioned and will soon be installed at the electron cooler.

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 DOI:10.15120/GR-2015-1-APPA-MML-AP-11