Ground-State Hyperfine Structure of Heavy Hydrogen-Like Ions

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Abstract. Contributions of quantum electrodynamics (QED) to the combined electric and magnetic interaction between the electron and the nucleus can be studied by optical spectroscopy in high-Z hydrogen-like heavy ions. The transition studied is the ground-state hyperfine structure transition, well known from the 21 cm line in atomic hydrogen. The hyperfine splitting of the is ground state of hydrogen-like systems constitutes the simplest and most basic magnetic interaction in atomic physics. The Z^3-increase leads to a transition energy in the UV-region of the optical spectrum for the case of Bi^{82+}. At the same time, the QED correction rises to nearly 1 fraction of higher order contributions. This situation is particularly useful for a comparison with non-perturbative QED calculations. The combination of exceptionally intense electric and magnetic fields electric and magnetic fields is unique. This transition has become accessible to precision laser spectroscopy at the high-energy heavy-ion storage ring at GSI-Darmstadt in the hydrogen-like $^{209}Bi^{82+}$ and $^{207}Pb^{81+}$. In the meantime, $^{165}Ho^{66+}$ and $^{185,187}Re^{74+}$ were also studied with reduced resolution by conventional optical spectroscopy at the SuperEBIT ion trap at Lawrence Livermore National Laboratory.

1 Introduction

In neutral and low-charge atoms, the predictions of QED are in perfect agreement with experiment. Radiative QED effects in highly charged hydrogenic ions increase by a scaling factor of Z^4, and the size of these higher-order contributions makes these systems exceptionally interesting for testing possible limits of validity of QED. This opportunity has given rise to renewed experimental effort to investigate the Lamb shift in heavy ions. Completely complementary is the possibility to test QED in the combination of strong electric and magnetic fields by precision laser spectroscopy of the ground state hyperfine splitting in high-Z hydrogenic systems.

The magnetic interaction of the 1s electron in the nucleus causes a hyperfine splitting in the ground state of hydrogen and heavier isotopes. In particular, the 1.4 GHz splitting frequency in hydrogen, corresponding to a transition

wavelength of 21 cm, has been extensively studied by precision microwave spectroscopy, and in hydrogen masers the splitting frequency has been determined to an accuracy of 7×10^{-13} [1].

Transition energies for highly-charged ions are shown in Tab. 1. For the highest-Z atoms the increase of the splitting with Z^3 shifts the HFS transition into the optical region of the spectrum, and makes it accessible to precision laser spectroscopy [2].

2 Storage Ring Laser Spectroscopy

A unique access for laser spectroscopy of such highly charged ions has been created by the advent of heavy-ion cooler rings. In the past, poor beam quality and short interaction time had restricted the application of lasers at accelerators to exotic single events, and laser spectroscopy appeared as a more or less parasitic user of these installations. The key experimental features of heavy-ion cooler rings in comparison to standard accelerators are the increase in interaction time and the dramatic improvement of the beam quality achieved by electron cooling. Electron cooling was demonstrated for the first time in 1969 at the proton storage ring in Novosibirsk [3] and was applied to heavy-ion storage rings starting with the TSR at the Max-Planck Institut für Kernphysik in Heidelberg.

There are a number of unique possibilities accessible for laser-based experiments in heavy-ion storage rings using the exotic properties of the stored ions to address fundamental problems of physics. Even laser-saturation spectroscopy is possible. This allows for resolution close to the natural line width of the transition, and was used to test Special Relativity at the TSR. The much higher velocity, compared to conventional experiments, makes this test particularly sensitive to higher order contributions. The full spectrum of possibilities for storage-ring laser spectroscopy is reached at the very high energies available at the ESR, where intense beams of highly-charged ions are available for precision laser spectroscopy, and give novel opportunities for the study of quantum electro-dynamics in high magnetic and electric fields. The stripping of uranium ions in a fixed metal foil requires a beam energy of 200 MeV per nucleon to reach a 10 percent efficiency. So far only the SIS (magnetic rigidity 18 Tm) – ESR (magnetic rigidity 9 Tm) facility, Fig. 1, can meet this requirement. The alternative production scheme by electron-bombardment in an electron-beam ion trap (EBIT) presently yields around 100 to 1000 ions per filling cycle for hydrogen-like uranium, compared to 10^7 particles per pulse at SIS. For heavy ions like bismuth and uranium, beam intensities of 10^8 stored ions are reached.

Heavy ions are pre-accelerated in the UNILAC linear accelerator to energies up to 20 MeV per nucleon. Before injection into the SIS heavy-ion synchrotron, the charge-state of these ions can be increased by passing them through a stripping foil. The final energy is limited by the bending fields of 18 Tm to e.g. 1 GeV per nucleon for uranium. At this energy naked ions can be prepared by additional stripping. Laser light is introduced either parallel or anti-parallel to the direction of the ions.

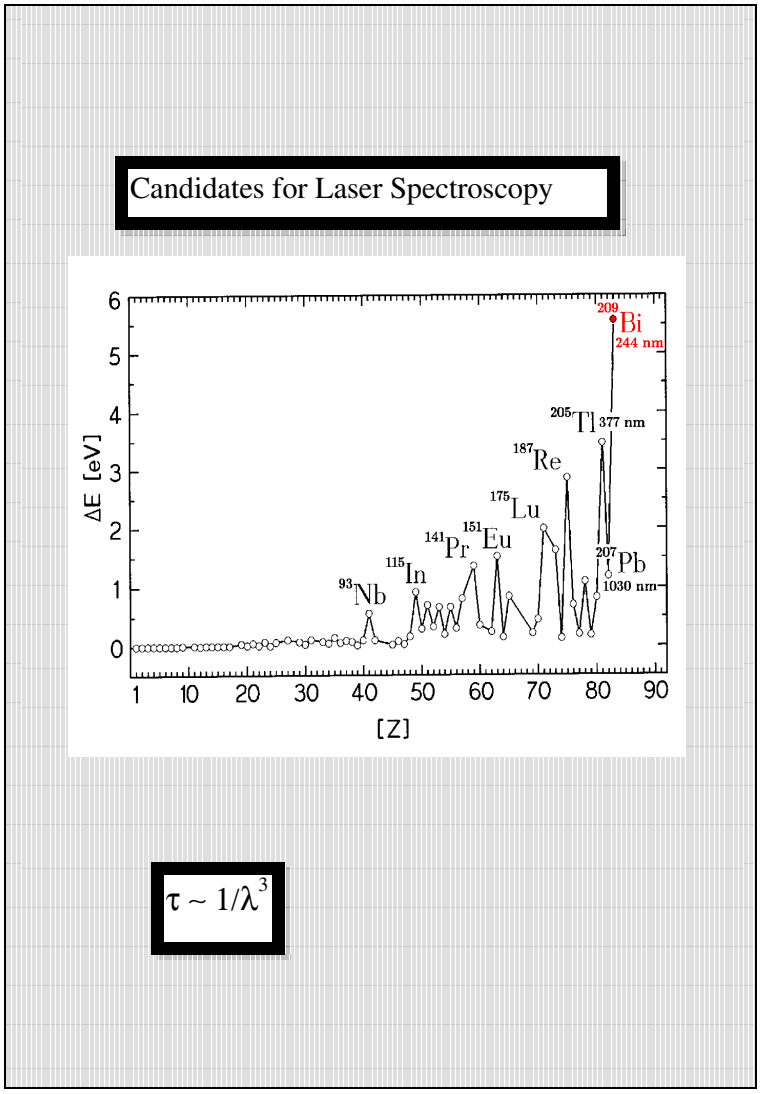

Fig. 1. Possible candidates for laser spectroscopy

An additional benefit for future experiments at the SIS – ESR facility is the availability of intense beams of unstable nuclei produced by fragmentation of the primary ion beam. At GSI, these secondary ions are separated from the primary beam in flight in the FRS (fragment separator), and the resulting beam of unstable nuclei can be stored in the ESR.

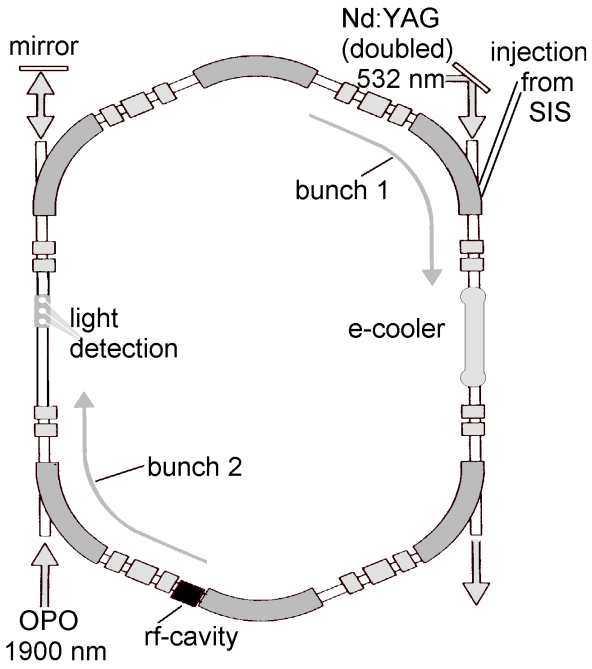

Fig. 2. Laser spectroscopy set-up at the ESR facility at GSI

3 Experimental Procedure

For laser light impinging onto an absorber moving at relativistic velocity, the resonance frequency is shifted relative to the transition frequency ν_0 in the rest frame of the ions according to the relativistic Doppler formula

$$\nu \;=\; \nu_0 \;[\,\gamma\,(1-\beta\cos\theta)\,]^{-1} \tag{1}$$

where θ denotes the angle between the ions and the laser beam ($theta = 0$ for the parallel case). This relation also causes the light emitted from the moving ion to be observed in the laboratory frame at a strongly shifted frequency. The large Doppler shift due to the relativistic ion velocity can be used to the advantage to excite transitions in the ultraviolet and infrared spectral regimes, even when no suitable lasers would be available at the transition wavelength in the rest frame. The detection of fluorescence after laser excitation of an infrared transition is facilitated by the large Doppler blue-shift under forward angles. This shifts and compresses the wavelength of the emitted light into the region detectable by single-photon sensitive photomultipliers. As a disadvantage, the velocity spread

$\frac{\delta\beta}{\beta}$ of the ion beam leads to a Doppler width of

$$\delta\nu_{Dopp} \approx \nu \cdot \gamma^2 \delta\beta \,. \tag{2}$$

This Doppler width can be avoided by typical sub-Doppler laser spectroscopy techniques. Laser saturation spectroscopy with a resolution close to the natural line width was used for a test of Special Relativity at the ESR. For such sub-Doppler resolution one must also take into account the small additional broadening and shift arising from the angle θ between laser beam and ion beam in the Doppler formula. At an interaction length of 10 meters and more, angles are easily controlled to be better than 1 mrad. This limits a possible shift, which enters by

$$\Delta\nu_\theta = -\nu\beta^2\theta^2 \tag{3}$$

to $2 \cdot 10^{-7}\ \nu$ or smaller.

In the same way the transverse beam temperature leads to a broadening via the betatron movement of the particles. For the straight sections this effect can be estimated to be of minor importance for cooled beams.

In order to increase the signal-to-noise ratio, experiments can be performed on a bunched beam. In this way a pulsed laser can cover a much larger percentage of the ions stored in the ring as compared to the coasting beam condition. An intrinsic background correction can be provided by using two bunches in the ESR, where only one bunch was excited by the laser. As an example a result from hydrogen-like lead is given in Fig. 3. The resonance was found at $\lambda_0 =$ 1019.7(2) nm. The transition was excited by a frequency-doubled Nd:YAG laser in collinear geometry.

4 Results and Outlook

Table 1. Ground-state hyperfine structure in some hydrogen-like ions

	RMS radius	Magnetic moment	Hyperfine Splitting	Ref.
$^{209}Bi^{82+}$	5.519 fm	4.1106(2) μ_N	243.87(2) nm	[4]
$^{207}Pb^{81+}$	5.497 fm	0.58219(2) μ_N	1019.7(2) nm	[5]
$^{165}Ho^{66+}$	5.21 fm	4.132(3) μ_N	572.79(15) nm	[6]
$^{185}Re^{74+}$	5.39 fm	3.1871(3) μ_N	456.05(30) nm	[6]
$^{187}Re^{74+}$	5.39 fm	3.2197(3) μ_N	451.69(30) nm	[6]

So far data on the energy difference of the hyperfine splitting and of the transition lifetime were measured by storage ring laser spectroscopy for hydrogen-like bismuth [4] and lead [5]. In addition data with lower resolution were measured for the transition wavelength in holmium and rhenium [6]. Excellent agreement was found for the transition lifetime in hydrogen-like bismuth. The decay probability of an excited 1s hyperfine structure level can be given in terms of the g-factor of

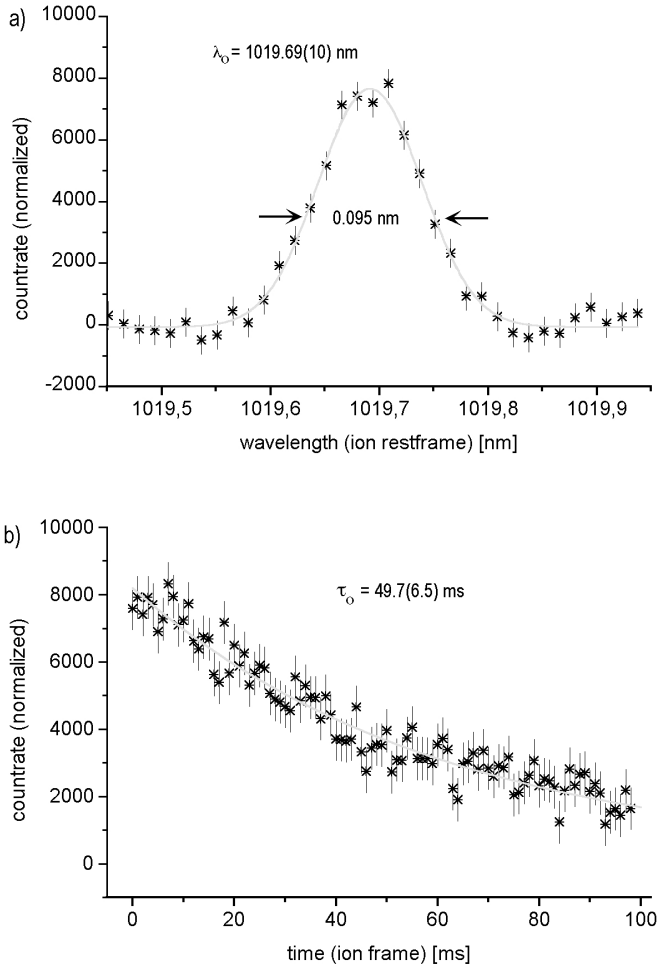

Fig. 3. Upper trace: Background corrected and normalized fluorescence signal. Lower trace: Time dependence of fluorescence count rate after excitation by the laser pulse

the electron bound in the electric field of the nucleus g_e. First measurements of g were performed only in rather light systems (H, D, He and C^{5+}). The earlier lifetime measurements of the excited hyperfine state in hydrogenlike bismuth and lead performed by laser spectroscopy in the ESR suffered from a lack in accuracy. Especially the measurement for bismuth was subject to doubt because of its large deviation from calculations. A remeasurement of the transition lifetime resulted in an accuracy sufficient to test the relativistic correction. In addition there is good agreement with the theoretical value including QED but some

disagreement, if QED effects are not included in theory, which would lead to g_e (no QED) = 1.7281 for hydrogenlike bismuth. Unfortunately, the agreement of the transition wavelengths with theoretical values is not very convincing [7]. This is probably due to the fact that the accuracy of the nuclear magnetic moment data and also of the theoretically deduced Bohr-Weisskopf values is hard to asset. Especially in the case of lead, two different values for the magnetic moment are found in the literature. Independent experimental verification, is difficult to achieve. Theoretical investigations indicate that it would be possible to eliminate this problem by the measurement of the 2s-hyperfine structure in lithium-like bismuth. The transition wavelength is predicted with high accuracy using the result from the 1s-hyperfine splitting in the hydrogen-like case as input for an elimination of the Bohr-Weisskopf-effect [8]. However, in an experiment performed at the ESR no resonance line was found within the limits given by the present theoretical estimates. A major improvement of this situation would arise from an accurate determination of the nuclear magnetic moments with an independent method, which would also support or disproof the Bohr-Weisskopf calculations.

References

1. L. Essen, R.W. Donaldson, M.J. Bangham, and E.G. Hope: Nature **229** (1971)
2. V. M. Shabaev: J. Phys. B27 (1994) 5825
3. G.I. Budker, A.N. Skrinsky: Us. Fiz. Nauk **124** (1978) 561; Sov. Phys. **21** (1978) 277
4. I. Klaft et al.: Phys. Rev. Lett. **73** (1994) 2425
5. P. Seelig et al.: Phys. Rev. Lett. vol. 81 (1998) **81** (1998) 4824
6. J.R. Crespo Lopez-Urrutia et al.: Phys. Rev. Lett. **77** (1996) 826, and presented at the conference *Hydrogen Atom 2* (unpublished)
7. V. Shabaev et al.: *this edition*, pp. 714–726
8. V.M. Shabaev, M.B. Shabaeva, I.I. Tupitsyn: Phys. Rev. A **52** (1995) 3686