Systematics in the Experimental Determination of the g-Factor of the Bound Electron in Hydrogen-Like Carbon (C^{5+})

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Introduction

In this contribution we investigate possible error sources in our measurement of the magnetic moment (*g-factor*) of the electron bound in hydrogen-like carbon (C^{5+}). The experimental determination of the magnetic moment of the bound electron in hydrogen-like ions is an important test of the theory of Quantum Electrodynamics in strong Coulomb fields [1]. It represents a clean test of pure QED effects because it is not very sensitive to nuclear structure effects [2].

In our experiment a single C^{5+}-ion is stored in a Penning trap, which consists of a strong magnetic field (4 T) and an electrostatic quadrupole potential [3]. Our trap is made by a stack of 13 ring electrodes, so that the ion can be trapped at different positions. The ion is cooled by resistive cooling to a temperature of 4 Kelvin within less than 1 second. Due to the low background gas pressure in the cryopumped vacuum chamber ($p < 10^{-16}$mbar) the storage time of the C^{5+}-ion is longer than one year. The oscillation frequencies (cyclotron frequency, axial frequency and magnetron frequency) of a single C^{5+}-ion are measured with high precision by a frequency analysis (FFT) of the image currents which are induced in the trap electrodes by the motion of the ion. By this method, the cyclotron frequency $\omega_c = q/m \cdot B$ of a C^{5+}-ion is determined with a resolution of $1 \cdot 10^{-9}$.

g-Factor Measurement

The g-factor of the bound electron is proportional to the ratio of the Larmor precession frequency and the cyclotron frequency. The cyclotron frequency of the C^{5+}-ion is measured by the image-current method as mentioned above. The measurement of the Larmor precession frequency of the bound electron is performed by observing quantum jumps between the two possible orientations (spin up and down) of the spin of the electron. The spin flips are induced by a microwave field at 104 GHz.

We detect the change of the spin direction of the bound electron via the continuous Stern-Gerlach effect [4] which employs an inhomogeneous magnetic field component ("magnetic bottle") to couple the spin direction to the axial frequency of the trapped particle. This technique was first used by Dehmelt and coworkers in their $g-2$ experiment on a free electron in a Penning trap [5]. Since the resulting axial frequency change is much smaller for atomic ions than in the case of the electron, our magnetic bottle is about 100 times stronger than the one used by Dehmelt and coworkers. This strong magnetic inhomogeneity limited our previous g-factor measurement to an accuracy of 10^{-6} [4].

In our new measurements we spatially separate the functions of inducing and detecting the spin flips in order to overcome this limitation of the measurement accuracy. After determining the spin direction in the "analysis trap", we transfer the ion to an adjacent potential well ("precision trap") where the magnetic field is much more homogeneous. In the precision trap the cyclotron frequency is determined while the ion is irradiated simultaneously by the microwaves to induce spin-flip transitions. In this procedure possible uncertainties arising from temporal fluctuations of the magnetic field cancel out. In order to detect the spin flips the ion is moved back to the analysis trap.

Systematics

The electron mass in atomic units is an important input parameter for the determination of the g-factor of the bound electron. Van Dyck and coworkers measured the electron mass with an uncertainty of 2 ppb [6]. In our new measurement we determined the ratio of the Larmor frequency and the cyclotron frequency with an accuracy of 0.5 ppb. Therefore, presently the knowledge of the electron mass is the main limitation to the theoretical interpretation of our g-factor measurement.

The second largest error of 0.4 ppb is the statistical uncertainty. The experimental data were taken continuously over a period of 2 months. Other systematic errors are estimated to be smaller than 0.3 ppb. The largest of these arises from the complicated line-shape which is due to magnetic field inhomogeneities and imperfections of the electrostatic trapping potential. Other systematic shifts like the image charge shift of the eigenfrequencies in the cavity were calculated to contribute 0.25 ppb and are included in the result. The resulting g-factor of the bound electron in hydrogen-like carbon (C^{5+}) is

$$g = 2.001\,041\,596\,(1)\,(1)\,(4)\,. \tag{1}$$

The first error is the statistical uncertainty, the second error arises from possible systematic shifts and the third one denotes the uncertainty in the knowledge of the atomic mass of the electron.

Acknowledgments: This work is supported by the European Union under the contract number ERB FMRX CT 97-0144.

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