Access to the quadratic and cubic Zeeman effects at ARTEMIS

M. Vogel[1,2], *G. Birkl*[1], *D. von Lindenfels*[2,3], *A. Martin*[1], *W. Quint*[2,3], *and M. Wiesel*[1,2,3]
[1]Institut für Angewandte Physik, TU Darmstadt; [2]GSI, Darmstadt; [3]Ruprecht Karls-Universität Heidelberg

We have conceived an experiment for laser-microwave double-resonance spectroscopy of highly charged ions in a Penning trap. Such spectroscopy allows a highly precise measurement of the Zeeman splittings of fine- and hyperfine-structure levels due the magnetic field of the trap. We also have performed detailed calculations of the Zeeman effect in the framework of quantum electrodynamics of bound states as present in such highly charged ions. We find that apart from the linear Zeeman effect, also second- and third-order Zeeman effects contribute to the splittings on a level of 10^{-4} and 10^{-8}, respectively, and hence are accessible to a determination within the achievable spectroscopic resolution of the currently prepared ARTEMIS experiment.

A quadratic contribution to the Zeeman effect has first been discovered by Segré and Jenkins in the 1930s. Since then, there have been numerous studies, both experimental and theoretical, of higher-order Zeeman contributions in atoms, molecules and singly charged ions in laboratory magnetic fields. Corresponding studies in observational astronomy have identified a quadratic Zeeman effect in abundant species like hydrogen and helium. Although highly charged ions are both abundant in the universe and readily accessible in laboratories, to our knowledge, no higher-order Zeeman effect in highly charged ions has been observed so far.

We are currently setting up a laser-microwave double-resonance spectroscopy experiment with highly charged ions in a Penning trap, which combines precise spectroscopy both of optical transitions and microwave Zeeman splittings [1, 2]. The experiment aims at spectroscopic precision measurements of such energy level splittings and magnetic moments of bound electrons on the ppb level of accuracy and better. At the same time, it allows access to the nuclear magnetic moment in absence of diamagnetic shielding. For first tests, the $^{40}Ar^{13+}$ ion has been chosen. It has a spinless nucleus, such that only a fine structure is present. Similar measurements in hyperfine structures are to be performed with ions of higher charge states such as for example $^{207}Pb^{81+}$ and $^{209}Bi^{82+}$ as available to ARTEMIS within the framework of the HITRAP facility.

In an external magnetic field, the Zeeman effect lifts the degeneracy of energies within fine- and hyperfine-structure levels. For highly charged ions in magnetic fields of a few Tesla strength, the Zeeman splitting is well within the microwave domain and thus accessible for precision spectroscopy. In addition, in case of fine- and hyperfine-structure transitions, the strong scaling with Z eventually shifts the corresponding energies into the laser-accessible region and thus makes them available for precision optical spectroscopy. Figure 1 schematically shows the Zeeman splitting of the $2\,^2P_J$ states of boron-like argon Ar^{13+} in an external magnetic field with higher-order contributions to the Zeeman effect. While the linear effect separates the two ground-state ($2\,^2P_{1/2}$) levels by about 65 GHz and the four excited-state ($2\,^2P_{3/2}$) levels by about 130 GHz, the quadratic effect shifts both $(1/2, \pm 1/2)$ levels down and the two $(3/2, \pm 1/2)$ levels up by about 3 MHz. The $(3/2, \pm 3/2)$ levels are shifted up by 74 kHz. The cubic effect increases the splitting between the ground-state levels by about 306 Hz, thus simulating a contribution of $3 \cdot 10^{-9}$ to $g_{1/2}$ which is still within achievable experimental resolution. The experimental approach chosen allows a separation of the respective higher-order contributions to the linear Zeeman effect and will hence be valuable as a benchmark of theoretical calculations which include QED effects in extreme fields [3].

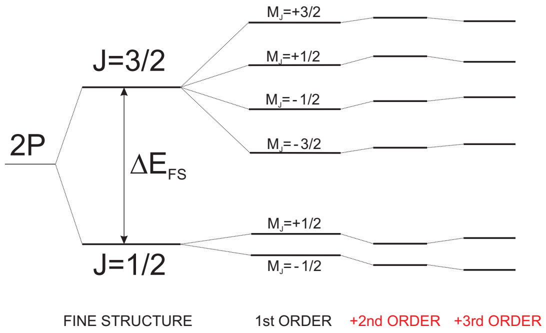

Figure 1: Level scheme of the $2\,^2P_J$ states of boron-like argon Ar^{13+} in an external magnetic field with higher-order contributions to the Zeeman effect (not true to scale)

This work has been performed in collaboration with D.A. Glazov, V.M. Shabaev, M.M. Sokolov, A.V. Volotka and G. Plunien from the St. Petersburg State University and the Technische Universität Dresden.

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References

[1] W. Quint, D. Moskovkin, V.M. Shabaev and M. Vogel, Phys. Rev. A **78** (2008) 032517.

[2] D. von Lindenfels, N. Brantjes, G. Birkl, W. Quint, V. Shabaev and M. Vogel, Can. J. Phys. **89**, 79 (2011).

[3] D. von Lindenfels, G. Birkl, D.A. Glazov, A. Martin, G. Plunien, W. Quint, V.M. Shabaev, M.M. Sokolov, M. Vogel, A.V. Volotka, and M. Wiesel, accepted for Phys. Rev. A (2013).