Studies on the Hyperfine Structure of Highly-Charged Hydrogen- and Lithium-like Ions

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A number of laser-spectroscopic experiments on the hyperfine structure of highly-charged ions has been carried out at GSI in Darmstadt during the last years. Such experiments provide a serious test of our understanding of the fundamental interactions of matter under extreme conditions. The fact that the relevant interactions are concentrated very close to the nucleus makes these investigations particularly sensitive to higher order contributions. For several hydrogen-like ions, however, recent laser experiments have determined level splittings [1, 2] which could not yet be fully reproduced by theory. By taking into account quantum electrodynamical (QED) corrections, the theoretical results occur – so far – outside of the experimental uncertainty. For example measurements have been carried out for hydrogen-like $^{209}Bi^{82+}$ and $^{207}Pb^{81+}$ ions. These studies yielded splittings of 5.0840(5) eV and 1.2159(2) eV while the values of detailed calculations are 5.056(9) eV and 1.2101(26) eV including QED, and 5.083(8) eV and 1.2166(20) eV without QED [3, 4]. A similar situation was found for the ground state hyperfine transition for lithium-like bismuth, where no signal was obtained within the range of theoretical predictions. Measurements in a small frequency range as been estimated by theory [5, 6] did however not yield an experimental signal yet. When compared with hydrogen-like ions, further information about the hyperfine interaction of the nucleus with the electronic cloud of high-Z ions can be obtained by studying the ground-state splitting of few-electron ions. The simplest systems which have a closed $K-$shell are lithium-like ions. For these systems, the hyperfine splitting arises first of all from the coupling of the $2s$ electron with the nuclear angular momentum I since the closed $K-$shell does not contribute to the total (electronic) angular momentum J. Moreover, a filled $1s^2$ shell yields the advantage to reduce the influence of both the nucleus and of quantum electrodynamical effects. On the other hand, difficulties arise from the correlated motion of the electrons and from a (possibly) enhanced polarization of the interaction among the electrons and the nucleus. In zero-order, the hyperfine interaction of the nuclear moment with the motion of the electrons is represented by a dipole field with a $1/r^3$ behaviour. This behaviour leads to the typically strong dependence of the hyperfine splitting on nuclear parameters. Like for the (extended) nuclear charge distribution, a point model for the magnetic interaction represents, of course, a rather crude model and should be replaced by an extended nuclear magnetization distribution. This is known as the Bohr-Weisskopf effect. But while in the traditional approach the different measured contributions are obtained additively, an improved treatment should include also nucleon-nucleon correlation to provide a consistent description of the interaction of the electron cloud with the nucleus. To obtain this magnetization distribution from nuclear structure calculations, nucleon-nucleon correlation effects need to be included beyond a single particle-model in which the magnetic distribution is determined just by the *odd* nucleon (like the unpaired proton in $^{209}Bi^{82+}$). In the traditional approach to theoretical hyperfine splitting studies, the different contributions from the electron-electron interaction, QED effects, and the extended nucleus are obtained *additively.* This also applies to the coupling of the electrons with the motion of the nucleons as is summarized by the Bohr-Weiskopf effect. An alternative view point is taken by the dynamic correlation model (DCM) which includes both the coupling of the internal nuclear motion as well as the electronic interaction and the creation and annihilation of virtual electron-positron pairs within the same framework. In this model, the hyperfine structure splitting for lithium-like $^{209}Bi^{80+}$ ions is reduced by about 1.3 % if compared with previous calculations. Table 1 displays the individual and total contributions to the hyperfine splitting from previous and our computations.

Table I: Comparison of different hfs calculations for Li-like bismuth and with experiment.

Contribution (meV)	Shabaev [5]	Indelicato [6]	this work
one-electron	958.50 (5)	958.49	958.51
DF correction	-.-	-43.02	-.-
charge distr.	-113.8 (3)	-108.42	-113.61
sum	844.7	807.05	844.9
mag. distr.	-13.9 (2)	-18.68	-14.1
total QED	-4.44	-4.06	-4.81
e-e interaction	-29.45 (4)	8.43	-34.4
positron	-.-	0.06	7.69
total theory	796.9 (2)	792.8	783.9 (3.0)
measurement (Super–EBIT) [7]		820 (26)	

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