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T. STÖHLKER, A.E. LIVINGSTON

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Gesellschaft für Schwerionenforschung mbH
Postfach 11 05 52 · D-64220 Darmstadt · Germany

The Structure of High-Z He-like Ions

Thomas Stöhlker *[1] and A. Eugene Livingston[2]

[1] *GSI-Darmstadt, D-64220 Darmstadt, Germany*

[2] *University of Notre Dame, Notre Dame, Indiana 46556, USA*

Abstract

The current progress of spectroscopic studies of heliumlike systems will be reviewed. Special emphasis will be given to both the groundstate as well as to the excited state investigations. For the heaviest ions, the potential of precision spectroscopy will be outlined and its relevance for atomic structure investigations will be discussed

1 Introduction

Heliumlike ions are the simplest multi-body systems. Investigations of the these ions along the isoelectronic sequence up to the heaviest species probe uniquely our understanding of correlation, relativistic, and quantum electrodynamical effects. Very recently the theoretical as well as the experimental investigations of these fundamental systems achieved

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*Invited Speaker, 'XXIV-Mazurian Lakes School of Physics', Piaski, Poland, 1995 a considerable improvement in precision. In theory a new generation of relativistic many-body calculations has established significantly improved benchmarks for the non-QED part in the electron-electron interaction [1, 2, 3]. For the groundstate the progress is particularly impressive, since even the two-electron QED effects can presently be calculated without any approximation [4]. Here, the achieved precision for the two-electron binding energies is now comparable with that for hydrogenic systems. The QED part of the predictions for the excited levels in He-like systems, however, is still incomplete at the level of $(Z\alpha)^4$. Experimentally, the results of precise n=2 state energy measurements are now available which are for the first time sensitive explicitly to the uncalculated QED terms [5]. For the groundstate the progress achieved experimentally manifests itself by a novel approach where the two-electron contribution to the binding energies can be experimentally isolated [6]. Here, the results are at the threshold of becoming sensitive to higher-order QED effects.

Despite this current progress in both theory and experiments there is still a lack of information in particular with respect to the excited L-shell levels in high-Z systems such as He-like uranium. Measurements of $\Delta n = 0$ transitions in high-Z two-electron ions are not only very sensitive to QED effects in these fundamental many-body systems. They are in particular crucial for testing theoretical predictions of near-degeneracies such as the n=2$({}^3P_0 - {}^1S_0)$ interval that has been discussed for atomic parity violation experiments [7, 8].

In section 2 the relevance of the new technique for the investigation of the pure two-electron contributions in high-Z He-like ions will be outlined and a comparison with results of very recent two-electron QED calculations will be given. In section 3 the current status of the precision measurements of the Δn=0 transitions in the L-shell of He-like systems will be reviewed in comparison with various theoretical predictions. In particular the relevance of such experiments for the heaviest ions will be discussed and the capability of the SIS/ESR facility for such studies will be emphasized. Finally, in section 4, a short summary will be given.

2 Groundstate Investigations

Until recently, the precision of the available experimental groundstate binding energies for high-Z ions ($Z > 54$) was not sufficient to probe sensitively theoretical predictions [9]. For He-like high-Z ions the individual $n=2 \rightarrow n=1$ groundstate transitions can be only incompletely resolved by present experimental techniques, which precludes a measurement at the level of precision available for hydrogenic ions. At the Super Electron-Beam-Ion-Trap (SEBIT), at the Lawrence Livermore National Laboratory, a novel experimental approach has been introduced which exploits Radiative Recombination (RR) transitions into the vacant 1s shell of bare and H-like ions [6]. This technique gives direct access to the two-electron part of the groundstate binding energy in heliumlike ions. In particular, all one-electron contributions to the binding energy such as the finite-nuclear size corrections and the one-electron self-energy cancel out completely in this type of experiment.

The SEBIT device can produce bare and hydrogenlike target ions of any element trapped in an electron beam of arbitrary energy up to 200 keV [10]. Normally, several charge states of a selected element are confined simultaneously in the trap by the high energy electron beam. For such collision conditions a fast electron may undergo a direct transition into a bound state of the stationary ion via the emission of a photon carrying away the energy difference between the initial and final electron state, i.e. $\hbar\omega = E_{kin} + E_B$. The difference in the centroid energies for such radiative recombination transitions into the vacant K-shell of bare and H-like high-Z ions is equal to the difference in the ionization potential between the hydrogenlike the heliumlike ions formed by the recombination process. It gives exactly the two-electron contribution to the groundstate energy of the heliumlike ions. The experiment was carried out for six different elements, i.e. germanium (Z=32), xenon (Z=54), dysprosium (Z=66), tungsten (Z=74), osmium (Z=76), and bismuth (Z=83). For a detailed description of the experimental setup and the data analysis used cf. Ref. [6].

	Z=32	Z=54	Z=66	Z=74	Z=76	Z=83
SEBIT (eV)	562±1.6	1027.2±3.5	1341.6±4.3	1568.9±15	1608 ±20	1876±14
RMBPT (eV)	562.0	1028.2	1336.6	1573.9	-	1881.5
2eQED (eV)	-0.4	1.4	2.3	-3.1	-	-4.3

Table 1: Experimental (SEBIT) [6] and theoretical (RMBPT) [4] two-electron contribution to the binding energy of some He-like ions (in eV). In addition, the predicted total two-electron QED contribution, which includes the screened Lamb shift and the Araki Sucher term, is given.

In the table the experimental results for the two-electron contribution to the groundstate binding energy in the He-like ions are compared with the predictions of relativistic many-body perturbation calculations (RMBPT) performed very recently by Persson et al. [4]. In this type of calculation the non-QED part of the two-electron interaction is considered within all orders whereas the two-electron QED contributions are calculated for the first time complete to second order. The latter includes the two-electron *screened Lamb Shift* (screened Vacuum Polarisation and the screened Self Energy) as well as the *non-radiative QED* part, the so called Araki-Sucher term. It is important to note that the overall uncertainties of these theoretical results are estimated to be of the order of only 0.2 eV [4]. This means that predictions for the total groundstate binding energies in He-like systems are now as precise as the corresponding ones for one-electron ions. From the table an excellent agreement between the experimental data from the SEBIT and the theoretical predictions can be seen. Although the experimental precision is only at the threshold to test sensitively the predicted two-electron QED contributions (compare in the table) the measurements already provide a meaningful test of the many-body part of the theory [4]. In particular, an improvement of only half an order of magnitude is required to test seriously the QED part of the calculation. This is illustrated in more detail in figure 1 where the various QED contributions are plotted on an absolute scale as a function of the nuclear charge Z. For comparison the experimental uncertainties are also given in the figure, defining the achieved experimental precision. It is important to note that the achieved precision is up to now only limited by counting statistics.

By using more intense electron beams at even higher energies we expect that the already achieved precision can be further improved by up to an order of magnitude. Moreover, the ESR storage ring at GSI is also well suited for such studies [11]. Due to the capability of the ESR to store simultaneously highly-charged heavy-ions with same atomic number Z but with different charge states, such a relative measurement can be alternatively conducted at the ESR cooler section. Here, the x-rays emitted via RR can be detected by a solid state detector viewing the electron-beam/ion-beam interaction zone close to an observation angle of 0°, a situation closely related to the one at the Super-EBIT device.

3 2p→2s transitions in high-Z He-like ions

In contrast to the groundstate, the predictions for the QED contributions to the excited levels of the L-shell in He-like ions are still incomplete at the level of $(Z\alpha)^4$, whereas the many-body non-QED contributions can now be calculated within all orders [1, 2, 3]. For the excited triplet states the most accurate QED calculations are still those of Drake [12]. The available experimental precision for the n=2 states in low-Z He-like ions provide