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THE STRUCTURE OF HIGH-Z He-LIKE IONS*

T. Stöhlker

GSI-Darmstadt, D-64220 Darmstadt, Germany
and

A.E. Livingston

University of Notre Dame, Notre Dame, Indiana 46556, USA

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The current progress of spectroscopic studies of helium like 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.

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1. Introduction

Helium like 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 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 [1–3]. 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

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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 $n = 2(^3\mathrm{P}_0 - ^1\mathrm{S}_0)$ 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 helium like 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 hydrogen like 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.* $\hbar\omega = E_{\text{kin}} + E_B$. 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 hydrogen like the helium like 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].

TABLE I

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.

	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

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 Polarization 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 Fig. 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.

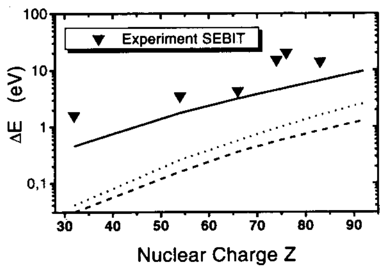

Fig. 1. The absolute size of two-electron QED contributions to the groundstate binding energy in He-like ions [4]; solid line: screened Lamb shift, dotted line: screened vacuum polarization, dashed line: Araki Sucher. The triangles in the figure represent the experimental uncertainties of the Super-EBIT experiment [6], *i.e.* the sensitivity of the experimental results.

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 [1–3. 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

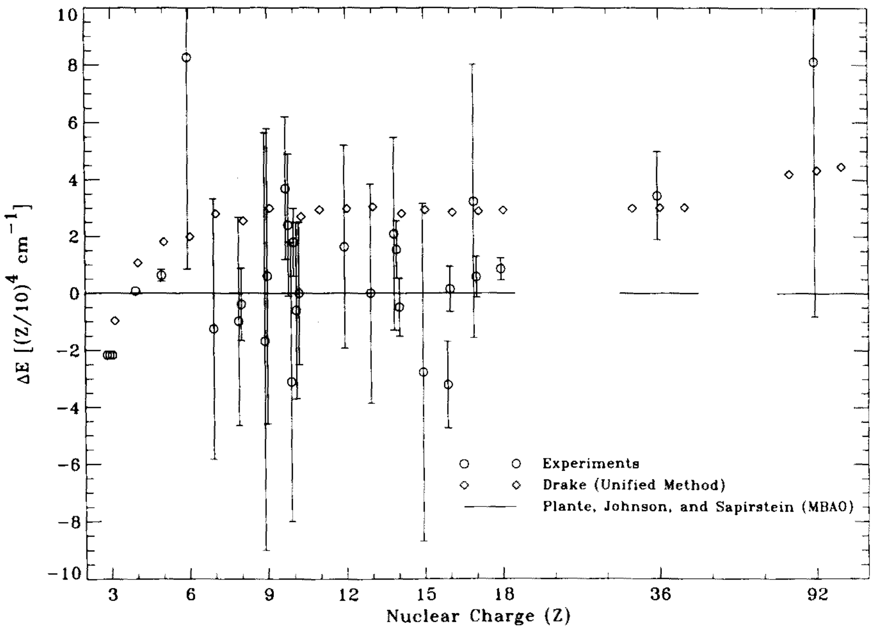

Fig. 2. Comparison of experiment and theory with respect to the MBAO calculations of Plante, Johnson, and Sapirstein [3]. The results of Drake [12] are shown in addition. The references to the various experimental results are found in [5].

now a benchmark test for QED calculations. For instance, by measuring the $\Delta n = 0 1s2s^3S_1 - 1s2p^3P_{0,2}$ fine structure transitions in Ar^{16+} a sensitivity to the two-electron QED corrections on the level of 5% has been achieved [5]. In contrast, practically, no experimental information is available for the $n = 2$ states in high-Z He-like ions ($Z > 54$)). For such systems only one experimental result has been reported in literature. For U^{90+} the measured lifetime of the $[1s_{1/2}, 2p_{1/2}]^3P_0$ level has been exploited to determine the $[1s_{1/2}, 2p_{1/2}]^3P_0 - [1s_{1/2}, 2s_{1/2}]^3S_1$ transition energy of 260.0 eV (experimental value) with a precision of 8 eV [13]. In Fig. 2 a summary of all available data for the $[1s_{1/2}, 2p_{1/2}]^3P_0 - [1s_{1/2}, 2s_{1/2}]^3S_1$ transitions in He-like ions are plotted as function of Z (references to these data can be found in Ref. [5]. Also shown are the theoretical predictions of Drake [12] in comparison with the many-body all order approach (MBAO) of Plante, Johnson, and Sapirstein [3]. The latter calculations include QED correction from Drake [12] to enable comparison of the accurate non-radiative calculations with experiment.

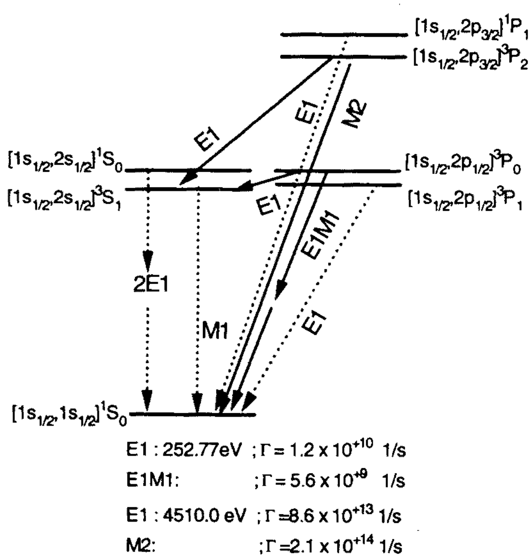

Fig. 3. Level scheme of the first excited states in He-like uranium. In addition, the various decay modes of the excited states of the L-shell in U^{90+} are depicted along with the transition energies [12] and rates [14] for the $E1(\Delta n = 0)$ transitions. The corresponding decay rates for the competing groundstate transitions are given as well.

As depicted by the level scheme in Fig. 3, the experimental situation for a precision measurement of the $\Delta n = 0$ transitions in high-Z He-like ions is quite favorable. Here, the various decay modes of the excited states in the L-shell of U^{90+} are given along with the transition energies [12] and rates [14] for the $E1(\Delta n = 0)$ transitions. In addition, the corresponding decay rates for the competing groundstate transitions are given (for the E1, M2 transitions see Ref. [15] and for the E1M1 transition Ref. [16]). Obviously, the $[1s_{1/2},2p_{1/2}]^3P_0$, $[1s_{1/2},2p_{3/2}]^3P_2$ states possess relatively long lifetimes and the probability of a decay of these levels via a $E1(\Delta n = 0)$ transition into $[1s_{1/2},2s_{1/2}]^3S_1$ is rather large compared to the direct transitions to the groundstate. Even more important, the resulting narrow linewidths allow accurate spectroscopy of these $E1(\Delta n = 0)$ transitions.

For such QED precision studies the $[1s_{1/2},2p_{1/2}]^3P_0 - [1s_{1/2},2s_{1/2}]^3S_1$ transition would be the most favorable candidate. Here, the QED contribution of −42.1 eV to the transition energy of 252.8 eV is a 17% effect whereas the Lamb shift screening of $0.68eV$ contributes with 0.3% [12]. This has to be compared with the total QED contribution of −40.4 eV to the energy of 4510.0 eV for the $[1s_{1/2},2p_{3/2}]^3P_2$ – $[1s_{1/2},2s_{1/2}]^3S_1$ transition which represents only a 0.9% effect [12]. However, experiments for both transitions are urgently needed in order to determine with precision the experimental level scheme of high-Z He-like ions where the theoretical predictions are still rather uncertain. This is illustrated in Fig. 4 for the particular case of the $[1s_{1/2},2p_{1/2}]^3P_0$, $[1s_{1/2},2s_{1/2}]^1S_0$ levels. Here, all available predictions for the $[1s_{1/2},2p_{1/2}]^3P_0$ – $[1s_{1/2},2s_{1/2}]^1S_0$ splitting are plotted for a Z regime around $Z = 92$ [3, 7, 12, 17]. As depicted in the figure, the discrepancies among the different theoretical approaches are comparable to the splitting itself. Here it is important to note that these differences are essentially caused by the different treatment of the many-body non-QED part for the electron-electron interaction.

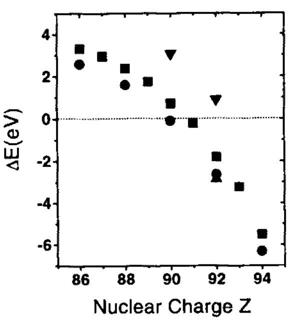

Fig. 4. All the available predictions for the $[1s_{1/2},2p_{1/2}]^3P_0$ – $[1s_{1/2},2s_{1/2}]^1S_0$ splitting plotted for a Z regime around $Z = 92$: solid squares [12], solid points [3] down-triangles [7], up-triangles [17].

The $[1s_{1/2},2p_{1/2}]^3P_0$ – $[1s_{1/2},2s_{1/2}]^1S_0$ interval has been discussed recently in the context of atomic parity violation experiments as both levels have the same total angular momentum J but different parity [7, 8, 18]. For such an experiment the precise knowledge of the energy splitting ($|\Delta E|$) between the levels is required. The absolute size of this splitting does not only decide on the most appropriate experimental approach. It is also important in order to identify the ion species with the strongest parity admixture $|\eta|$ (as $|\eta|$ scales with $1/|\Delta E|$). We conclude that a more precise experimental determination of the level scheme of high-Z He-like ions is required in order to determine the energy splitting between ${}^3P_0 -{}^1 S_0$ levels which would be an essential first step for a parity violation experiment using these ions.

Experiments to investigate these transitions in He-like uranium have been started at SEBIT, aiming at precise spectroscopy of $[1s_{1/2},2p_{3/2}]^3P_2$

– $[1s_{1/2},2s_{1/2}]^3S_1$ transition [19]. However, the production efficiency of the $[1s_{1/2},2p_{1/2}]^3P_2$ level in the Super-EBIT device turned out to be rather low which circumvents up to now a meaningful experimental result. Due to the difference in the excitation mechanisms, ion-atom collisions seem to provide more favorable conditions for such studies than high-energetic ion-electron collisions. In ion-atom collisions the excited levels of the L-shell in high-Z ions can be efficiently populated via electron capture. Therefore, the SIS/ESR heavy ion facility appears to be well suited for such experiments. Here, also different experimental approaches can be applied. Whereas for the 4.5 keV transitions crystal spectrometer measurements are the most promising ones [20], the Doppler tuned technique seems to be most appropriate for the 253 eV soft x-ray energy regime [20]. The feasibility of performing precise $2p_{1/2} \rightarrow 2s_{1/2}$ transition spectroscopy based on this technique has already been demonstrated by Schweppe *et al.*[21]. For the case of Li-like U^{89+}, the 280.6 eV (experimental value) transition energy was measured with an absolute precision of 0.1 eV, which still represents the most sensitive QED test performed up to now for high-Z highly charged ions. Also, the beam intensity requirements are less severe compared to a crystal spectrometer experiment. Therefore this technique seems to be well suited for possible studies of the $2p_{1/2} \rightarrow 2s_{1/2}$ transitions in different isotopes of one particular element. For this purpose isotopes produced in the Fragment Separator can be stored and investigated in the ESR. Keeping in mind that for $^{238}U^{90+}$ the nuclear size contribution to the $[1s_{1/2},2p_{1/2}]^3P_0$ – $[1s_{1/2},2s_{1/2}]^3S_1$ transition energy is a 13% effect [12] such measurements would provide detailed information about the influence of the nuclear properties on the atomic structure. This might be of particular interest with respect to possible parity violation experiments in order to find the isotope with the smallest $[1s_{1/2},2p_{1/2}]^3P_0$ – $[1s_{1/2}, 2s_{1/2}]^1S_0$ energy interval.

4. Summary

For the groundstate in high-Z He-like ions a novel experimental approach has been established which allows for the first time to isolate the two-electron contributions to the groundstate binding energy in high-Z He-like ions. In this type of experiment one-electron effects such as lowest order QED corrections and the nuclear-size effect cancel out completely and the results are only sensitive to a very limited number of higher-order Feynman diagrams. An anticipated improved accuracy of only half an order of magnitude will provide a very first test of the groundstate QED beyond the lowest order Lamb shift. For these kinds of experiments the Super-EBIT device as well as the ESR storage ring are well suited.

For the excited levels of the L-shell in He-like high-Z ions practically no experimental information is available up to now. Here, the E1(Δn=0) transitions are of particular interest as they are strongly affected by QED contributions and may deliver precise information about the possibilities of parity violation experiments in such systems. In the near future systematic experimental investigations of these transitions can be expected for which the intense high-Z ion beams of high quality delivered from the SIS/ESR facility provide ideal experimental conditions.

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