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**DIRECT MEASUREMENT OF TWO-ELECTRON
CONTRIBUTIONS TO THE GROUND STATE ENERGY
OF HELIUMLIKE HIGH-Z IONS**

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Direct Measurement of Two-Electron Contributions to the Ground State Energy of Heliumlike High-Z Ions

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Abstract

We report on a novel technique which exploits Radiative Recombination transitions for a direct experimental determination of the two-electron contributions to the ground state energy in heliumlike high-Z ions. Results are presented of a first experiment which was conducted at an electron beam ion trap for various elements ranging from $Z=32$ to 83 . The comparison with theoretical predictions demonstrates that the achieved precision already provides a sensitive test of second order many-body contributions and approaches the size of the two-electron (screened) Lamb shift. The potential of the new technique will be outlined and the capability of the ESR storage ring for future investigations will be emphasized.

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this type of experiment.

2 Experimental Method

The experiment was performed with the Super Electron Beam Ion Trap (Super EBIT) at the Lawrence Livermore National Laboratory. This device can produce bare and hydrogenlike target ions of any element trapped in an electron beam of arbitrary energy up to 200(keV) [12]. Normally, several charge states of a selected element are confined simultaneously in the trap by the high energy electron beam. At such collision conditions a fast moving electron may undergo a direct transition into a bound state of the stationary ion via the emission of a photon carrying away the the energy difference between the initial and final electron state, i.e. $\hbar\omega = E_{KIN} + E_B$ where E_{KIN} denotes the kinetic energy of the electron captured and E_B the binding energy in its final bound state. 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 and heliumlike ions formed by the recombination process (see also Fig. 1). It gives exactly the two-electron contribution to the ground state energy of the heliumlike ion. 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 ($Z=83$). The electron-beam/ion interaction area is viewed through a beryllium vacuum window by a Ge(i) x-ray detector. For calibration purposes standard γ - and x-ray sources were permanently installed in front of the detector. The x-ray spectra were saved at intervals of two hours in order to search for possible drifts in the electronic gain or in the beam energy.

Sample RR lines from typical data runs for capture into the vacant K-shell of germanium and bismuth ions are shown in Fig. 2. The large change in the relative intensity

Z	Experiment	Relativistic RMBPT	Relativistic All Order	MCDF	Unified
32	562.5 ± 1.6	561.9 (+0.6)	562.1 (+0.4)	562.1(+0.4)	562.1(+0.4)
54	1027.2 ± 3.5	1028.1(-0.9)	1028.4(-1.2)	1028.2(-1.0)	1028.8(-1.6)
66	1341.6 ± 4.3	1336.6(+5.0)	1337.2(+4.4)	1336.5(+5.1)	1338.2(+3.4)
74	1568 ± 15	1574.6(-7)	1574.8(-7)	1573.6(-6)	1576.6(-9)
76	1608 ± 20		1639.2(-31)	1637.8(-30)	1641.2(-33)
83	1876 ± 14	1882.7(-7)		1880.8(-5)	1886.3(-10)

Table 1: Two electron contribution to the ionization potential of He-like ions (in eV). The numbers quoted in the brackets give the difference between experiment and theory.

are compared in table 2 with the individual two-electron contributions as predicted recently by Lindgren et al.[15]. For these RMBPT calculations an extended nucleus with uniform nuclear charge is assumed and the "screened Lamb shift" part of the two electron contribution is only estimated. Very recently, the latter contribution has been explicitly calculated and the new results are found to be in very good agreement with the values quoted in the table 2 [6, 8]. In the context of RMBPT, our uncertainties are smaller than the second-order many body contributions (except at higher Z) so the experimental results are sensitive to this part of the theory. In the case of dysprosium (Z=66) the experimental precision approaches the size of the "screened Lamb shift". In general, our data are insensitive to the two-electron QED part. However, only a moderate increase in accuracy is needed in order to provide a significant sensitivity for these effects. For this an absolute precision of about $\pm 1\text{eV}$ would be required. The result for germanium demonstrates that such a precision can be achieved, which is not limited by systematic uncertainties but only by counting statistics.

uncertainty corresponds to the difference between the size effects for the homogeneously-charged-sphere model and a Fermi charge distribution. Persson et al. [8] have applied the same technique for the ground state of He-like uranium. Their calculations reveal that the size effect causes only an uncertainty of 16 meV for the two-electron contribution. In general, they found a very weak dependence of these contributions on the nuclear structure, e.g. a change of the root-mean-square nuclear radius for uranium of $R=5.86$ fm by 1% causes a variation of the two-electron contribution of less than 0.1eV [8].

One-Electron Contr.[1]:	-104 132.9	Two-Electron Contr.[15]:	1 882.7
Self Energy :	+236.5	2nd Order :	-11
Vacuum Polarization:	-51.6	2e Lamb shift :	-4.5
Nuclear Size :	+74.9	Araki Sucher :	+0.85
Total Ionization Potential of He-like Bi:-102 250.2			

Table 3: Total one- and two-electron contributions to the ionization potential of He-like bismuth (in eV). In addition some important correction terms are quoted.

4 Future Arrangement at the ESR Storage Ring

The experimental technique established at the Super-EBIT can also be applied at the ESR storage ring at GSI Darmstadt. A prerequisite for such studies is the simultaneous storage of two beams of highly charged heavy ions with same atomic number Z but different charge states Q . Such an operation mode of the storage ring has already been exploited in some atomic physics experiments [17] by using the charge state breeding technique. The experimental situation is depicted in Fig. 3. Bare ions are injected into the ring and

5 Summary

A novel experimental approach has been established at the Super-EBIT which has allowed us to obtain the first direct measurement of the two-electron contribution to the ground state binding energy of high-Z heliumlike ions. The experimental data are found to be in agreement with the available theoretical predictions. By using more intense electron beams we expect that the experimental uncertainty can be improved in future experiments by up to an order of magnitude. This would provide for the first time an experimental sensitivity for the ground state QED of H- and He-like ions which is beyond the lowest order Lamb shift. For future experiments the ESR storage ring is also well suited. Similar to the Super-EBIT experiment possible sources of systematic errors are essentially eliminated and the final results are expected to be entirely limited by counting statistics.

6 Acknowledgment

We would like to thank I. Lingren, H. Persson, Sten Salomonson and Per Sunnergren for interesting discussions and for providing us with their theoretical results prior to publication. We are grateful to A.E. Livingston for stimulating suggestions and helpful comments on the manuscript.

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Figure 2: The K-shell RR lines for germanium ($Z=32$) and bismuth ($Z=83$) as observed in typical runs.

Figure 3: Schematic presentation of a possible experimental arrangement at the ESR storage ring. Here, the breeding technique is illustrated for the case of initially bare uranium ions (see text).

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We report on a novel technique which exploits Radiative Recombination transitions for a direct experimental determination of the two-electron contributions to the ground state energy in heliumlike high-Z ions. Results are presented of a first experiment which was conducted at an electron beam ion trap for various elements ranging from $Z=32$ to 83 . The comparison with theoretical predictions demonstrates that the achieved precision already provides a sensitive test of second order many-body contributions and approaches the size of the two-electron (screened) Lamb shift. The potential of the new technique will be outlined and the capability of the ESR storage ring for future investigations will be emphasized.

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1 Introduction

One of the most promising experimental approaches for the investigation of effects of quantum electrodynamics (QED) in the strongest available Coulomb fields is a precise determination of the ground state transition energies in one- and two- electron high-Z ions, e.g. uranium. Here, the binding energies are strongly influenced by higher-order QED effects [1, 2]. In recent years the majority of experiments has focused on the investigation of one-electron high-Z ions [3, 4, 5]. For these systems the ESR storage ring provides unique experimental conditions and the available results are now at the threshold of becoming sensitive to the higher-order QED contributions.

The heliumlike ions are the simplest multielectron systems. In contrast to the hydrogenlike species, there is no exact solution for the structure of high-Z heliumlike ions. Very recently, substantial progress in the theory of two-electron systems has been achieved [6, 7, 8]. The theoretical precision for the ground state binding energies in heliumlike ions is now expected to be as precise as those for one-electron systems [9]. The two-electron contributions to the binding energy include, in addition to the dominant Coulomb term, effects from electron correlation, the Breit interaction, screening of the Lamb shift, and higher order radiative corrections. Up to now, the precision of the available experimental binding energies is not sufficient to probe these various theoretical contributions. For He-like high-Z ions the individual $n=2 \rightarrow n=1$ ground state transitions can be only incompletely resolved by present experimental techniques, which precludes a measurement at the level of precision available for hydrogenlike ions [10].

Here we report the results of a novel experimental approach which exploits Radiative Recombination (RR) transitions into the vacant $1s$ shell of bare and H-like ions [11]. It gives direct access to the two-electron part of the ground state binding energy in heliumlike ions. In particular, all one-electron contributions to the binding energy such as finite-nuclear size corrections and the one-electron self-energy cancel out completely in

this type of experiment.

2 Experimental Method

The experiment was performed with the Super Electron Beam Ion Trap (Super EBIT) at the Lawrence Livermore National Laboratory. This device can produce bare and hydrogenlike target ions of any element trapped in an electron beam of arbitrary energy up to 200(keV) [12]. Normally, several charge states of a selected element are confined simultaneously in the trap by the high energy electron beam. At such collision conditions a fast moving electron may undergo a direct transition into a bound state of the stationary ion via the emission of a photon carrying away the the energy difference between the initial and final electron state, i.e. $\hbar\omega = E_{KIN} + E_B$ where E_{KIN} denotes the kinetic energy of the electron captured and E_B the binding energy in its final bound state. 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 and heliumlike ions formed by the recombination process (see also Fig. 1). It gives exactly the two-electron contribution to the ground state energy of the heliumlike ion. 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 ($Z=83$). The electron-beam/ion interaction area is viewed through a beryllium vacuum window by a Ge(i) x-ray detector. For calibration purposes standard γ - and x-ray sources were permanently installed in front of the detector. The x-ray spectra were saved at intervals of two hours in order to search for possible drifts in the electronic gain or in the beam energy.

Sample RR lines from typical data runs for capture into the vacant K-shell of germanium and bismuth ions are shown in Fig. 2. The large change in the relative intensity

of the peak from the bare ions between germanium and bismuth is due to the rapidly decreasing 1s ionization cross sections with increasing atomic number Z . At present, this prevents us from extending these measurements to elements beyond $Z=83$. It is important to note that the measured difference in the RR centroid energies is insensitive to any drifts in the electron energy because any drift affects all RR lines equally. Also Doppler shift corrections are completely absent and all other possible sources of systematic errors are found to be negligible compared to the statistical uncertainty. For a detailed description of the experimental set up and the data analysis see Ref. [11].

3 Results and Discussion

In table 1 the results for the difference in the ionization potential between H- and He-like ions are given, i.e. the two-electron contribution to the K-shell binding energy in helium-like systems. In the table the experimental data are compared with various theoretical predictions which are based on the unified method [13], the multiconfiguration Dirac Fock treatment (MCDF) [9], the relativistic many body perturbation theory (RMBPT) [6], and the all-order relativistic MBPT theory [14]. In the case of the unified and the all-order MBPT method only the total ionization energies are available. For comparison with our data the one electron contribution was subtracted by using the hydrogenlike energies given by Johnson and Soff [1]. Within the experimental uncertainty, general agreement exists between the experimental data and the predictions of all four theories. However, at higher Z , our results favor somewhat the many body perturbation theories and the MCDF treatment over the unified theory. In fact, the MBPT calculations are more appropriate for high- Z systems, since the unified method uses a relativistic $1/Z$ expansion which is known to be incomplete at the level of $(Z\alpha)^4$ [13].

In order to elucidate in more detail the achieved experimental sensitivity, our results

Z	Experiment	Relativistic RMBPT	Relativistic All Order	MCDF	Unified
32	562.5 ± 1.6	561.9 (+0.6)	562.1 (+0.4)	562.1(+0.4)	562.1(+0.4)
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are compared in table 2 with the individual two-electron contributions as predicted recently by Lindgren et al.[15]. For these RMBPT calculations an extended nucleus with uniform nuclear charge is assumed and the "screened Lamb shift" part of the two electron contribution is only estimated. Very recently, the latter contribution has been explicitly calculated and the new results are found to be in very good agreement with the values quoted in the table 2 [6, 8]. In the context of RMBPT, our uncertainties are smaller than the second-order many body contributions (except at higher Z) so the experimental results are sensitive to this part of the theory. In the case of dysprosium (Z=66) the experimental precision approaches the size of the "screened Lamb shift". In general, our data are insensitive to the two-electron QED part. However, only a moderate increase in accuracy is needed in order to provide a significant sensitivity for these effects. For this an absolute precision of about $\pm 1\text{eV}$ would be required. The result for germanium demonstrates that such a precision can be achieved, which is not limited by systematic uncertainties but only by counting statistics.

Nucl. charge	1st order contrib.	2nd order contrib.	Araki- Sucher	Screened Lamb shift	Total	Experiment
32	567.6	-5.2	0.03	-0.5	561.9	562±1.6
54	1036.5	-6.9	0.16	-1.6	1028.1	1027.2±3.5
66	1347.4	-8.6	0.35	-2.5	1336.6	1341.6±4.3
74	1586.9	-9.4	0.55	-3.4	1574.6	1568.9±15
83	1897.5	-11.0	0.85	-4.5	1882.7	1876±14

Table 2: Comparison between the RMBPT calculations of Lindgren et al.[15] and the experimental results (in eV).

In table 3 the advantage of the present relative measurement is outlined with respect to the standard $K\alpha$ spectroscopy technique, where the absolute ground state binding energies are deduced. In the table the one- and two-electron contributions for the ground state binding energy in He-like bismuth are given along with some important correction terms. As seen from the table the second order two-electron contribution and in particular the two-electron QED contribution are considerably smaller than the one-electron QED terms and the nuclear size effect. Within their experimental precision, the available data for $K\alpha$ transitions probe essentially these one-electron contributions. In contrast, the energy differences measured in the present experiment isolate the true two-electron contribution and all the one-electron contributions cancel out completely. This is of particular relevance with respect to nuclear effects. For the heaviest H-like ions the uncertainty introduced by these effects dominates the total error in the theoretical ground state binding energy [1]. In the case of uranium it may prevent the probing of the QED corrections on an absolute level of precision of better than ± 1 eV. For hydrogen-like uranium, Franosch and Soff [16] have estimated that the error introduced by the nuclear size correction amounts to 0.36 eV. This

uncertainty corresponds to the difference between the size effects for the homogeneously-charged-sphere model and a Fermi charge distribution. Persson et al. [8] have applied the same technique for the ground state of He-like uranium. Their calculations reveal that the size effect causes only an uncertainty of 16 meV for the two-electron contribution. In general, they found a very weak dependence of these contributions on the nuclear structure, e.g. a change of the root-mean-square nuclear radius for uranium of $R=5.86$ fm by 1% causes a variation of the two-electron contribution of less than 0.1eV [8].

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Table 3: Total one- and two-electron contributions to the ionization potential of He-like bismuth (in eV). In addition some important correction terms are quoted.

4 Future Arrangement at the ESR Storage Ring

The experimental technique established at the Super-EBIT can also be applied at the ESR storage ring at GSI Darmstadt. A prerequisite for such studies is the simultaneous storage of two beams of highly charged heavy ions with same atomic number Z but different charge states Q . Such an operation mode of the storage ring has already been exploited in some atomic physics experiments [17] by using the charge state breeding technique. The experimental situation is depicted in Fig. 3. Bare ions are injected into the ring and

accumulated up to a certain number of stored ions. In the electron cooler section of the ring the initially bare ions recombine with cooler electrons via radiative recombination thus producing in addition a beam of H-like ions. In the cooler section the beams are merged together, a situation which is closely related to the one at the Super-EBIT. The x-rays emitted via RR of the cooler electrons into the ground state of the bare- and H-like ions can now be detected simultaneously by a solid state detector viewing the interaction region at an observation angle close to 0° . Such a detector set-up has already been used in various experiments conducted at the electron cooler [5]. In these experiments the x-ray emission has always been detected in coincidence with the downcharged ions in order to suppress possible background radiation. The charge state breeding technique requires the sacrifice of this coincidence option for x-ray events associated with capture into the bare ions (compare Fig. 3). Depending on the background this may constitute a serious experimental restriction. One can overcome this drawback by shifting the particle detector into a position where capture into the bare ions can be measured, which will of course also destroy the beam of H-like ions. On the other hand, one can still measure sequentially the RR peaks for bare and H-like ions within one storage cycle, i.e.: breeding of the H-like charge state and measuring RR into H-like ions and, subsequently, detection of RR into the bare ions.

Up to now, the precision in the Doppler shift corrections of $\Delta E/E \approx 5 \cdot 10^{-5}$ at the ESR [5] is determined by the uncertainty in the determination of the absolute beam velocity. It constitutes the most serious limitation for precision x-ray experiments involving ground state transitions in H-like ions. In the proposed relative measurement, where energy differences of 2.2 keV or less are to be determined, this uncertainty would introduce an error of less than ± 0.1 eV.

5 Summary

A novel experimental approach has been established at the Super-EBIT which has allowed us to obtain the first direct measurement of the two-electron contribution to the ground state binding energy of high- Z heliumlike ions. The experimental data are found to be in agreement with the available theoretical predictions. By using more intense electron beams we expect that the experimental uncertainty can be improved in future experiments by up to an order of magnitude. This would provide for the first time an experimental sensitivity for the ground state QED of H- and He-like ions which is beyond the lowest order Lamb shift. For future experiments the ESR storage ring is also well suited. Similar to the Super-EBIT experiment possible sources of systematic errors are essentially eliminated and the final results are expected to be entirely limited by counting statistics.

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Figure 1: Schematic presentation of the RR process of free electrons into the initially bare and H-like ions. The energy difference $\hbar\omega_H - \hbar\omega_{He}$ gives exactly the two-electron contribution to the ionization potential in He-like ions (see text).