Access to Two-Photon QED Contributions via $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ Transitions in Heavy Li-Like Ions [B, G]

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In the strong central fields of heavy ions, $Z\alpha \Rightarrow 1$, the detailed atomic structure is – beyond relativistic effects – sensitively determined by quantum electrodynamic effects (QED). A rigorous theoretical treatment of these effects is compulsory and may show modifications compared to the results at small fields, i.e. at small nuclear charges. Hence, precise Lamb-shift measurements for the innermost electrons which probe for the heaviest ions the strongest possible fields are a permanent and hot issue in atomic structure investigations. Presently, the ground state Lamb-shift deduced from Lyman transitions in H-like Uranium is experimentally known with a precision of 2.8% (468 ± 13 eV) [1]. Still this high precision has to be improved by another factor of 10 in order to really be able to test QED calculations. In contrast to ground state transitions in H- or He-like ions, the relative QED contributions for intra-L shell transitions is considerably larger. Hence those transitions in Li-like ions can reveal even higher order QED contributions; however, the fields probed are about a factor of 10 smaller than for the K shell.

In systematic investigations we concentrated on a precise determination of $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ transition energies in Li-like heavy ions up to Xe^{51+} [2-4]. For these transitions the relative QED contributions increase up to 10% for the one-electron and up to almost 1% for the two-electron QED terms. Beam foil spectroscopy utilizing the GSI 5m gracing incidence VUV spectrometer was applied [2]. The precision of the VUV spectrometer has been improved over the years and allows now a determination of the transition energies on a level of $5 \cdot 10^{-5}$ of relative accuracy, which is better than the accuracy of present day calculations [5]. Due to a limited maximum energy of 13 MeV/u at the UNILAC, the heavier elements could not be investigated.

A new theoretical approach has been recently forwarded by Yerokhin *et al.* [5], wherein the QED screening contributions have been completely evaluated. These contributions can be represented by two-photon exchange diagrams and scale as $\alpha^2(\alpha Z)^3$. The calculation starts from hydrogenic wave functions and applies a strict QED formalism so that no "QED corrections" have to be added as in the case of the many body calculations [6-8]. All electron correlation effects are described by the exchange of virtual photons between the electrons. While this method is very systematic, it requires the evaluation of an increasing amount of Feynman diagrams for higher order contributions. At present only single-photon exchange terms in the treatment of electron correlations have been completely calculated and higher order effects in Yerokhin *et al.* [5] are taken from many body calculations (mainly from Kim *et al.* [6]). The separate calculation of two-photon exchange diagrams describing electron correlations is in preparation ([5] and references therein).

In Fig. 1 the difference between our recent and earlier experimental values and results from [5] is shown versus the atomic number. The difference as well as the experimental and theoretical uncertainties are normalized to the QED contribution of the transition energy [6].

An excellent agreement between experiment and calculation within one experimental standard deviation is observed. The theoretical errors, (see dash lines in Fig. 1) which are mainly due to the uncertainties of the extraction method for second and higher order electron correlation terms, are considerably larger than the actual differences between experiment and theory. As they are quoted to be only order of magnitude estimates, the much better agreement with experiments may be fortuitous. The anticipated calculations for the second order correlation terms should help to clarify this situation. The high sensitivity of the currently available experimental data thus constitutes a challenge to present calculations.

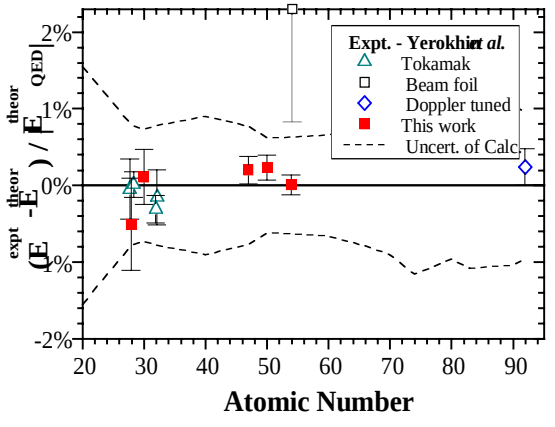

Figure 1: Normalized difference between experimentally determined and calculated $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ transition energies along the Li isoelectronic sequence. Data points are shown only where theoretical and experimental values exist for the same atomic number. (References of experiments in [4]; calculations are from [5]).

To show this sensitivity, the relative experimental uncertainty for all known experiments with Z > 20 is plotted in Fig. 2 along the Li-isoelectronic sequence in comparison with the relative size of the contributions to the total transition energy communicated by Yerokhin *et al*. [5]

The main contribution represents one-photon exchange between electrons. The relative contribution of two and more exchanged photons, which is extracted out of many body calculations [6], is almost constant at the 10% level along the isoelectronic series. The one electron QED effects (first order SE and VP terms) are small for small Z, but exceed the 10% range at high Z. The extended nuclear size correction term is insignificant at low Z and also increases above 10% for lithium-like uranium. The QED screening correction terms (two-electron SE and VP) are for the first time calculated completely and almost reach a relative size of 1%. The remaining nuclear recoil and the nuclear polarization terms are the smallest calculated contributions and remain below 300 ppm. Fig. 2 also shows two contributions to the theoretical error, where the main source of the present theoretical uncertainty stems from the two- and more-photon exchange terms extracted from the many body calculations. The influence of the uncertainty of the nuclear rms radius is also shown.

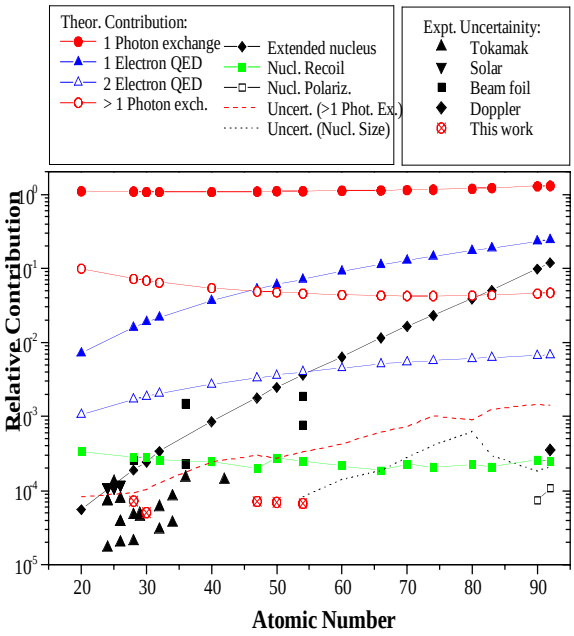

Figure 2: Comparison of relative contributions to the total $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ transition energy calculated by Yerokhin et al. [5] as a function of Z with the relative uncertainties of all available precision experiments. Different symbols denote different spectroscopic techniques. Relative uncertainty of the calculation is also shown.

Furthermore the relative uncertainties of all available experiments are depicted as different symbols for different spectroscopic techniques. While at lower Z precise Tokamak data are abundant, the most sensitive data at medium Z have been supplied by our collaboration. Clearly the relative uncertainties of the Ag, Sn and Xe experiments are smaller than the smallest calculated contributions to the transition energy.

At Z = 54 the relative accuracy of 70 ppm would allow for a QED test at the 0.1% level, if the theoretical uncertainty, especially in the higher order electron correlation terms, could be significantly reduced, which would be very important also for a test of second order two-loop QED terms. In this way, measurements and calculations of $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ transitions become one of the most stringent tests of strong field QED available to date.

Although sufficient experimental data now exist up to Z = 54, the only experiment above Z = 54 is still the Doppler tuned spectroscopy result of Schweppe *et al*. for lithium-like uranium [9]. An extension of the experimental database at high Z is absolutely necessary. This means, that spectroscopic methods with increased sensitivities at SIS have to be applied. Estimations of signal rates show that the Doppler tuned spectroscopy is an adequate method and will be pursued.

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