1*s* Lamb Shift in Hydrogenlike Uranium Measured on Cooled, Decelerated Ion Beams

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The Lyman-α transitions of hydrogenlike uranium associated with electron capture were measured in collisions of stored bare U^{92+} ions with gaseous targets at the storage ring ESR. By applying the deceleration technique, the experiment was performed at slow collision energies in order to reduce the uncertainties associated with Doppler corrections. From the measured centroid energies, a ground state Lamb shift of 468 eV $\pm$ 13 eV is deduced which gives the most precise test of quantum electrodynamics for a single electron system in the strong field regime. In particular, the technique applied paves the way towards the 1 eV precision regime.

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One of the frontiers of quantum electrodynamics (QED) is the study of electrons in intense electromagnetic fields. An important experiment is the measurement of the 1s Lamb shift in the most highly charged, one-electron ion available in the laboratory, U^{91+}. This is a highly relativistic system containing high momentum components, and the electric field strength begins to approach the critical value for the spontaneous emission of electron-positron pairs. All of this makes it ideal for testing the limits of our understanding of bound state QED. Although QED has had tremendous success in describing electrons in weak fields [1,2], recent calculations of the two-loop self-energy corrections [3–5] give surprisingly large values and indicate the convergence of the usual series expansion in powers of $Z\alpha$ ($\alpha = 1/137$) may be poor. Initially these results were in disagreement with experiments done in singly ionized helium, but the most recent measurement shows good agreement [5,6]. For hydrogen, the situation is clouded by a disagreement between two measurements of the charge radius of the proton. Laser experiments at intermediate Z (P^{14+} and S^{15+}) [6] confirm the new two-loop binding corrections at the 2 standard deviation level, but clearly a more definitive test is needed and, since the new corrections increase rapidly with nuclear charge, an experiment in hydrogenlike uranium is particularly important. Here, and in contrast to the low-Z regime, a perturbative treatment of the QED corrections in terms of $Z\alpha$ is not appropriate and QED calculations must be complete in all orders of $Z\alpha$. Whereas this has been accomplished recently for the one-loop corrections, i.e., the one-photon self-energy and vacuum polarization, the calculations of the two-loop contributions must be regarded as still incomplete for the high-Z regime. Note that the calculations published recently by different theory groups for the two-loop self-energy contributions differ markedly from each other at low and intermediate Z [7,8]. For uranium these corrections are expected to approach a size of 1 eV; thus the challenging experimental goal is to reach here a precision of 1 eV or better. Note that the theoretical uncertainty from the finite nuclear size correction for uranium (about 0.1 eV [9,10]) is insignificant at this level of precision.

Recent progress in production and cooling of intense beams of fully stripped uranium at the synchrotron storage ring facility SIS/ESR at GSI, Darmstadt, allows unprecedented precision in the spectroscopy of these ions. Experiments at the gas jet target [11] and at the electron cooler [12] of the storage ring ESR provide measurements of the energies of the Lyman-α (Ly-α) lines resulting from electron capture by bare ions. These measurements determine the 1s Lamb shift which is defined as the deviation of the experimental value for the ground state binding energy from that predicted by the Dirac theory for a point nucleus. The high circulating currents of cooled ions available in the storage ring provide the optimum conditions for precision spectroscopy. The main limitation in existing experiments is the uncertainty in the correction for the Doppler shift, given by

$$E_{\mathrm{lab}}(\theta) = \frac{E_{\mathrm{proj}}}{\gamma(1 - \beta\cos\theta)}, \qquad (1)$$

where E_{lab} and E_{proj} denote the photon energy in the laboratory and in the emission frame, θ is the observation angle in the laboratory, β is the projectile velocity in units of speed of light, and γ is the Lorentz factor. This correction is large because the ions are stripped at relatively high energy (e.g., 360 MeV/u, $\beta \approx 0.69$) in order to obtain the bare charge state. A significant reduction in the Doppler correction is possible if the ions are decelerated after stripping. In addition to reducing the Doppler effect at the lowest energy used, the measurements can be performed at several different energies. Here we report the first Lamb shift measurement utilizing the deceleration capability of the ESR storage ring. The experiment was done at the gas jet target and achieved an accuracy of 13 eV. This is a modest improvement over previous measurements of the 1s Lamb shift in uranium but the significance of this measurement is that it demonstrates a procedure for handling the Doppler problem via active deceleration which will ultimately allow experiments with a precision at the 1 eV level.

For the experiment, bare uranium ions were injected at the initial energy of 358 MeV/u into the ring [13]. In the electron cooler device, the ions were cooled by an electron beam of 200 mA providing U^{92+} ions with a longitudinal momentum spread of about 5×10^{-5}. Up to 10^8 bare uranium ions were stored and cooled, forming a beam with a diameter (full width half maximum) of 2 mm. After the initial accumulation and cooling of the stored ions, the ions were decelerated to the final beam energies of 68 and 49 MeV/u. For this purpose, the electron cooler was switched off and the coasting beam was rebunched and decelerated by synchronized ramping of the magnetic field of the ring magnets and of the frequency of the rf system. At the final stage of beam handling the electron cooler was switched on again at the energy which corresponds to the energy of the decelerated ions. The beam current was measured by means of a calibrated current transformer, while the revolution frequency and momentum spread of the stored ions were monitored by means of Schottky noise analysis. At the two lowest beam energies, the electron cooler current was kept at the relatively low values of 50 mA at 68 MeV/u and of 20 mA at 49 MeV/u. Finally, after finishing the deceleration procedure, a N_2 supersonic jet target with an effective area density of $\approx 10^{12}$ particles/cm^2 and with a diameter of 5 mm (FWHM) was switched on. By local closed orbit corrections around the target, the overlap between ion beam and jet target was optimized (for details see Ref. [14]).

Because of the geometrical constraints, the experimental technique applied at the gas target area of the ESR is based on a highly redundant x-ray detection setup. This allows for an intrinsic control of the beam/target/x-ray detector geometry by the simultaneous use of various x-ray detector devices at different observation angles. The experimental setup for the measurements of the Lyman-α radiation at the gas jet target is illustrated in Fig. 1. The figure shows the reaction area which is surrounded by four Ge(i) detectors mounted at observation angles of 48°, 90°, and 132° with respect to the center of the chamber (i.e., assumed position of the jet target). By using stainless steel guide tubes at the viewport positions, the detectors were mechanically fixed to the jet chamber and viewed the beam-target interaction volume through 125 μm thick Be x-ray windows (at 90° a 50 μm thick stainless steel window was used). Since the two detectors at 48° are installed symmetrically on opposite sides of the interaction chamber, the chosen geometry exhibits a forward left/right symmetry. A forward/backward symmetry was established by the detectors installed at 48° and 132°. At 48°, one of the detectors is a conventional solid state detector equipped with an x-ray collimator in order to confine the angular acceptance, thus reducing the Doppler broadening. The other detector consists of seven equidistant, parallel segments (strip width 3.5 mm) each furnished with a separate readout and with a very precise relative geometry (0.1 mm). They deliver seven independent x-ray spectra. At 90° a similar segmented detector is used, whereas at 132° a conventional Ge(i) detector was installed. For all detectors, the distance to the beam/target interaction zone amounts to $\approx$350 mm defining the geometrical solid angle to be $\Delta\Omega/4\pi \approx 10^{-4}$. Downstream from the reaction region, behind the first dipole magnet, a fast plastic scintillator was installed. It registered uranium ions having captured one electron so producing the characteristic radiation of H-like uranium [13]. All x-ray spectra of the various detectors were recorded in coincidence with the downcharged U^{91+} ions. A sample coincident x-ray spectrum of the Lyman ground state transitions in U^{91+} is displayed in Fig. 2 which was recorded by one strip of the segmented detector at 48° at a beam energy of 68 MeV/u. In the spectrum, the Ly-α_2 + **M1** and the Ly-α_1 transitions are the most prominent features with almost equal intensities (Ly-α_2: $2p_{1/2} \rightarrow 1s$; **M1**: $2s_{1/2} \rightarrow 1s$; Ly-α_1: $2p_{3/2} \rightarrow 1s$). Because of the intrinsic resolution of the detectors used (between 500 and 650 eV at 122 keV) the **M1** line blend of the Ly-α_2 decay cannot be resolved experimentally since the $2s_{1/2} - 2p_{1/2}$ line spacing amounts to 70 eV (classical Lamb shift). Note, because of the moderately low collision velocity, Doppler broadening is of minor relevance (200 eV at 122 keV for the strip detector at 48°).

Knowing precisely the relative angles between all the detectors the individual position of each x-ray detector can be determined via Eq. (1) by assuming that the origin of the radiation is the same for all detectors used. This procedure is required, as the absolute position of the gas jet/beam interaction zone is not precisely known. Therefore, the whole detector arrangement, i.e., the detector positions

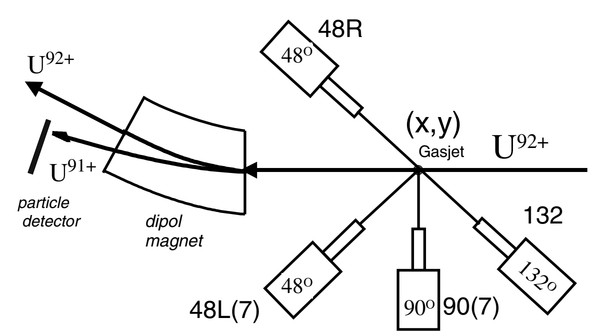

FIG. 1. Sketch of the experimental setup used in the experiment.

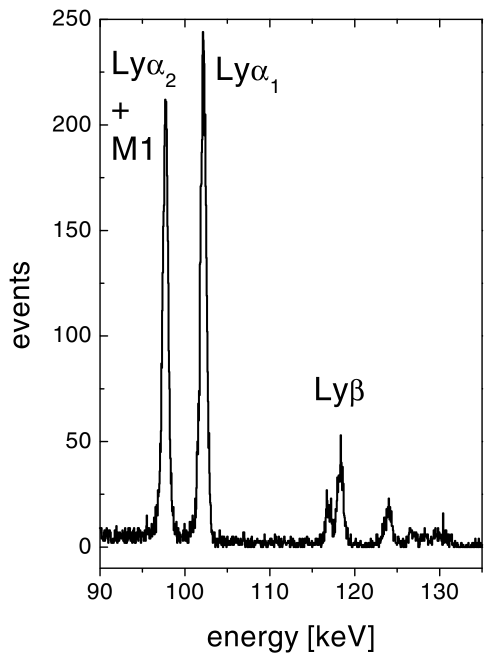

FIG. 2. Sample x-ray spectrum of the Lyman ground state transitions observed by one strip of the segmented Ge(i) at 48°. The spectrum was recorded in coincidence with electron capture at 68 MeV/u.

relative to each other, were measured within a Cartesian coordinate system by applying laser assisted trigonometry. This measurement was conducted just before and directly after the experiment. From a comparison of both measurements, a mean angular stability of the setup of $\pm 0.015°$ was deduced. The angular information of the individual detectors with respect to the ideal ion optical axis is given in Table I. As can be seen from the table, the measured detector angles show pronounced deviations from the originally assumed values. Besides the mechanical stability, the control over possible electronic drifts was most important. For this purpose, all detectors were calibrated frequently during the experiment by using ^{169}Yb and ^{182}Ta standard calibration lines. In total 30 calibration runs were conducted during a total beam time of 15 days. For the final data analysis, the collected coincident x-ray spectra were subdivided into six groups for the data collected at 68 MeV/u and five groups for data obtained at 49 MeV/u. All data bins were evaluated separately. Finally, the centroid energies of the ground state transition lines of each

TABLE I. Detector angles relative to the ion-optical axis as obtained by laser assisted measurement of the detector setup (for the detector assignment compare Fig. 1).

Detector	Assumed Angle [deg]	Measured Angle [deg]	Deviation [deg]
48L(7)	48	47.596 ± 0.014	−0.404 ± 0.014
48R	48	48.868 ± 0.018	0.868 ± 0.018
90(7)	90	89.995 ± 0.004	−0.005 ± 0.004
132	132	133.493 ± 0.005	1.493 ± 0.005

detector were fitted with Gaussian distributions (germanium detector response functions [15]). Since the line shapes might be influenced by the Doppler effect, the appropriateness of the applied fit procedure was checked by Monte Carlo simulations [16]. Typically, an accuracy for the determination of the centroid energies of 10 to 20 eV was achieved. The latter turned out to be limited by calibration uncertainties rather than by counting statistics.

The centroids of the Ly-α transitions in the projectile frame were determined separately for the two beam energies of 68 and 49 MeV/u. For this purpose an uncertainty minimizing procedure based on Eq. (1) was applied, by considering the known positions of each detector/detector segment. Within this procedure, the origin (x, y coordinates) of the ion-beam/target interaction point was spectroscopically determined by considering all Lyman-α centroid energies of the individual segments at the various observation angles. As a result the spectroscopically determined observation angles are all within 2σ of the angles defined by the chamber geometry. This is illustrated in Fig. 3, where the centroid energies of the Ly-α transitions observed by the 48° detectors are compared. In the figure (left side: 68 MeV/u; right side: 49 MeV/u), the open symbols refer to the segmented detector, whereas the solid symbols depict the result of the single Ge(i) (square: Ly-α_1; circle: Ly-α_2 + **M1**). As can be observed, both detectors show a quite symmetric alignment with respect to 48°, in contrast to values given in Table I. From the fitting procedure we deduce that the y coordinate of the beam/target interaction point shows, depending on the beam energy, a displacement of -1 to -2 mm.

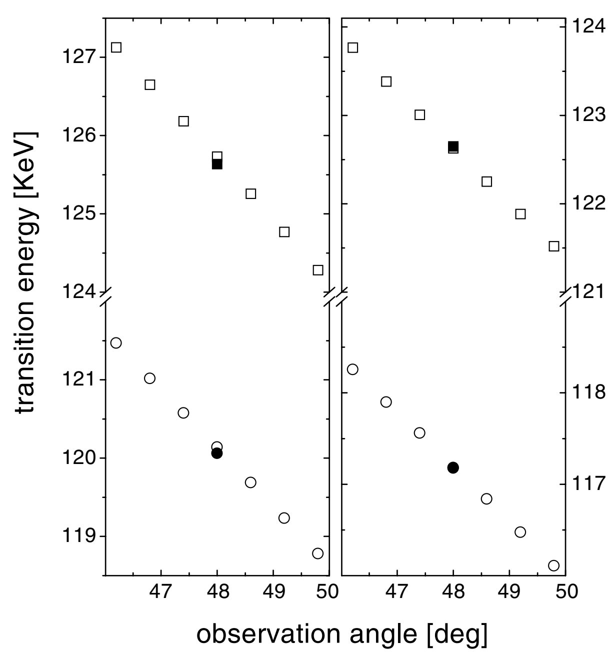

FIG. 3. Centroid energies of the Ly-α transitions observed by the 48° detectors are compared (left side: 68 MeV/u; right side: 49 MeV/u). The open symbols refer to the segmented detector, whereas the solid symbols depict the result of the single Ge(i) (square: Ly-α_1; circle: Ly-α_2 + **M1**).

TABLE II. Result for the Ly-α_1 transition energy in U^{91+} (compare text). All values are given in eV.

	ΔE (β)	ΔE (fit)	ΔE (geometry)	Ly-α_1
49 MeV/u	± 3	± 13.2	± 8	$102\,162 \pm 15.7$
68 MeV/u	± 2.3	± 14.3	± 9	$102\,179 \pm 17.0$
Result	± 2.6	± 9.7	± 8.5	$102\,170.7 \pm 13.2$

Indeed, this was confirmed months after the experiment by a new adjustment of the whole ESR storage ring where a displacement of the whole target chamber by 2 mm was observed. Also, the uncertainty in the knowledge of the absolute beam velocity has to be considered. As established recently, the latter is caused by a systematic uncertainty in the cooler voltage of 10 V. For the decelerated ions used in our experiment where low-cooler voltages of 32 277 V (at 68 MeV/u) and 26 822 V (at 49 MeV/u) were applied, this assumption is quite conservative [17]. However, the latter only slightly affects the overall accuracy of the experimental results (see Table II) and leads to $\Delta\beta/\beta = \pm 1.7 \times 10^{-4}$ at 49 MeV/u and $\Delta\beta/\beta = 1.2 \pm 10^{-4}$ at 68 MeV/u. Note that for the determination of the absolute beam velocity ($\beta = 0.3624$ at 68 MeV/u and $\beta = 0.3119$ at 49 MeV/u) the space charge correction introduced by the cooler current also had to be considered. The latter was deduced via the Schottky beam diagnostics by measuring the revolution frequency as a function of the cooler current.

In Table II, the final experimental result for the Ly-α_1 transition energy as deduced from the fitting procedure is given. Only the Lyman-α_1 centroid energy allows a direct comparison with the ground state *Lamb shift* prediction since here only the transition steaming from the decay of the $2p_{3/2}$ state contributes to the observed line. In addition, the various sources of uncertainty are given separately. Here, column ΔE (geometry) refers to the error introduced by the geometrical stability, whereas ΔE (β) gives the uncertainty caused by the imprecisely known cooler voltage. Finally, ΔE (fit) reflects the accuracy of the applied fit procedure. In order to combine from the individual results the final value for the Ly-α_1 transition energy, we assume that the contribution of ΔE (geometry) and ΔE (β) can be deduced from the mean value of the corresponding numbers quoted for the two beam energies since both are pure systematic sources of uncertainties. In contrast, we assumed for ΔE (fit) a statistical error propagation. To estimate the final accuracy, the various uncertainties are added quadratically giving ± 13 eV. Moreover, assuming that the $2p_{3/2}$ binding energy of $-29\,640.99$ eV [18] is known exactly from theory (it includes a Lamb shift correction of 8.8 eV) we deduce a total $1s$ ground state binding energy of $-131\,812$ eV. By comparison with the Dirac eigenvalue for the $1s$ state of $-132\,279.96$ eV [9] the experimental value of 468 ± 13 eV follows for the ground state *Lamb shift* in H-like uranium. This result agrees well with the most recent theoretical prediction of 465.8 [9] and with a former experiment conducted at the electron cooler device which gave a result of 470 eV with an absolute precision of ± 16 eV [12].

In conclusion, a $1s$ Lamb shift experiment has been conducted at the ESR by using cooled and decelerated bare uranium ions. The result obtained gives the most precise test of QED for a single electron system in the strong field region and is now at the threshold of a meaningful test of higher-order QED contributions. By using decelerated beams, further progress towards an absolute accuracy of 1 eV may be anticipated. The deceleration mode not only reduces the uncertainties in the Doppler corrections but, in particular, it provides a very efficient production of characteristic projectile radiation. The current experiment was mainly limited by systematic errors introduced by the x-ray detector setup used along with the limited energy resolution. In order to obtain a significantly improved precision, future experiments will also use a highly redundant setup at the jet target and will focus in addition on decelerated ions combined with the application of high-resolution devices such as crystal spectrometers or bolometers which presently are under construction.

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