Ground-State Lamb Shift for Hydrogenlike Uranium Measured at the ESR Storage Ring

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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 x-ray–particle coincidence techniques the ground-state transition energies in the rest frame could be determined with a precision of about 600 ppm. The experimental result is in excellent agreement with the theoretical prediction for the ground-state *Lamb shift* in hydrogenlike uranium and is already sensitive to the 2*s* *Lamb shift*.

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Hydrogenlike ions are the simplest atomic systems. Transitions in these one-electron ions give precise information on the atomic structure and the fundamental principles involved in theory. Not only relativistic effects but also quantum electrodynamic effects (QED) have to be included for an exact description of the atomic structure. The difference in binding energy between the correct relativistic *Dirac-Coulomb* energy and the real one is the so-called *Lamb shift*. It is largest for *s* states, where the binding energies with respect to the $p_{1/2}$ states will be lowered, and can be represented by the following function [1]: $L_{ns} = \frac{\alpha}{\pi}\frac{(Z\alpha)^4}{n^3}F(Z\alpha)m_0c^2$, where α is the fine structure constant, Z the atomic number of the ion, and m_0c^2 the electron rest mass. The function $F(Z\alpha)$ comprises all the necessary correction terms and can be approximated by a $(Z\alpha)^n$ power expansion. The leading term is the self-energy correction (SE). For the heaviest ions also the vacuum polarization (VP) and, in particular, the nuclear size correction (NS) have to be considered [1]. For hydrogen the first order terms in the *Lamb shift* (mainly SE) were determined experimentally to an extraordinary precision of 10^{-5} [2], whereas the higher order $Z\alpha$ terms (also mainly SE) can be probed only by heavy one-electron ions. Measurements for the ground-state *Lamb shift* via an energy determination of the $L \rightarrow K$ shell transitions were performed even for very heavy ions like Xe^{53+} [3], Dy^{65+} [4], Bi^{82+} [5], and U^{91+} [6] where higher order QED corrections are largest. In contrast to very heavy more-electron systems—for instance, Li-like U^{89+} [7], where the 2*s* *Lamb shift* is probed in the mean time to a precision of 10^{-3}—the accuracy in *ground-state Lamb-shift* measurements for very heavy one-electron ions was up to now not sufficient to test sensitively the subtleties of the theory.

In this Letter we report on spectroscopic investigations of the *Lyman* α transitions performed for the first time for hydrogenic uranium at a storage ring where the projectile x-ray emission associated only with the hydrogenic charge state could be studied in collisions of stored and cooled bare uranium ions with thin gaseous targets. The unprecedented quality of the background-free x-ray spectra taken in coincidence with electron capture at the internal gas jet of the storage ring ESR [8], together with the precise energy definition of stored and cooled ion beams, demonstrates the feasibility of the ESR for high precision x-ray experiments even for the heaviest ions. For the experiment a segmented solid state Ge(i) x-ray detector with a dedicated design was used. The granularity of this detector allowed to correct for the large Doppler shift, a technique already introduced by an earlier pilot experiment at the fragment separator at the heavy-ion synchrotron SIS [5]. Although we did not yet utilize high resolution dispersive spectrometers, the accuracy of the measurement for the ground-state *Lamb shift* of U^{91+} could already be improved by a factor of 2 compared to an earlier crystal spectrometer experiment performed at the BEVALAC [6]. Our measurement is now already sensitive to the 2*s* *Lamb shift*, which was not the case for all the previous *ground-state Lamb-shift* measurements done for very heavy ion species, and provides a crucial step towards true high precision experiments for the heaviest one-electron systems.

For the experiment, bare ions of ^{238}U were injected into the ESR and stored at an energy of 294.68 MeV/u. Up to 10^7 U^{92+} projectiles were accumulated and cooled in the ring. The ESR electron cooler guarantees a well defined constant energy of the stored beam and reduces its relative momentum spread to about 5×10^{-5}; it also provides a small beam size with a diameter of 5 mm. The velocity of the circulating beam was measured precisely via Schottky diagnostics as $\beta = 0.6503(2)$. After stacking the internal gas jet of the ESR was switched on; N_2 or Ar were used as gaseous targets with thicknesses of 4×10^{11} cm^{-2} and 5×10^{11} cm^{-2}, respectively. The beam–gas-jet interaction radius was determined to 2.5 mm (FWHM). Projectiles having captured one electron at the target area were registered downstream behind the next dipole magnet in a position-sensitive multiwire particle detector [9]. For the detection of projectile x rays the target area of the gas jet was viewed by two Ge(i) x-ray detectors

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mounted at observation angles θ of 48° and 132° with respect to the ion optical axis.

In Fig. 1 the redshifted x-ray spectrum of U^{91+}, seen by the backward detector in coincidence with electron capture, is shown (295 MeV/u $U^{92+} \rightarrow$ Ar). One remarkable aspect of the spectrum is the low background. We did not subtract any random coincidences, which were found to be indeed completely negligible. Because of the high collision energy and the light gaseous target used this spectrum is dominated by radiative electron capture (REC) into the ground state of the projectile (see the K-REC intensity in the spectrum) and into excited projectile states ($L, M, \ldots$REC); for cross sections see Ref. [10]. Via cascades, the latter ones lead to the well resolved *Lyman* transitions. Taking into account that for uranium the $2s_{1/2} \rightarrow 1s_{1/2}$ $M1$ decay is already prompt with a transition rate of about $2 \times 10^{+14}$ s^{-1} [11] and that REC feeds in fast collisions, dominantly projectile states with low n, j, l quantum numbers [12], the observed dominance of the combined *Lyman* α_2 $+M1$ intensity over the *Lyman* α_1 line can be explained. In contrast to the backward direction, where a conventional standard Ge(i) detector with a large active area of 500 mm^2 and a thickness of 15 mm was used, the strong Doppler broadening at forward angles required the use of a specially designed high-granular x-ray detector. The 12 mm thick detector mounted at an observation angle of 48° is subdivided into seven independent, parallel segments (equidistant vertical stripes) with a total active area of 625 mm^2. The segmentation allows an event-by-event Doppler correction of the registered x rays. The width of each stripe and the distance between the stripes is known precisely to be 3.57$\pm$0.01 mm [13], which corresponds to a Doppler width of 1.3 keV, whereas the energy difference between the unresolved (*Lyman* α_2+$M1$) line and the *Lyman* α_1 line amounts to 6 keV at an observation angle of 48°. In Fig. 2(a) the coincident *Lyman* α transitions produced in $U^{92+} \rightarrow$ Ar collisions registered with the most forward and the middle segment of the forward detector are shown. The x-ray spectra for each detector and detector segment were recorded event by event in coincidence with the particle detector. For this purpose standard NIM and CAMAC modules were used. All x-ray detectors (segments) and their electronics were energy calibrated using ^{57}Co, ^{133}Ba, ^{182}Ta, and ^{241}Am sources. The energy resolution (FWHM) at about 120 keV was measured to be $\sim$ 600 for the backward detector and between $\sim$ 600 and $\sim$ 700 eV for the various segments of the forward detector. The exact geometry of the whole detector arrangement was measured by laser assisted trigonometry. For instance, this measurement allowed us to determine the observation angle for the forward and the backward detector with respect to the ideal ion-optical axis with a precision of about 0.01°. The ground-state transition lines from each segment (detector) were fitted by Gaussian distributions convoluted with rectangular functions in order to take into consideration the Doppler broadening. By means of an error minimizing fitting procedure, by including all centroid energies of the individual seg-

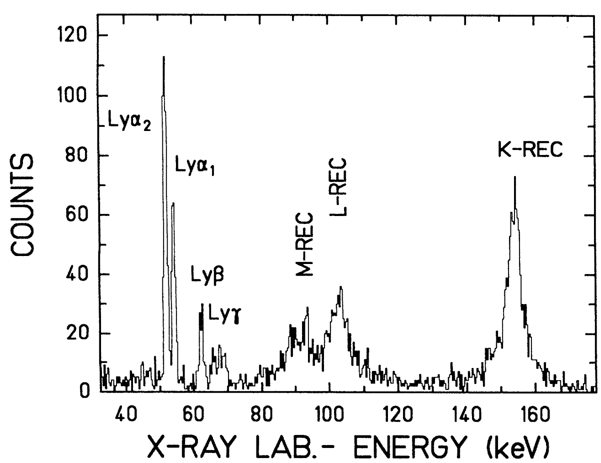

FIG. 1. X-ray spectrum (laboratory system) associated with electron capture for $U^{92+} \rightarrow$ Ar collisions taken by the backward detector ($\theta = 132°$).

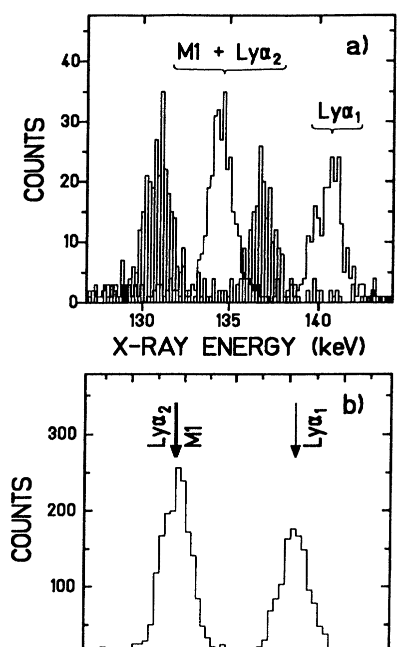

FIG. 2. (a) X-ray spectra (laboratory system) associated with electron capture for 295 MeV/u $U^{92+} \rightarrow$ Ar collisions taken by the most forward and middle (hatched area) segment of the multistripe detector ($\theta = 48°$). (b) Doppler-corrected sum spectrum (c.m. system) of the multistripe detector for 295 MeV/u $U^{92+} \rightarrow$ Ar collisions.

ments at the various observation angles, and by considering the known relative positions of each detector, the absolute observation angles θ with respect to the beam axis could be extracted with an accuracy of better than $\pm 0.04°$. This corresponds to an absolute uncertainty of the measured transition energies E transformed to the projectile system (c.m. system) of $\Delta E/E = 5.5 \times 10^{-4}$. The error summarizes the uncertainty in the beam velocity ($\Delta E/E = 3.1 \times 10^{-4}$) as well as the main contribution to the overall error, the statistical uncertainty ($\Delta E/E = 4.5 \times 10^{-4}$). For the central segment of the forward detector, for instance, the mean on-line observation angle was determined to 48.30(4)°. With the aid of the precisely determined observation angles, the spectra of the segmented x-ray detector were individually Doppler corrected and summed up. In Fig. 2(b) the resulting sum spectrum for the *Lyman* α energy region recorded by the forward detector and transformed to the emitter frame is shown for $U^{92+} \to$ Ar. The markers at the top of the spectrum reflect the theoretically expected transition energies [1] contributing to the observed ground-state transition lines.

Table I compares the experimentally determined centroid energies with theoretical predictions for the *Lyman* α transitions in hydrogenic uranium [1]. The total errors of 63 eV for the *Lyman* α_1 transitions and of 61 eV for the *Lyman* α_2 +*M1* transitions include the specified individual errors as well as the systematic errors of the measurement of 30 eV. The latter comprises the uncertainty introduced by detector calibration, spectral line analysis, and electronic shifts.

More recently, Soff [14] recalculated the binding energies for hydrogenic uranium based on new values of the NS correction to the electron self-energy for ^{238}U [15]. The new result for the $1s$ *Lamb shift* is 5 eV larger than the value quoted in Ref. [1]. For clarity, however, we compare our results with the values given in Ref. [1]. For hydrogenic uranium the $2s_{1/2}$-$2p_{1/2}$ level splitting due to the $2s$ *Lamb shift* is calculated to be 75 eV [1], whereas the $1s_{1/2}$ *Lamb shift* contributes by 458 eV to the total ground-state binding energy [1]. As we cannot resolve the x rays emitted by the transitions from the $2s_{1/2}$ and the $2p_{1/2}$ levels to the ground state, the $2s_{1/2}$ *Lamb shift* cannot be measured directly by our experiment. However, assuming a statistical population of the $2p_{1/2}, 2p_{3/2}$ levels, we can extract from the *Lyman* α_1/(*Lyman* α_2+M1) intensity ratio (0.61 for Ar and 0.4 for N_2 targets) that the $M1$ decay contributes to the observed intensity of the (*Lyman* α_2 + $M1$) line by 70% and by 80% for Ar and N_2, respectively. Based on these numbers, we compare in Table I the measured energy for the *Lyman* α_2+M1 transition line with theory. A very good agreement between our experiment and theory can be stated.

The *Lyman* α_1 centroid energy allows a direct comparison with the ground-state *Lamb-shift* prediction. Here, only one state, i.e., the $2p_{3/2}$ one, contributes to the observed line. Considering only the *Lyman* α_1 transitions and assuming that the $2p_{3/2}$ binding energy is known exactly by theory we deduce a ground-state *Lamb shift* in hydrogenic uranium of 429±63 eV which differs from the theoretical value [1] by only -29 ± 63 eV (-34 ± 63 eV according to Ref. [14]). An excellent agreement between theory and experiment can be stated. Moreover, we would like to point out that the deviation between experiment and theory for the *Lyman* α_1 energy is, within 4 eV, the same as that for the *Lyman* α_2+M1 transition. This agreement supports our assessment on the dominance of the $M1$ transition in the *Lyman* α_2+M1 line demonstrating that the experiment is already sensitive to the $2s_{1/2}$-$2p_{1/2}$ level splitting of 75 eV [1].

In conclusion, we measured the *Lyman* α transitions of U^{91+} for stored bare uranium ions in collisions with gaseous targets at the ESR storage ring. The experimental values for the transition energies compare very well with theoretical prediction [1,14]. In particular, the predicted ground-state *Lamb shift* of 458 eV [1] (463 eV according to [14]) is confirmed by the experimental value of 429 ± 63 eV on a 15% level of accuracy which is a factor of 2 more precise than the experimental value reported in the literature [6]. The precision of our present experimental results is still restricted by two factors, the counting statistics and the high beam velocity. The latter factor is the most important one for a future precision spectroscopy of very heavy one-electron systems. The high velocities are needed in order to produce bare ions with sufficient intensities. Future experiments, which are already in preparation at the ESR, are expected to overcome this difficulty by decelerating the highly charged stored projectiles. This deceleration mode will allow us to study x-ray transitions in H-like uranium for energies below 50 MeV/u.

TABLE I. Ground-state transition energies measured for hydrogenlike uranium ions in 295 MeV/u $U^{92+} \to N_2$, Ar collisions in comparison with theoretical predictions [1]. All values are given in eV. The theoretical transition energy for the *Lyman* α_2+M1 line was calculated on the basis of the predictions given in Ref. [1] ($M1$: 976 92 eV; *Lyman* α_2 : 976 17) assuming that the $M1$ transitions contribute by 75% to the observed line.

Experiment		Theory [1]	Exp.−Theory
Ly α_1	102 209 ± 63	102 180	+29 ± 63
Ly $\alpha_2 + M1$	97 706 ± 61	97 673	+33 ± 61

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