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ARTICLE TYPE

High-resolution Wavelength-dispersive Spectroscopy of K-shell Transitions in Hydrogen-like Gold

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Abstract

We present a measurement of K-shell transitions in H-like gold (Au⁷⁸⁺) using specially developed transmission type crystal spectrometers combined with Ge(i) micro-strip detectors. The experiment has been carried out at the Experimental Storage Ring (ESR) at GSI in Darmstadt. This is a first high-resolution wavelength-dispersive measurement of a K-shell transition in a high-Z H-like ion, thus representing an important milestone in this field. Ideas on possible future improvements are discussed as well.

KEYWORDS:

Storage rings, X-ray spectroscopy, Highly-charged ions, QED

1 | INTRODUCTION

Precise measurements of atomic structure and transitions have provided throughout many years a driving force for developing the fundamental theories in physics. In particular, the discovery of the Lamb shift in hydrogen has played a major role in the development of the quantum electrodynamics (QED). Nowadays, the measurements on hydrogen and light atoms achieve an extraordinary precision of up to 10^{-15} which is often matched by the QED calculations emphasizing its impressive predicting power [13, 28, 18, 24, 12, 23].

The situation is quite different in the realm of heavy hydrogen-like systems, i.e. heavy ions with only one electron. Here, both experimental and theoretical precision are still orders of magnitude lower than those available for light atoms. On the theoretical side, the main challenge is related to the fact that since the parameter $\alpha Z \sim 1$ one can not use perturbative methods (as for light atoms) and one has to perform all-order numerical calculations in the relativistic framework. On the experiment side, the challenges are: firstly, the production of the heavy H-like ions in sufficient quantities and then storing them with proper quality for precise measurements. Furthermore, the binding energies of such heavy H-like ions are of the order of several 10s of keV up to 100 keV. Therefore, instead of the laser spectroscopy techniques used for the light systems, here x-ray spectroscopy has been used throughout the years [11, 10, 9, 25, 4, 6], except for hyperfine transitions [20, 21, 27].

Heavy-ion accelerators and storage rings as well as new generation ion traps have been the facilities where H-, He- and Li-like ions with highest nuclear charges up to $Z = 92$ have been made available for precision experiments [8, 22, 2, 7, 26, 16, 1].

For the case of the ground state Lamb shift in high- Z H-like systems, where the strongest Coulomb fields can be obtained and thus QED effects are strongest, the spectroscopy was until recently conducted with solid state Ge(i) detectors ensuring a high detection efficiency. The first-order QED contributions (the self energy and vacuum polarization) have been tested at the level of 1%. However, the current experimental precision is still not enough to test the higher-order QED effects, whose evaluations have been recently completed after many years of extensive theoretical work (see [29] and references therein). In order to gain the sensitivity to the higher-order QED effects, the experimental uncertainty of the 1s Lamb shift has to be reduced below 1 eV. One of the main limitations here is due to the energy resolution of the conventional semiconductor detectors used in these experiments. To circumvent this problem, dedicated crystal spectrometers together with micro-strip Ge(i) detectors have been developed, optimized for hard x-ray spectroscopy at storage rings. In this work, we present the first high-statistics measurement using this instrument at the Experimental Storage Ring (ESR) at GSI in Darmstadt. The measurement was carried out for H-like gold (Au^{78+}).

2 | THE EXPERIMENT

The detailed description of the experiment can be found in [5, 14]. Briefly, up to 10^8 of fully ionized gold ions (Au^{79+}) with an initial kinetic energy of about 300 MeV/u were injected into the ESR. Here, they were stored, cooled, and decelerated to final velocity of $\beta = v_{ion}/c = 0.47136(10)$. The cooled ion beam was then colliding with a supersonic gasjet of Krypton atoms having an areal density of $\sim 10^{12}$ atoms/cm². Some of the collisions lead to the capture of the target electron into an excited state of the projectile ion, thus forming the H-like gold. These excited states then decay to the ground-state leading (among others) to the emission of the Lyman- α radiation which is measured by our spectrometers.

For the measurement of the Ly- α_1 transition wavelength, two twin spectrometers operated in the focussing compensated Laue (FOCAL) geometry have been used [5]. The schematics of the FOCAL setup at the gasjet target of the ESR is shown in Fig. 1.

One of the main challenges for precision spectroscopy of relativistic ions is the Doppler effect. In the current experiment, the two identical crystal spectrometer arms are aligned perpendicular with respect to the ion beam at

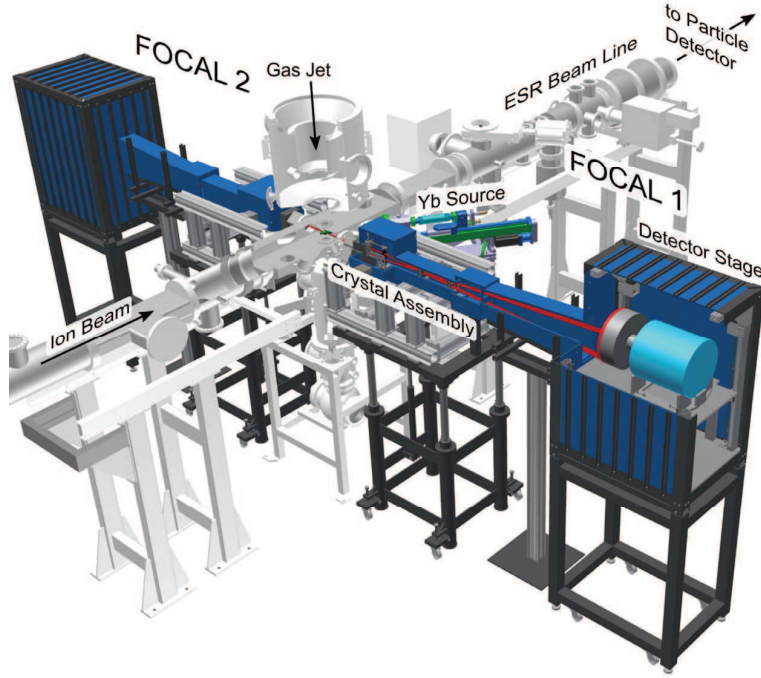


FIGURE 1 Schematic view of the FOCAL setup at the gasjet target of the ESR. The two spectrometer arms with lead shielding are shown in blue as well as the reflected x-ray path in red impinging on the Ge(i) micro-strip detector.

both sides of the interaction chamber on one common line of sight. In this special geometry rest-frame transition wavelength λ_0 can be derived via

$$\lambda_1 + \lambda_2 = 2\gamma\lambda_0, \quad (1)$$

where $\lambda_{1,2}$ are the wavelengths measured by the two crystal spectrometer arms and γ is Lorentz factor. In this way, the uncertainty due to the observation angle stemming from the possible misalignment of the beam is cancelled.

The wavelengths $\lambda_{1,2}$ are measured with respect to a well known 63120.44(4) eV γ transition from an isotope enriched ^{169}Yb source. The ion-beam velocity has been chosen such ($\beta = 0.47136(10)$), that the Doppler-shifted lab-frame energy of the $\text{Ly-}\alpha_1$ transition approximately coincides with this calibration energy thus avoiding systematic uncertainties due to large extrapolations.

3 | RESULTS

Our experimental value for the Lyman- α_1 transition energy in H-like gold is $E_{\text{Ly}\alpha_1}^{\text{exp}} = 71531.5(15.0)$ eV [14]. The uncertainty of 15 eV includes all the statistical and systematic uncertainties (added quadratically). The experimental value for the 1s Lamb shift is obtained by subtracting our value for the Lyman- α_1 transition energy from the theoretical value for the $2p_{3/2}$ binding energy, which is sufficiently well known [29]. In Table 1, our experimental result for the ground-state Lamb shift in H-like gold is presented together with the experimental value obtained with a Ge(i) detector in an early experiment at the ESR electron cooler [3] and the result obtained with a microcalorimeter detector in the same beam time [19]. In the last entry of the table, the theoretical value of Yerokhin and Shabaev [29] is given. Our present value of the Lamb shift is higher than the theoretical value and the other experimental results by about 2.5 standard deviations of the estimated experimental uncertainty.

TABLE 1 The $1s$ Lamb shift of Au^{78+} in eV.

Our result	244.1(15.0)
Beyer <i>et al.</i> 1995 [3]	202.3(7.9)
Kraft-Bermuth <i>et al.</i> 2017 [19]	211(42)
Theory, Yerokhin and Shabaev 2015 [29]	205.2(2)

TABLE 2 Different contributions to the total uncertainty of the Lyman- α_1 transition energy.

Source	Value (eV)
Statistics	2.2
Temporal Drift	2.8
Gas-Target Position	13.0
Ion-Beam Velocity	4.3
Detector-Crystal Position	5.1
Total	15.0

4 | EXPERIMENTAL UNCERTAINTIES AND POSSIBLE FUTURE IMPROVEMENTS

In table 2, various sources of uncertainties for our measured value of the transition energy are presented. The achieved statistical uncertainty of 2.2 eV is already quite impressive, especially for a crystal spectrometer operated in the region of hard x rays of H-like high-Z ions. However, it is still at least factor of 2 higher than what is needed to test the higher-order QED effects. Furthermore, the systematic uncertainties due to the target and detector crystal positions as well as those due to beam velocity and the temporal drift of the whole setup are unacceptably high.

In the following, we briefly present few ideas on how to reduce these uncertainties.

Statistics: here, a further increase of the stored beam intensity in the ESR could be possible. In addition, four detectors, instead of the two used in the present measurement and with bigger areas covering fully all the reflexes of the FOCAL spectrometer would lead to significant increase in the statistics.

Temporal drift: here, by using a rigid support structure (with steel and granite) mounted several months before the measurement along with temperature controls, we could expect a significant improvement.

Beam velocity: the ion-beam velocity can already be determined with a much higher accuracy using a high-voltage divider from the Physikalisch-Technische Bundesanstalt (PTB) in the electron-cooler terminal, which will establish an absolutely calibrated velocity standard [17]. Here, we expect a relative uncertainty in the measurement of the cooler voltage well below 10^{-4} and thus the resulting contribution to the error budget of less than 1 eV.

Target and crystal positions: these represent currently the biggest contribution to the systematic uncertainty and probably most challenging to reduce to the needed level. In the current experiment, those positions have been measured separately with a telescope and special alignment devices [15, 14]. Here, one of the ideas is to use a modified assembly making it possible to measure the gas target position relative to the detector crystal in situ, which would eliminate the need of using the telescope and thus would reduce the uncertainty to close to 1 eV. Another possibility would be to use the two spectrometers tilted by 90 degrees with respect to each other, thus resulting in the perpendicular dispersion planes of the two spectrometer arms. This arrangement together with using four detectors instead of two has a potential of reducing this systematic uncertainty to the level of 0.1 eV. However, here more studies and simulations are needed which are currently ongoing. Here, we would like to add that this topic has also been intensively discussed recently by international experts at the so-called EMMI Rapid Reaction Task Force which took place in September 2018 (<https://indico.gsi.de/event/7662/overview>). The results of these discussions and of the ongoing work will be the subject of the forthcoming publication.

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