



HAL
open science

High-resolution wavelength-dispersive spectroscopy of K-shell transitions in hydrogen-like gold

T. Gassner, A. Gumberidze, M. Trassinelli, R. Hess, U. Spillmann, D. Banaś,
K.-h. Blumenhagen, F. Bosch, C. Brandau, W. Chen, et al.

► **To cite this version:**

T. Gassner, A. Gumberidze, M. Trassinelli, R. Hess, U. Spillmann, et al.. High-resolution wavelength-dispersive spectroscopy of K-shell transitions in hydrogen-like gold. X-Ray Spectrometry, 2019, 10.1002/xrs.3098 . hal-02362557

HAL Id: hal-02362557

<https://hal.science/hal-02362557>

Submitted on 13 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ARTICLE TYPE

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

T. Gassner^{1,2} | A. Gumberidze^{*2} | M. Trassinelli³ | R. Heß² | U. Spillmann^{1,2} | D. Banaś⁴ | K.-H. Blumenhagen¹ | F. Bosch^{‡2} | C. Brandau^{2,5} | W. Chen² | Chr. Dimopoulou² | E. Förster^{1,6} | R.E. Grisenti^{2,7} | S. Hagmann^{2,7} | P.-M. Hillenbrand² | P. Indelicato⁸ | P. Jagodzinski⁹ | T. Kämpfer¹ | M. Lestinsky² | D. Liesen^{2,10} | Yu. A. Litvinov² | R. Loetzsch^{1,6} | B. Manil¹¹ | R. Martin¹ | F. Nolden² | N. Petridis^{2,7} | M. P. Sanjari² | K.S. Schulze^{1,6} | M. Schwemlein¹ | A. Simionovici¹² | M. Steck² | Th. Stöhlker^{1,2,6} | C. I. Szabo^{8,13} | S. Trotsenko^{1,2} | I. Uschmann^{1,6} | G. Weber¹ | O. Wehrhan¹ | N. Winckler² | D.F.A. Winters² | N. Winters² | E. Ziegler¹⁴ | H.F. Beyer²

¹Helmholtz-Institut Jena, Jena, Germany

²GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

³INSP, CNRS and SU, Paris, France

⁴Institute of Physics, Jan Kochanowski University, Kielce, Poland

⁵Physikalisches Institut, Justus-Liebig-Universität, Gießen, Germany

⁶IOQ, FSU, Jena, Germany

⁷IKF, Goethe-Universität, Frankfurt am Main, Germany

⁸LKB, CNRS-UMR 8552, Collège de France, ENS-PSL Research University, SU, UPMC, Paris, France

⁹Department of Mathematics and Physics, Kielce University of Technology, Kielce, Poland

¹⁰Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität, Heidelberg, Germany

¹¹LPL, UMR 7538 CNRS - Université Paris 13, Villetaneuse, France

¹²ISTerre, UGA, CNRS, CS 40700, Grenoble, France

¹³Theiss Research, La Jolla, CA 92037, United States

¹⁴ESRF, Grenoble, France

Correspondence

Email: a.gumberidze@gsi.de

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

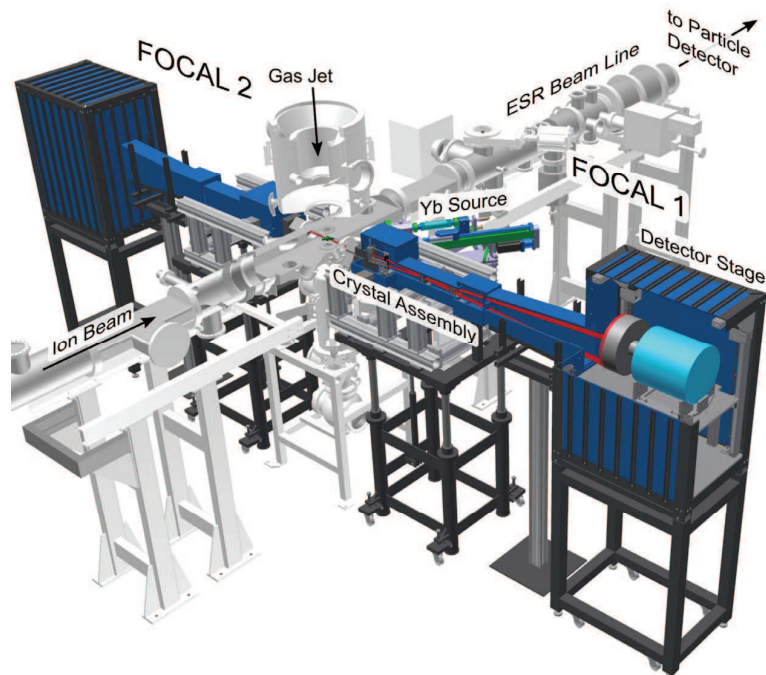


FIGURE 1 Schematic view of the FOCAL setup at the gasjet target of the ESR. The two spectrometer arms with lead shielding are shown in blue as well as the reflected x-ray path in red impinging on the Ge(i) micro-strip detector.

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 $\text{Ly}\text{-}\alpha_1$ 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.

ACKNOWLEDGEMENTS

Laboratoire Kastler Brossel (LKB) is “Unité Mixte de Recherche de Sorbonne University-UPMC, de ENS-PSL Research University, du Collège de France et du CNRS n° 8552”. Institut des NanoSciences de Paris (INSP) is “Unité Mixte de Recherche de Sorbonne University-UPMC et du CNRS n° 7588”. This work has been partially supported by: the European Community FP7 - Capacities, contract ENSAR n° 262010, the Allianz Program of the Helmholtz Association contract n° EMMI HA-216 “Extremes of Density and Temperature: Cosmic Matter in the Laboratory, the Helmholtz-CAS Joint Research Group HCJRG-108 and by the German Ministry of Education and Research (BMBF) under contract 05P15RGFAA.

References

- [1] Beiersdorfer, P., H. Chen, D. B. Thorn, et al., 2005: Measurement of the two-loop lamb shift in lithiumlike u^{89+} . *Phys. Rev. Lett.*, **95**, no. 23, 233003–4.
- [2] Beiersdorfer, P., A. L. Osterheld, J. H. Scofield, et al., 1998: Measurement of qed and hyperfine splitting in the $2s_{1/2} - 2p_{3/2}$ x-ray transition in li-like $^{209}bi^{80+}$. *Phys. Rev. Lett.*, **80**, 3022.
- [3] Beyer, H., G. Menzel, D. Liesen, et al., 1995: Measurement of the ground-state lambshift of hydrogenlike uranium at the electron cooler of the esr. *Z. Phys. D*, **35**, no. 3, 169–175.
- [4] Beyer, H. F., R. D. Deslattes, F. Folkmann, et al., 1985: Determination of the 1s lamb shift in one-electron argon recoil ions. *J. Phys. B*, **18**, no. 2, 207–215.
- [5] Beyer, H. F., T. Gassner, M. Trassinelli, et al., 2015: Crystal optics for precision x-ray spectroscopy on highly charged ions – conception and proof. *J. Phys. B*, **48**, 144010.
- [6] Beyer, H. F., P. Indelicato, K. D. Finlayson, et al., 1991: Measurement of the 1s lamb shift in hydrogenlike nickel. *Phys. Rev. A*, **43**, no. 1, 223.
- [7] Bosselmann, P., U. Staude, D. Horn, et al., 1999: Measurements of $2s^2S_{1/2} - 2p^2P_{1/2,3/2}$ transition energies in lithiumlike heavy ions. ii. experimental results for ag^{44+} and discussion along the isoelectronic series. *Phys. Rev. A*, **59**, no. 3, 1874–1883.
- [8] Briand, J. P., P. Chevallier, P. Indelicato, et al., 1990: Observation and measurement of $n = 2 \rightarrow n = 1$ transitions of hydrogenlike and heliumlike uranium. *Phys. Rev. Lett.*, **65**, 2761–2764.
- [9] Briand, J. P., P. Indelicato, M. Tavernier, et al., 1984: Observation of hydrogenlike and heliumlike krypton spectra. *Z. Physik A*, **318**, no. 1, 1–5.
- [10] Briand, J. P., J. P. Mossé, P. Indelicato, et al., 1983: Spectroscopy of hydrogenlike and heliumlike argon. *Phys. Rev. A*, **28**, no. 3, 1413–1417.
- [11] Briand, J. P., M. Tavernier, P. Indelicato, et al., 1983: High-precision spectroscopic studies of lyman α lines of hydrogenlike iron: A measurement of the 1s lamb shift. *Phys. Rev. Lett.*, **50**, no. 11, 832.
- [12] Cancio Pastor, P., L. Consolino, G. Giusfredi, et al., 2012: Frequency metrology of helium around 1083 nm and determination of the nuclear charge radius. *Phys. Rev. Lett.*, **108**, no. 14, 143001.
- [13] Fee, M. S., S. Chu, A. P. Mills, et al., 1993: Measurement of the positronium $1^3s_1 - 2^3s_1$ interval by continuous-wave two-photon excitation. *Phys. Rev. A*, **48**, no. 1, 192–219.
- [14] Gassner, T., A. Gumberidze, M. Trassinelli, et al., 2018: Wavelength-dispersive spectroscopy in the hard x-ray regime of a heavy highly-charged ion: the 1s lamb shift in hydrogen-like gold. *New Journal of Physics*, **20**, 073033.
- [15] Gassner, T. and H. F. Beyer, 2015: Spatial characterization of the internal gas target at the esr for the focal experiment. *Phys. Scripta*, **2015**, no. T166, 014052.

- [16] Gumberidze, A., T. Stöhlker, D. Banaś, et al., 2005: Quantum electrodynamics in strong electric fields: The ground-state lamb shift in hydrogenlike uranium. *Phys. Rev. Lett.*, **94**, 223001.
- [17] Hällström, J., A. Bergman, S. Dedeoğlu, et al., 2014: Performance of a wideband 200-kv hvdc reference divider module. *IEEE Trans. Instrum. Meas.*, **63**, no. 9, 2264–2270.
- [18] Karshenboim, S. G., 2005: Precision physics of simple atoms: Qed tests, nuclear structure and fundamental constants. *Phys. Rep.*, **422**, no. 1-2, 1–63.
- [19] Kraft-Bermuth, S., V. Andrianov, A. Bleile, et al., 2017: Precise determination of the 1s lamb shift in hydrogenlike lead and gold ions using microcalorimeters. *J. Phys. B*, **50**, 055603.
- [20] López-Urrutia, J. R. C., P. Beiersdorfer, D. W. Savin, et al., 1996: Direct observation of the spontaneous emission of the hyperfine transition $f=4$ to $f=3$ in ground state hydrogenlike $^{165}\text{ho}^{66+}$ in an electron beam ion trap. *Phys. Rev. Lett.*, **77**, 826.
- [21] López-Urrutia, J. R. C., P. Beiersdorfer, K. Widmann, et al., 1998: Nuclear magnetization distribution radii determined by hyperfine transitions in the 1s level of h-like ions $^{185}\text{ho}^{74+}$ and $^{187}\text{ho}^{74+}$. *Phys. Rev. A*, **57**, 879.
- [22] Lupton, J. H., D. D. Dietrich, C. J. Hailey, et al., 1994: Measurements of the ground-state lamb shift and electron-correlation effects in hydrogenlike and heliumlike uranium. *Phys. Rev. A*, **50**, 2150–2154.
- [23] Notermans, R. P. M. J. W. and W. Vassen, 2014: High-precision spectroscopy of the forbidden $2\ ^3S_1 \rightarrow 2\ ^1P_1$ transition in quantum degenerate metastable helium. *Phys. Rev. Lett.*, **112**, no. 25, 253002.
- [24] Parthey, C. G., A. Matveev, J. Alnis, et al., 2011: Improved measurement of the hydrogen $1s\ ^\sim 2s$ transition frequency. *Phys. Rev. Lett.*, **107**, no. 20, 203001.
- [25] Richard, P., M. Stockli, R. Deslattes, et al., 1984: Measurement of the 1s lamb shift in hydrogenlike chlorine. *Phys. Rev. A*, **29**, no. 5, 2939–2942.
- [26] Stöhlker, T., P. H. Mokler, F. Bosch, et al., 2000: 1s lamb shift in hydrogenlike uranium measured on cooled, decelerated ion beams. *Phys. Rev. Lett.*, **85**, 3109–3112.
- [27] Ullmann, J., Z. Andelkovic, C. Brandau, et al., 2017: High precision hyperfine measurements in bismuth challenge bound-state strong-field qed. *Nat. Commun.*, **8**, 15484.
- [28] van Wijngaarden, A., F. Holuj, and G. W. F. Drake, 2000: Lamb shift in he^+ : resolution of a discrepancy between theory and experiment. *Phys. Rev. A*, **63**, no. 1, 012505.
- [29] Yerokhin, V. A. and V. M. Shabaev, 2015: Lamb shift of $n = 1$ and $n = 2$ states of hydrogen-like atoms, $1 \leq z \leq 110$. *J. Phys. Chem. Ref. Data*, **44**, no. 3, 033103.

