EXPERIMENTAL DETERMINATION OF TANTALUM L-SHELL FLUORESCENCE YIELDS AND COSTER-KRONIG TRANSITION PROBABILITIES

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ABSTRACT
Using radiometrically calibrated instrumentation of Physikalisch-Technische Bundesanstalt, the L-shell fluorescence yields and Coster-Kronig factors of tantalum (including the uncertainty budget) were experimentally determined based on transmission and X-ray fluorescence experiments. The determined fluorescence yields ($\omega_{L3} = 0.247(12)$, $\omega_{L2} = 0.278(15)$, $\omega_{L1} = 0.157(12)$) were independently validated through XRR-GIXRF experiments. Both, the Coster-Kronig factors ($f_{23} = 0.123(84)$, $f_{13} = 0.328(152)$, $f_{12} = 0.14(11)$) as well as the fluorescence yields are in good agreement with the most established databases in the field of X-ray fluorescence.

Keywords tantalum · fluorescence yield · Coster-Kronig · fundamental parameter · Photon-in/photon-out experiment · XRF · GIXRF · XRR

1 Introduction
The knowledge of atomic fundamental parameters (FP) such as the fluorescence yield, the photoionization cross section and the Coster-Kronig transition probabilities is of great importance for any quantitative analysis involving X-ray fluorescence (XRF). The majority of the available experimental and theoretical FP values for different elements were obtained more than forty years ago. For some chemical elements and some FPs, the tabulated data is based solely on interpolations as no experimental or theoretical data exists. Unfortunately, the uncertainties of most tabulated FP data often are not available or only estimated. As this is certainly an improvable situation, the International initiative on X-ray fundamental parameters [1] and others are working on revisiting and updating FP databases with new experiments and calculations employing state-of-the-art techniques.

In this work, the tantalum L-shell fundamental parameters, namely the fluorescence yields and the Coster-Kronig factors, are being experimentally redetermined. Tantalum is a key element in microelectronics [2, 3], solar industry [4], medicine and more. On the other hand, the availability of experimentally determined Ta-L shell FPs is rather scarce. The majority of the available experimental data is older than 30 years and the uncertainties as estimated for the most common tabulations [5, 6] are only estimated. In this work, we apply the reference-free XRF equipment of PTB [7] and dedicated transmission and fluorescence measurements [8] using to revisit these parameters for tantalum.

2 Experimental
2.1 Photon-in/photon-out experiment
The experiments were performed at the wavelength-shifter beamline BAMline [9] at the BESSY II electron storage ring. This beamline provides hard monochromatic X-ray synchrotron radiation in the photon energy range from 5 keV up to 60 keV. Usually, the double crystal monochromator (DCM, with Si(111) crystals, $\Delta E/E = 0.2%$ between 8 and 50...
keV) is used for applications comparable to the one in this study. The experiments were carried out using an in-house developed vacuum chamber[10] equipped with calibrated photodiodes and an energy-dispersive silicon drift detector (SDD) with experimentally determined response functions and radiometrically calibrated detection efficiency[11]. The sample was placed into the center of the chamber by means of an x-y scanning stage and the incident angle $\theta_{in}$ between the surface of the sample and the incoming beam was set to 45°. As a sample, we have obtained a nominally 250 nm thick Ta deposition on a Si₃N₄-membrane. The membrane has a thickness of nominally 1000 nm. Furthermore, a blank Si₃N₄-membrane deposition was used to subtract the membrane contribution.

For both samples, transmission experiments were performed in the vicinity of the Ta-L absorption edges between 7 keV and 13 keV. In addition, the X-ray fluorescence emission from the coated sample was measured for photon energies ranging from about 10 keV to 13 keV. From these experiments, the Ta L-shell fluorescence yields and the Coster-Kronig factors can be determined as follows.

The procedure to determine L-shell fluorescence yields, as well as Coster-Kronig factors using physically calibrated instrumentation for reference-free X-ray spectrometry of PTB is already quite well established[8][12][13][14]. Here, Sherman’s equation[15] provides the basis for the calculation of fluorescence intensities of thin foils. It is a product of the incident monochromatic photon flux, a fluorescence production factor for a given shell $\sigma_L$, an instrumentation factor containing the solid angle of detection and the detection efficiency and the self-attenuation correction factor. This factor considers the attenuation of the photons on their way through the sample: For the incoming photons $\Phi_0(E_0)$ the attenuation on their way to the point of interaction is considered, for the fluorescence photons $\Phi_i(E_0)$ the attenuation on their way from the point of interaction to the detector is considered. Employing tunable photon sources or as recently shown also employing energy dispersive detectors[16], this factor can be easily determined by transmission measurements for the relevant photon energies.

The fluorescence production factor $\sigma_{L,i}$ is defined as follows:

$$\sigma_{L3}(E_0) = \omega_{L3}(\tau_{L3}(E_0) + f_{23}\tau_{L2}(E_0) + [f_{13} + f_{12}f_{23}]\tau_{L1}(E_0))$$

$$\sigma_{L2}(E_0) = \omega_{L2}(\tau_{L2}(E_0) + f_{12}\tau_{L1}(E_0))$$

$$\sigma_{L1}(E_0) = \omega_{L1}\tau_{L1}(E_0)$$

It is depending on the photon energy $E_0$ and is calculated employing the respective subshell fluorescence yield $\omega_{L,i}$, the subshell photoionization cross sections $\tau_{L,i}(E_0)$ as well as the Coster-Kronig factors $f_{ji}$. The latter are irrelevant for photon energies below the edge energy of the respective subshell as the photoelectric cross section is zero for energies below the corresponding subshell threshold energy. Thus, for photon energies between $E_{L2}$ and $E_{L3}$, $\sigma_{L3}(E_0)$ is simply the product of fluorescence yield and photoionization cross section so that the fluorescence yield $\omega_{L3}$ can be derived. By further employing this selective excitation to the other edges, also the $L_2$ and $L_1$ subshell fluorescence yields as well as the Coster-Kronig factors can be determined.

In other words, if $E_{L3} \leq E_0 \leq E_{L2}$, the fluorescence production factor for $L_3$ reduces to

$$\sigma_{L3}(E_0)\rho d = \omega_{L3}\tau_{L3}(E_0)\rho d = \frac{\Phi_i(E_0) M_{i,E_0}}{\Phi_0(E_0) \frac{\Omega}{4\pi}}$$

with

$$M_{i,E_0} = \frac{\mu_S(E_0)\rho d}{\sin \theta_{in}} + \frac{\mu_S(E_0)\rho d}{\sin \theta_{out}} \left(1 - \exp\left[-\left(\frac{\mu_S(E_0)\rho d}{\sin \theta_{in}} + \frac{\mu_S(E_0)\rho d}{\sin \theta_{out}}\right)\right]\right)$$

where $\theta_{in}$ and $\theta_{out}$ are incident and exit angles respectively. Due to the use of PTB’s physically calibrated instrumentation for reference-free X-ray spectrometry, all of the relevant measures can be accessed. The fluorescence photon flux $\Phi_i(E_0)$ is derived from the recorded fluorescence spectra by means of a spectral deconvolution procedure. Here, the detector response functions for all relevant fluorescence lines as well as relevant background contributions, e.g. bremsstrahlung, originating from photo-electrons are included. In addition, we determine and apply fixed line sets for each of the three L-shells in order to stabilize the deconvolution[8]. An exemplary spectrum including the deconvolution is shown in fig. 1. The incident photon flux $\Phi_0(E_0)$ and the solid angle of detection $\frac{\Omega}{4\pi}$ are known due to the use of calibrated instrumentation[17]. The sample specific attenuation correction factor $M_{i,E_0}$ for the incident ($E_0$) – as well as the fluorescence radiation ($E_i$) is calculated according to Eq. 5 using the experimentally determined sample specific attenuation coefficients $\mu_S(E_0)\rho d$ and $\mu_S(E_i)\rho d$.

Employing the experimental $\mu_S(E_0)\rho d$ and $\mu_S(E_i)\rho d$ values, one can calculate the total sample specific photoionization cross sections $\tau_S(E_0)\rho d$ and $\tau_S(E_i)\rho d$ by removing the scattering contributions. For this purpose, we derive the relative scattering contribution at each photon energy from a database (e.g. X-raylib) and use this data to determine $\tau_S(E_0)\rho d$. The thereby obtained photoionization cross sections are shown in figure 2 as blue dots. For the determination
of the subshell fluorescence yields as well as the Coster-Kronig factors, one needs to isolate the subshell photoionization cross sections $\tau_{Li}(E_0)\rho_d$. This is performed by scaling the Ebel polynomials [17] for the lower bound shells as well as the three L-subshells to the $\tau_S(E_0)\rho_d$ as shown in the figure.

With the $\tau_{Li}(E_0)\rho_d$, all relevant parts of eq. 4 are known and it can be solved for the fluorescence yield. The same procedure is applied for the $L_2$ and $L_1$ shells. By applying the same procedure for incident energies above the subsequent absorption edges, the Coster-Kronig factors can be derived. In figure 3, this is shown for the case of $\omega_{L_3}$ and $\omega_{L_2}$. Here, the derived fluorescence yield values marked with a star, for example $\omega_{L_3}^\ast(E_i)$ are being calculated by only taking into account the normalized fluorescence intensity of the $L_3$ shell as well as the derived $\tau_{L_3}(E_i)\rho_d$ (red line in figure 3). If the incident photon energy is above the subsequent absorption edge (marked as grey dashed vertical lines), the $\omega_{L_3}^\ast$ jumps due to the additional Coster-Kronig related contributions to the total effective photoionization cross section, namely the term $f_{23L_2}(E_0)$ in the case shown in figure 3 as red crosses. As the fluorescence yield value must be constant and not dependent on the incident photon energy, the Coster-Kronig factor can be determined so that the Coster-Kronig corrected $\omega_{L_3}(E_{L_2})$ matches the one determined for an excitation below the $L_2$ absorption edge.

### 2.2 Validation measurement with combined XRR and GIXRF

As an independent validation of the experimentally determined $L_3$ fluorescence yield, a combined reference-free GIXRF-XRR measurement [18] was carried out on two different tantalum layer samples. These experiments have been carried out employing an in-house build ultrahigh vacuum chamber dedicated to reference-free XRS [19] at
Figure 3: Experimentally determined Ta-L$_3$ (left image) and Ta-L$_2$ (right image) fluorescence yield versus excitation photon energy without taking into account the Coster-Kronig transitions (red or green symbols), as well as the mean value for CK transitions turned off (horizontal dashed lines). The CK factors are chosen in order to match the average corrected fluorescence yields with the dashed lines (blue and purple symbols and lines). The vertical dashed lines mark the L$_2$ and L$_1$ absorption edge above which the respective CK transition appears.

Figure 4: Comparison of measured and calculated data: reflectance (top) and the normalized fluorescence intensity (bottom)

PTB’s four-crystal-monochromator (FCM) beamline [20]. The two layer samples employed consist of pure Ta layers on silicon wafers with nominal thicknesses of 30 nm and 50 nm. The energy of the incident beam was set to 10 keV to only excite the L$_3$ shell of tantalum. For both samples, the incident angle dependent Ta-L$_3$ fluorescence emission as well as the reflected incident radiation have been recorded. The experimental data including a basic evaluation (spectra deconvolution, normalization to incident photon flux and solid angle of detection) are shown in Fig. 4.

To determine the FPCS (fluorescence production cross section) from the experimental data, a quantitative combined modeling of the GIXRF-XRR data was performed as shown in ref. [21]. For this purpose, a model based on a thin carbonaceous contamination layer on tantalum oxide on tantalum on native oxide covered silicon was used. For each layer, with the exception of the substrate, the thickness and relative density were used as model parameters. In addition, the top surface roughness as well as the tantalum layer roughness were modeled. The roughness of the tantalum oxide layer was set to be the same as the previous. Experimental parameters such as the beam divergence or the photodiode’s dark current were modeled as well. The modeling process is realized using the Sherman equation [15] which is shown below, for the GIXRF measurement and using the matrix method [22] for the XRR measurement.

\[
\frac{4\pi \sin \theta_i}{\Omega(\theta_i)} F(\theta_i, E_i) = W_i \rho \tau(E_i) \omega_{L3} dz \cdot \sum_z P(z) \cdot I_{XSW}(\theta_i, E_i, z) \cdot \exp \left[-\rho \mu E_j z \right].
\]
Here, the experimentally derived fluorescence count rate $F(\theta_i, E_i)$ of the lineset related to the Ta-L$_3$-edge, excited using photons of energy $E_i$, at an incident angle $\theta_i$ is the essential measurand. A normalization on the effective solid angle of detection $\Omega(\theta_i, E_i)$, the incident photon flux $\Phi_0$, and the detection efficiency of the used fluorescence detector $\epsilon_{E_i}$ is also required. By calculating the X-ray standing wave field intensity distribution $I_{XSW}(\theta_i, E_i, z)$, a numerical integration in conjunction with the depth distribution $P(z)$ of the tantalum distribution and an attenuation correction factor, the experimental data can be reproduced. For a quantitative modeling, the atomic fundamental parameters, namely the L$_3$-subshell photoionization cross section $\tau(E_i)$ and the fluorescence yield $\omega_{L3}$, and material-dependent parameters, e.g. the weight fraction $W_i$ of element $i$ within the matrix as well as the density $\rho$ of the matrix must also be considered. For the latter, we have adopted the density of the 50 nm Ta layer ($14.2 \text{ g/cm}^3$) from a previous study of the same sample \cite{23} in order to reduce the degrees of freedom. The ratio of this density with respect to the Ta bulk density can be considered. For the latter, we have adopted the density of the 50 nm Ta layer ($14.2 \text{ g/cm}^3$) from a previous study of the same sample \cite{23} in order to reduce the degrees of freedom. The ratio of this density with respect to the Ta bulk density was applied to both the Ta$_2$O$_5$ and the Ta layers of both samples.

The relevant optical constants were taken from X-raylib \cite{4} using the respective $\rho_{bulk}$ and are also scaled using each material’s relative density. The FPCS for the Ta-L$_3$ shell was also taken from X-raylib and is scaled employing a factor during the modeling. The optimization was performed using a Markov chain Monte Carlo (MCMC) algorithm \cite{24}.

The final model calculations are also shown in Fig. \cite{4} and agree very well with the experimental data. The determined layer thickness of the Ta layers is about 28.9 nm or 46.9 nm and thus reasonably in line with the nominal values.

### 3 Results

The results derived for the Ta-L subshell fluorescence yields are shown in figure \cite{5} as well as in table \cite{1} in comparison to selected data from the literature. They were averaged from the values derived at the different excitation photon energies below the subsequent absorption edge as indicated in figure \cite{5}. The uncertainty budget of the determined fluorescence yields is calculated using the relative uncertainty contributions of the involved parameters. The main contributors to the total uncertainty budget are the determined subshell photoionization cross sections (2.5 % for L$_3$, 6 % for L$_1$) and the uncertainty contribution of the spectral deconvolution (2 %). The uncertainty budget one can achieve by employing PTB’s reference-free XRF approach for the determination of atomic fundamental parameters is discussed in more detail in ref. \cite{25}.

In general, our experimental values agree reasonably well with commonly used X-raylib \cite{4} data and the theoretical predictions of Puri et al. \cite{26}. Significant deviations larger than the uncertainty are observed for the L$_2$-shell yield with respect to X-raylib and the L$_1$-shell yield with respect to Puri. The agreement to the shown older experimental data is good considering the stated respective uncertainties. It should be noted, that there are more published values for the L-subshell fluorescence yields of Ta with different origins (experimental or interpolated). They are nicely summarized in a recent work by Sahnoune et al. \cite{27}.

From the GIXRF-XRR modeling, Ta-L$_3$ fluorescence yield values of 0.239(27) (sample A, 30nm Ta) and 0.231(32) (sample B, 50nm Ta) assuming that the L$_3$-subshell photoionization cross section for Ta from X-raylib at the employed excitation photon energy of 10 keV is correct. These results are also shown in tab. \cite{1} and figure \cite{5} in combination with the other data. The uncertainty of the GIXRF determined value is estimated based on the confidence interval of the modeling and an estimated uncertainty of the tabulated L$_3$-subshell photoionization cross section. Unfortunately, the uncertainties are too large in order to reliably judge which fluorescence yield is more accurate. For such small deviations between the determined experimental value and the tabulated value, the sensitivity of the GIXRF-XRR approach is not sufficient. This is mainly due to the strong parameter correlation with the layer densities. If the densities could be determined independently and thus kept fixed for the modeling, it would significantly improve the sensitivity for the fluorescence production cross section.

The experimentally determined Coster-Kronig factors are also shown in table \cite{1} in comparison to selected data from the literature. For $f_{22}$ also a graphical comparison is shown in figure \cite{6}. The derived value for $f_{22}$ is in good agreement with the data from the literature, even when considering a much lower uncertainty budget. A similar behaviour can be found for $f_{13}$, where the observed differences are much lower than our stated uncertainty. Only for $f_{12}$, the deviations with respect to the commonly used database values are somewhat large but still within our stated uncertainty.

The determined relative uncertainties of the Coster-Kronig factors are higher than those of the fluorescence yields because of the required error propagation. For the Coster-Kronig factors, the relation between the different subshell photoionization cross sections increases the total relative uncertainty. Hence, a reliable uncertainty budget for the determined Coster-Kronig factors leads to large uncertainties in the order of the values itself \cite{8}. But as can be seen by the non-agreeing values by Mohan and Werner, our uncertainty seems more reasonable and is more reliable.
Figure 5: Experimentally determined Ta-L fluorescence yields in comparison to selected literature data from other experimental works of Mohan[28] and Werner[29] (blue), theoretical calculations by Puri[26] (orange) or commonly used compilations[5, 6, 30] (black). The experimental uncertainties of our values are plotted as grey boxes for easier comparison. For the Ta-L₃ fl. yield, both the XRF result and the GIXRF-XRR values are shown.
Figure 6: Experimentally determined Coster-Kronig factor $f_{23}$ for Ta-L fluorescence in comparison to selected literature data from other experimental works of Mohan [28] and Werner [29] (blue), theoretical calculations by Puri [26] (orange) or commonly used compilations [5, 6] (black). The experimental uncertainty of our value is plotted as a grey box for easier comparison.

Table 1: Overview of the experimentally determined Ta-L subshell fluorescence yields and Coster-Kronig factors as well as a comparison to the most commonly used database [6] and selected values from the literature. For the GIXRF-XRR results, the value marked with A refers to the 30 nm Ta sample and the other to the 50 nm sample.

|                  | Ta $\omega_{L3}$ | Ta $\omega_{L2}$ | Ta $\omega_{L1}$ |
|------------------|------------------|------------------|------------------|
| this work (XRF)  | 0.247(12)        | 0.278(15)        | 0.157(12)        |
| this work (GIXRF-XRR) | 0.239(27) (A), 0.231(32) (B) | 0.258        | 0.144        |
| X-raylib [6]     | 0.243            |                  |                  |
| Puri et al. [26] | 0.251            | 0.28             | 0.131            |
| Werner et al. [29]| 0.233(9)         | 0.262(15)        |                  |

|                  | Ta $f_{23}$ | Ta $f_{13}$ | Ta $f_{12}$ |
|------------------|------------|------------|------------|
| this work (XRF)  | 0.123(84)  | 0.328(152) | 0.14(11)   |
| X-raylib [6]     | 0.135      | 0.351      | 0.186      |
| Puri et al. [26] | 0.139      | 0.351      | 0.186      |
| Werner et al. [29]| 0.111(10)  | 0.339(20)  | 0.104(15)  |

4 Conclusion

The tantalum L-shell fluorescence yields and Coster-Kronig factors have been experimentally determined employing the radiometrically calibrated instrumentation of PTB using Ta coated Si$_3$N$_4$-membranes. The determined fluorescence yields are agreeing well with the commonly used X-raylib tables except for the L$_2$-shell. Here, our value is slightly larger than the tabulated value. The achieved experimental uncertainties for the three fluorescence yields are in the same order as the Krause estimates [5]. This not only puts the estimated uncertainties on more solid grounds, it also allows to conclude with reasonable reliability that the estimated uncertainties for the L-shell yields of neighbouring elements are in the right order of magnitude as well. Considering both the determined fluorescence yields and the Coster Kronig factors, we can conclude that the X-raylib table gives a relatively good collection of the relevant Ta-FPs. This is also in line with observations from earlier FP determinations from our group [21, 25, 31]. Thus, the X-raylib tables are a very good starting point if a consistent database is needed.
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References

[1] International initiative on x-ray fundamental parameters. https://www.exsa.hu/?inh=635, 2021. Accessed: 2022-06-03.
[2] T. Shoki, T. Kinoshita, N. Sakaya, M. Hosoya, R. Ohkubo, Y. Usui, H. Kobayashi, and O. Nagarekawa. Damage-free extreme ultraviolet mask with tantal absorber. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, 21(6):3021–3026, 2003.
[3] K. Choi and S. Yoon. Characteristics of Pt and TaN metal gate electrode for high-κ hafnium oxide gate dielectrics. Electrochemical and Solid-State Letters, 7(3):G47, 2004.
[4] X. Yang, E. Aydin, H. Xu, J. Kang, M. Hedhili, W. Liu, Y. Wan, J. Peng, C. Samundsett, A. Cuevas, and S. De Wolf. Tantalum nitride electron-selective contact for crystalline silicon solar cells. Advanced Energy Materials, 8(20):1800608, 2018.
[5] M. O. Krause. Atomic radiative and radiationless yields for K and L shells. J. Phys. Chem. Ref. Data, 8(2):307–327, 1979.
[6] T. Schoonjans, A. Brunetti, B. Golosio, M. Sanchez del Rio, V.A. Solé, C. Ferrero, and L. Vincze. The xraylib library for x-ray–matter interactions. recent developments. Spectrochim. Acta B, 66:776 – 784, 2011.
[7] B. Beckhoff. Reference-free x-ray spectrometry based on metrology using synchrotron radiation. J. Anal. At. Spectrom., 23:845 – 853, 2008.
[8] M. Kolbe, P. Hön nieke, M. Müller, and B. Beckhoff. L-subshell fluorescence yields and coster-kronig transition probabilities with a reliable uncertainty budget for selected high- and medium-z elements. Phys. Rev. A, 86:042512, 2012.
[9] W. Görner, M. P. Hentschel, B. R. Müller, H. Riesemeier, M. Krumrey, G. Ulm, W. Diete, U. Klein, and R. Frahm. BAMline: the first hard X-ray beamline at BESSY II. Nucl. Instrum. Meth. A, 467–468(1):703 – 706, 2001.
[10] M. Kolbe, B. Beckhoff, M. Krumrey, and G. Ulm. Thickness determination for Cu and Ni nanolayers: Comparison of reference-free fundamental-parameter based x-ray fluorescence analysis and x-ray reflectometry. Spectrochimica Acta B, 60:505–510, 2005.
[11] F. Scholze and M. Procop. Modelling the response function of energy dispersive x-ray spectrometers with silicon detectors. X-Ray Spectrom., 38(4):312–321, 2009.
[12] P. Hön nieke, M. Kolbe, M. Müller, M. Mantler, M. Krämer, and B. Beckhoff. Experimental verification of the individual energy dependencies of the partial l-shell photoionization cross sections of Pd and Mo. Phys. Rev. Lett., 113(16):163001, 2014.
[13] M. Kolbe and P. Hön nieke. Fundamental parameters of Zr and Ti for a reliable quantitative x-ray fluorescence analysis. X-Ray Spectrom., 44(4):217–220, 2015.
[14] Y. Ménéguen, M.-C. Lépy, J. M. Sampaio, J. P. Marques, F. Parente, M. Guerra, P. Indelicato, J. P. Santos, P. Hön nieke, and B. Beckhoff. A combined experimental and theoretical approach to determine x-ray atomic fundamental quantities of tin. X-Ray Spectrom., 47(5):341–351, 2018.
[15] J. Sherman. The theoretical derivation of fluorescent x-ray intensities from mixtures. Spectrochim. Acta, 7:283–306, 1955.
[16] H. Huang, K. Sequoia, M. Yamaguchi, K. J. Boehm, K. Engelhorn, J. Walker, F. Elsner, J. Tomlin, M. Farrell, C. J. Fontes, and J. P. Colgan. Improved x-ray mass attenuation coefficient (opacity) measurements for Fe, Ni and Au. Journal of Physics B: Atomic, Molecular and Optical Physics, 54(11):115003, jun 2021.
[17] H. Ebel, R. Svagera, M. F. Ebel, A. Shaltout, and J. H. Hubbell. Numerical description of photoelectric absorption coefficients for fundamental parameter programs. X-Ray Spectrom., 32:442–451, 2003.
[18] P. Hön nieke, B. Detlefs, E. Nolot, Y. Kayser, U. Mühle, B. Pollakowski, and B. Beckhoff. Reference-free grazing incidence x-ray fluorescence and reflectometry as a methodology for independent validation of x-ray reflectometry on ultrathin layer stacks and a depth-dependent characterization. J. Vac. Sci. Technol., A, 37(4):041502, jul 2019.
[19] J. Lubeck, B. Beckhoff, R. Fliegauf, I. Holfelder, P. Hönicke, M. Müller, B. Pollakowski, F. Reinhardt, and J. Weser. A novel instrument for quantitative nanoanalytics involving complementary x-ray methodologies. Rev. Sci. Instrum., 84:045106, 2013.

[20] M. Krumrey. Design of a four-crystal monochromator beamline for radiometry at BESSY II. J. Synchrotron Rad., 5(1):6–9, 1998.

[21] P. Hönicke, R. Unterumsberger, N. Wauschkuhn, M. Krämer, B. Beckhoff, P. Indelicato, J. Sampaio, J. P. Marques, M. Guerra, F. Parente, and J. P. Santos. Experimental and theoretical approaches for determining the K-shell fluorescence yield of carbon. Radiat Phys Chem, page 110501, sep 2022.

[22] F. Abelès. Recherches sur la propagation des ondes électromagnétiques sinusoïdales dans les milieux stratifiés. Annales de Physique, 12(5):596–640, 1950.

[23] R. Ciesielski, Q. Saadeh, V. Philipsen, K. Opsomer, J.-P. Soulié, M. Wu, P. Naujok, R. W. E. van de Kruijs, C. Detavernier, M. Kolbe, F. Scholze, and V. Soltwisch. Determination of optical constants of thin films in the EUV. Applied Optics, 61(8):2060, mar 2022.

[24] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman. emcee: The MCMC hammer. Publications of the Astronomical Society of the Pacific, 125(925):306–312, mar 2013.

[25] R. Unterumsberger, P. Hönicke, J. Colaux, C. Jeynes, M. Wansleben, M. Müller, and B. Beckhoff. Accurate experimental determination of gallium K- and L3-shell xrf fundamental parameters. J. Anal. At. Spectrom., 33(6):1003–1013, 2018.

[26] S. Puri, D. Mehta, B. Chand, N. Singh, and P. N. Trehan. L shell fluorescence yields and Coster-Kronig transition probabilities for the elements with 25 < z < 96. X-Ray Spectrom., 22(5):358–361, 1993.

[27] Y. Sahnoune, A. Kahoul, Y. Kasri, B. Deghfel, D. E. Medjadi, F. Khalfallah, S. Daoudi, V. Aylikçi, N. Küp Aylikçi, and M. Nekkab. L1, L2, and L3 subshell fluorescence yields: Updated database and new empirical values. Radiation Physics and Chemistry, 125:227–251, 2016.

[28] S. Mohan, R. W. Fink, R. E. Wood, J. M. Palms, and P. Venugopala Rao. Electron capture decay of 181w: L subshell fluorescence and coster-kronig yields in Ta. Zeitschrift für Physik, 239(5):423–428, oct 1970.

[29] U. Werner and W. Jitschin. L-vacancy decay in heavy elements (72≤z≤82) by the synchrotron photoionization method. Physical Review A, 38(8):4009–4018, oct 1988.

[30] S. T. Perkins, D. E. Cullen, M. H. Chen, J. Rathkopf, J. Scofield, and J. H. Hubbell. Tables and graphs of atomic subshell and relaxation data derived from the llnl evaluated atomic data library (eadl), z = 1-100. UCRL 50400, 30, 1991.

[31] P. Hönicke, M. Kolbe, M. Krumrey, R. Unterumsberger, and B. Beckhoff. Experimental determination of the oxygen k-shell fluorescence yield using thin SiO2 and Al2O3 foils. Spectrochim. Acta B, 124:94–98, 2016.