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ABSTRACT

This report reviews x-ray fluorescence yield experimental and theoretical information beyond that available in earlier extensive reviews by Fink et al., (1966), Bambynek et al. (1972), and by Krause (1979). An annotated bibliography 1978-1988 is included. Tables and fits of the K shell fluorescence yield ω_K, and the average L and M shell fluorescence yields $\bar{\omega}_L$ and $\bar{\omega}_M$, for use in computing photon energy-absorption coefficients μ_{en}/ρ, are presented.

KEYWORDS: Auger effect; energy-absorption coefficient; fluorescence yield; ionization; photon; radiationless transitions; vacancies; x-ray.

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I. INTRODUCTION: DEFINITIONS, HISTORY

Values of the fluorescence yield $\omega_i(Z)$, where i represents a given atomic electron shell or subshell, of an atom with atomic number Z, are required in a variety of applications including atomic physics studies, x-ray fluorescence (XRF) surface chemical analysis, and dosimetric computations for health physics, cancer therapy, and industrial irradiation processing. The focus of this report will be on fluorescence yield information for the latter application, in particular the computation of the photon energy-absorption coefficient μ_{en}/ρ.

An excellent description of the fluorescence yield given by Compton and Allison (35Co01) is briefly paraphrased as follows. When an inner shell atomic electron is ejected from an atom as a result of a collision process involving a photon or other incoming projectile, a vacancy is created in that electron's pre-collision subshell. For incoming photons, such processes could be the photoelectric effect, Compton collisions, and triplet production (electron-positron pair production in the field of the atomic electrons, by photons with energy in excess of 2.04 MeV). Associated with this inner-shell vacancy is an excess of energy above the atom's ground state. The atom returns to its ground state, including filling the vacancy, by one of two modes. In one mode a fluorescence (or characteristic) x-ray is emitted from the atom, with photon energy equal to the difference between the vacancy-site inner-shell energy level and the energy level of the particular outer shell which happens to supply the electron to fill the vacancy. In the other mode, no fluorescence x-ray is emitted, but instead the excess energy ejects an outer-shell electron from the atom (in addition to the ejected electron causing the original vacancy). This second ejected electron is known as an

Auger electron, after the cloud chamber confirmation and explanation by Auger (25Au01, 25Au02) of earlier conjectures by Sadler (09Sa01) and Barkla (17Ba01) and observations by Wilson (23Wi01, 23Wi02).

In simplest terms, the fluorescence yield $\omega_i(Z)$ is

$$\omega_i(Z) = f_i(Z)/v_i(Z) \qquad (1)$$

where $f_i(Z)$ is the average number of fluorescence (characteristic) x rays emitted as a result of $v_i(Z)$ vacancies created in the i^{th} shell or subshell. In reality the situation is quite complex due to the multiplicity of transitions of varying likelihood involving the participating inner and outer subshells, the details of which are described in the extensive reviews by, e.g., Fink et al. (66Fi01), Bambynek et al. (72Ba01), Krause (79Kr01), Mitchell and Barfoot (81Mi01), and Cohen (87Co01). This report is an annex to, and not a replacement of, these earlier major reviews.

Compton and Allison (35Co01) and some later authors, e.g., Tertian and Claisse (82Te01) consider the Auger effect a two stage process in which the characteristic x ray is first emitted but then reabsorbed by an outer electron shell in a photoeffect type process. However, other authors, such as N. A. Dyson (73Dy01), contend that the Auger effect must be a one stage process because of strong lines (such as the $K \rightarrow L_1$ transition) in the Auger spectra which are forbidden in radiative transitions.

The annotated bibliography in this report combines an automated search of Physics Abstracts with a manual search by Trehan and collaborators (89Tr01), and focuses on the time period 1978-1988 following the Krause (79Kr01) 1979 review article. Additional text references are listed separately following the annotated bibliography.

II. APPLICATION OF FLUORESCENCE YIELD DATA IN COMPUTING MASS ENERGY-ABSORPTION COEFFICIENTS

The mass energy-absorption coefficient μ_{en}/ρ (cm^2/g or m^2/kg, where 1 cm^2/g = 0.1 m^2/kg), a key parameter in computations of energy deposited in media subjected to photon irradiation, is defined (see, e.g., R. T. Berger (61Be01), Hubbell (77Hu01), Hubbell (82Hu01), and Higgins et al. (89Hi01)) as

$$\mu_{en}/\rho = (\mu/\rho)f \quad . \tag{2}$$

In this expression, f is the average fraction of the incident photon energy E_0 which does not leave the site of the primary collision in the form of secondary photon radiation (fluorescence, Compton scattered photons, annihilation radiation, bremsstrahlung, etc.). This fraction f goes into kinetic energy of particles, particularly electrons, for dissipation locally in the medium via collision losses as ionization and excitation. Here μ/ρ is the total mass attenuation coefficient (see, e.g., Hubbell (69Hu01)) for a given incident photon energy E_0 in a given substance:

$$\mu/\rho = \sigma_{incoh}/\rho + \sigma_{coh}/\rho + \tau/\rho + \kappa_n/\rho + \kappa_e/\rho + \sigma_{ph.n.}/\rho \tag{3}$$

in which the significant interaction components are incoherent (Compton) scattering σ_{incoh}/ρ, coherent (Rayleigh) scattering σ_{coh}/ρ, atomic photoeffect τ/ρ, electron-positron pair production in the field of the atomic nucleus κ_n/ρ, pair production in the field of the atomic electrons (triplet production) κ_e/ρ, and photonuclear interactions (e.g., (γ,n), $(\gamma,2n)$, (γ,p), $(\gamma,fiss)$, etc.) $\sigma_{ph.n.}/\rho$.

In equations (2), (3), and (4) the units of μ/ρ and μ_{en}/ρ have been customarily cm^2/g, as well as all of the term on the right hand side of eq (3) (e.g., σ_{incoh}/ρ in cm^2/g). However, the preferred units for these quantities (μ/ρ, μ_{en}/ρ, etc.) are in the SI base units m^2/kg (where 1 m^2/kg = 10 cm^2/g) as in the tables of Hubbell (82Hu01) and in ICRU Report 44 (89Ic01).

For computational purposes eq (2), using the information on the individual processes indicated in eq (3), becomes:

$$\mu_{en}/\rho = (\mu/\rho)f = (\sigma_{incoh}/\rho)f_{incoh} + (\tau/\rho)f_{\tau} + (\kappa_n/\rho)f_{\kappa_n} + (\kappa_e/\rho)f_{\kappa_e} + (\sigma_{ph.n.}/\rho)f_{\sigma_{ph.n.}} \qquad (4)$$

in which the σ_{coh}/ρ term in eq (3) is omitted because the coherent scattering process deposits negligible energy at the collision site. Also, in existing μ_{en}/ρ tables, the photonuclear term $(\sigma_{ph.n.}/\rho)f_{\sigma_{ph.n.}}$ has been ignored. In eq (4) the energy-absorption weighting fractions f_{incoh}, f_{τ}, f_{κ_n}, and f_{κ_e} follow the f definition in eq (2), each for the individual interaction process indicated.

Although the incoherent scattering σ_{incoh}/ρ and triplet production κ_e/ρ processes produce vacancies in the atomic electron subshells, resulting in the emission of either fluorescence or Auger electrons, existing tables ignore fluorescence emission (in effect, set $\omega_i = 0$) for these processes in which the subshell distribution of vacancy creation is not well known. Computational procedures for evaluating f_{incoh} and f_{κ} (treating κ_n and κ_e alike), ignoring fluorescence, are given, e.g., by Hubbell (77Hu01) and by Higgins et al. (89Hi01).

For the atomic photoeffect term $(\tau/\rho)f_\tau$, Hubbell (77Hu01) calculated f_τ using the formulation by R. T. Berger (61Be01), modified as suggested by Carlsson (71Ca01) to include additional fluorescence cascade effects. For each atomic electron shell group i, where i signifies K, L, M, ..., a photoeffect energy-absorption fraction f_{τ_i} was calculated for each incident photon energy E_0 and element Z as

$$f_{\tau_i}(E_0,Z) = \left(1 - \frac{\eta_i}{E_0}\right) \cdot [1 - G_{br}(E_0 - \eta_i)] + \frac{\eta_i}{E_0}\left(1 - \frac{\omega_i E_i}{\eta_i} - N_{i,i+1}\frac{\omega_{i+1} E_{i+1}}{\eta_i}\right) \qquad (5)$$

in which η_i is the mean absorption-edge energy of the i-shell, $G_{br}(E_0-\eta_i)$ is the bremsstrahlung yield (see, e.g., Berger and Seltzer (83Be01) and ICRU (84Ic01)) for the photoelectron of energy $E_0 - \eta_i$, ω_i is the i-shell fluorescence yield, E_i is the i-shell fluorescence x-ray mean energy, and $N_{i,i+1}$ is the average number of vacancies created in the (i + 1)-shell per primary i-shell vacancy.

For μ_{en}/ρ in mixtures, where the bremsstrahlung yield $G_{br}(E_0-\eta_i)$ is a function of the matrix rather than the atom suffering the primary collision, further refinements in the computations have been proposed by Attix (84At01).

Since the K fluorescence x rays predominate over the L x rays, and L x rays over M x rays, etc, both in photon energy and yield, particularly for low-Z elements, the approximation f'_τ for the photoeffect energy-absorption fraction f_τ has sometimes been used, e.g., by R. T. Berger (61Be01), in computing μ_{en}/ρ:

For E_0 above the K edge:

$$(\tau/\rho)f'_\tau \approx (\tau_K/\rho)\left(1 - \frac{\omega_K \bar{E}_K}{E_0}\right) + (\tau_L/\rho) + (\tau_M/\rho) + \ldots \qquad (6)$$

which reduces to

$$f'_\tau \approx 1 - \frac{(\tau_K/\rho)}{(\tau/\rho)}\left(\frac{\omega_K \bar{E}_K}{E_0}\right) . \qquad (7)$$

For E_0 between the K and L edges:

$$(\tau/\rho)f'_\tau \approx (\tau_L/\rho)\left(1 - \frac{\bar{\omega}_L \bar{E}_L}{E_0}\right) + (\tau_M/\rho) + \ldots \qquad (8)$$

or

$$f'_\tau \approx 1 - \frac{(\tau_L/\rho)}{(\tau/\rho)}\left(\frac{\bar{\omega}_L \bar{E}_L}{E_0}\right) . \qquad (9)$$

and similarly between the L and M edges:

$$f'_\tau \approx 1 - \frac{(\tau_M/\rho)}{(\tau/\rho)}\left(\frac{\bar{\omega}_M \bar{E}_M}{E_0}\right) . \qquad (10)$$

with further ad hoc approximations within the L and M multiple-edge regions.

III. K-SHELL FLUORESCENCE YIELD ω_K

The bulk of the fluorescence yield measurements reported in the literature have been for the K shell, and this trend has continued through the 1978-1988 period, as indicated in the annotated bibliography in Section VIII in this report. A semi-empirical fitting formula for ω_K, introduced by Burhop (55Bu01), has become established in the literature, of the form

$$\left(\frac{\omega_K}{1-\omega_K} \right)^{1/4} = C_0 + C_1 Z + C_2 Z^2 + C_3 Z^3$$

$$= \sum_{i=0}^{3} C_i Z^i \qquad (11)$$

which can be rewritten

$$\omega_K = \left[\sum_{i=0}^{3} C_i Z^i \right]^4 / \left\{ 1 + \left[\sum_{i=0}^{3} C_i Z^i \right]^4 \right\} . \qquad (12)$$

This fitting formula is also applicable to average L-shell fluorescence yields $\bar{\omega}_L$, as will be seen in Section IV following.

Bambynek et al. (72Ba01), in their 1972 review article (the most comprehensive and widely quoted fluorescence yield reference to date), have fitted their collection of "selected 'most reliable' experimental values," listed in their Table III.IV with parameters for eq (12), above, of values:

$$C_0 = 0.015 \pm 0.010$$

$$C_1 = 0.0327 \pm 0.0005$$

$$C_2 = 0$$

$$C_3 = -(0.64 \pm 0.07) \times 10^{-6} \ . \qquad (13)$$

In Table 1 of this report, ω_K values for $1 \leq Z \leq 110$, matching the range of the Krause (79Kr01) table, generated from the above eqs (12) and (13), are given in the first ω_K column, and are compared with measured values (averaged when more than one measurement per element is given) in the next column.

In a subsequent review, Krause (79Kr01) incorporated additional new data in a revised evaluation, and presented a table of ω_K "adopted values" for all elements $5 \leq Z \leq 110$, but did not provide a corresponding parametric fit or fits. These 1979 Krause adopted values are included in Table 1 of this report along with percent differences of these adopted values from the 1972 Bambynek et al. (72Ba01) fit.

In 1984 Bambynek (84Ba01) presented a further reevaluation of ω_K, incorporating about 100 new measurements subsequent to the 1972 Bambynek et al. (72Ba01) evaluation. Using a stepwise regression analysis with 119 selected ω_K measurements, Bambynek fitted his new evaluation to the form in eq (12) above, with parameters C_i now:

$$\begin{aligned} C_0 &= 0.0370 \pm 0.0052 \\ C_1 &= 0.03112 \pm 0.00044 \\ C_2 &= (5.44 \pm 0.11) \times 10^{-5} \\ C_3 &= -(1.250 \pm 0.070) \times 10^{-6} \quad . \end{aligned} \tag{14}$$

This revised fit was used to generate the ω_K values in the next to the last column in Table 1 for all elements $1 \leq Z \leq 110$.

For $35 \leq Z \leq 107$ the 1984 values differ from the 1972 values by less than 1%. For $1 \leq Z \leq 34$ the new values exceed the old by more than 1%, and for $1 \leq Z \leq 11$ by more than 10%. However, in the range $1 \leq Z \leq 11$ ω_K is small,

ranging from 2.160×10^{-5} for Z = 1 to 0.02133 for Z = 11. Since ω_K enters the computations of photon energy-absorption coefficients μ_{en}/ρ approximately as $(1 - \omega_K \frac{\bar{E}_K}{E_0})$, see eq (6), where $E_K/E_0 < 1$, these differences, even the 317% at Z = 1, result in less than 1% differences in μ_{en}/ρ for all elements $1 \leq Z \leq 100$.

The fitting formula eq (12), rewritten from eq (11), with the 1984 Bambynek (84Ba01) parameters in eq (14) is the ω_K evaluation recommended in this report for current μ_{en}/ρ computations, and the numerical values are repeated for convenience in the summary Table 4 for $1 \leq Z \leq 100$.

IV. L-SHELL AVERAGE FLUORESCENCE YIELD $\bar{\omega}_L$

The status of fluorescence yield data for the L subshells L_1, L_2 and L_3, and particularly for the average yield $\bar{\omega}_L$, is well summarized in the recent review by Cohen (87Co01). Besides tables and standard-form fits (eq (12)) of the $\bar{\omega}_L$ values given by Bambynek et al. (72Ba01) and by Mitchell and Barfoot (81Mi01), Cohen presents new theoretical values of $\bar{\omega}_L$ calculated using the ECPSSR (Energy loss, Coulomb deflection, Perturbed Stationary State, Relativistic effects) theory of Brandt and Lapicki (79Br01) and the resulting L-shell ionization cross sections computed by Cohen and Harrigan (85Co02).

Cohen's (87Co01) fitting parameters for $\bar{\omega}_L$ in eq (12) are:

Bambynek et al. (72Ba01), $\bar{\omega}_L$, $23 \leq Z \leq 96$:

$$\begin{aligned} C_0 &= 0.238209 \\ C_1 &= -0.00216099 \\ C_2 &= 1.85156 \times 10^{-4} \\ C_3 &= -7.47647 \times 10^{-7} \end{aligned} \qquad (15)$$

Mitchell and Barfoot (81Mi01), $\bar{\omega}_L$, $23 \leq Z \leq 92$:

$$\begin{aligned} C_0 &= 0.326968 \\ C_1 &= -0.00242879 \\ C_2 &= 1.71660 \times 10^{-4} \\ C_3 &= -6.96583 \times 10^{-7} \end{aligned} \qquad (16)$$

Cohen (87Co01), $\bar{\omega}_L$, ECPSSR, $30 \leq Z \leq 96$:

$$C_0 = 0.177650$$
$$C_1 = 0.00298937$$
$$C_2 = 8.91297 \times 10^{-5}$$
$$C_3 = -2.67184 \times 10^{-7} \qquad (17)$$

Numerical values generated from these fits are compared with the tables presented by Cohen (87Co01), in Table 2 of this report.

The Cohen ECPSSR fit, using the above eq (17) parameters, was extended to lower Z's, down to Z = 3, the first element with an L-shell electron. The $\bar{\omega}_L$ values computed from the fit for the lowest Z's appeared too high, exceeding the ω_K values. However, the Mitchell and Barfoot (81Mi01) table actually extends down to Z = 12, based on results in a thesis by Hoffmann (78Ho01).

A log-log plot of the Mitchell-Barfoot-Hoffmann values was found to be linear over the range $12 \leq Z \leq 50$ except for two anomalously low points for Z = 17 and 18, perhaps due to round-off in the two-digit table. Using the slope of this log-log linear plot, and normalizing from 0.024 to the 3-digit 0.0242 ECPSSR Cohen-fit value at Z = 37 a fit is here presented:

Present work, $\bar{\omega}_L$, $3 \leq Z \leq 36$:

$$\bar{\omega}_L = 1.9390 \times 10^{-8} \times Z^{3.8874} \qquad (18)$$

In the summary Table 4, $\bar{\omega}_L$ is generated using eq (18) for $3 \leq Z \leq 36$, and eq (12) with the Cohen (87Co01) ECPSSR fit parameters in the above eq (17) for $37 \leq Z \leq 100$, as recommended $\bar{\omega}_L$ values for current μ_{en}/ρ computations.

V. M-SHELL AVERAGE FLUORESCENCE YIELD $\bar{\omega}_M$

An extended-range table of M-shell average fluorescence yield values $\bar{\omega}_M$, suitable for systematic computations of mass energy-absorption coefficients μ_{en}/ρ, was not found in the literature, so this report has undertaken to provide a provisional $\bar{\omega}_M$ fit and table.

Burhop (55Bu01) fitted the $\bar{\omega}_M$ Lay (34La01) and Jaffe (54Ja01) data available in 1955 by a formula

$$\bar{\omega}_M = 1.7 \times 10^{-9} (Z-13)^4 \quad . \tag{19}$$

Subsequent measurements by Jopson et al. (65Jo01), corrected by Bambynek et al. (72Ba01) for a 20% correction from double M-shell vacancies to convert ω_{LM} into $\bar{\omega}_M$ data, and by Konstantinov and Sazonova (68Ko01), by Hribar et al. (82Hr01), and by Shatendra et al. (84Sh01) are shown in Table 3. The average difference of all three measurements 1934-1984 from the Burhop (55Bu01) eq (19) values is a factor 0.758, with no significant trend as a function of Z over this limited high-Z range $76 \leq Z \leq 92$.

Hence a provisional fit is proposed:

$$\bar{\omega}_M = 0.758 \times 1.7 \times 10^{-9} (Z-13)^4$$

$$= 1.29 \times 10^{-9} (Z-13)^4 \tag{20}$$

from which numerical values are given in the last column in Table 3, and for the range $13 \leq Z \leq 100$ in the summary Table 4.

Also shown in Table 3, for comparison, are some theoretical $\bar{\omega}_M$ values derived from Chen et al. (80Ch02) and given by Sarkar et al. (81Sa01). The Chen et al. (80Ch02) values listed were obtained from their theoretical ω_{L_4} and ω_{L_5} values using a recipe quoted by McGuire (72Mc01) from Jopson et al. (65Jo01):

$$\bar{\omega}_M \approx \omega_{LM} \approx 0.4\ \omega_{M_4} + 0.6\ \omega_{M_5} \quad . \tag{21}$$

The Sarkar et al. (81Sa01) values listed in Table 3 were also derived from the Chen et al. (80Ch02) theoretical ω_{M_i} subshell values, but by Sarkar et al. using the relation

$$\bar{\omega}_M = \sum_{i=1}^{5} \frac{1}{18} N_{M_i}\ \omega_{M_i} \tag{22}$$

in which N_{M_i} are the numbers of electrons in each M_i subshell.

Equation (20), used in generating the $\bar{\omega}_M$ values listed in the summary Table 4 for $13 \leq Z \leq 100$, could be further refined by including additional ω_{M_i} subshell measurements by Karttunen et al. (71Ka01) and by Baker et al. (74Ba01), perhaps combined using eq (22) above.

VI. N- AND HIGHER-SHELL AVERAGE FLUORESCENCE YIELDS

No N-shell or higher shell ω measurements were found in the literature. For the N shell, the best source of $\bar{\omega}_N$ data, if required, is probably the theoretical work of McGuire (74Mc01), which provides ω_{N_1}, ω_{N_2}, and ω_{N_3} values for 25 elements over the range $38 \leq Z \leq 103$, and ω_{N_4}, ω_{N_5}, and $\omega_{N_{6,7}}$ values for 20 elements over the range $50 \leq Z \leq 103$. For average $\bar{\omega}_N$ values, this information would need to be combined using an expression analogous to either eq (21) or (22) above.

VII. SUMMARY AND RECOMMENDATIONS

Based on information in the works listed in the appended annotated bibliography 1978-1988, and in key earlier works listed in the additional text references, a recommended set of extended-range ω_K, $\bar{\omega}_L$, and $\bar{\omega}_M$ values is provided in Table 4. These values may be regenerated using the following fits, as described and documented earlier in this report:

$$\omega_K \ (1 \leq Z \leq 100) = \left[\sum_{i=0}^{3} C_i Z^i\right]^4 \Big/ \left\{1 + \left[\sum_{i=0}^{3} C_i Z^i\right]^4\right\} \qquad (12)$$

where

$$\begin{aligned} C_0 &= 0.0370 \pm 0.052 \\ C_1 &= 0.03112 \pm 0.00044 \\ C_2 &= (5.44 \pm 0.11) \times 10^{-5} \\ C_3 &= -(1.250 \pm 0.070) \times 10^{-6} \ . \end{aligned} \qquad (14)$$

$$\bar{\omega}_L \ (3 \leq Z \leq 36) = 1.9390 \times 10^{-8} \times Z^{3.8874} \qquad (18)$$

$$\bar{\omega}_L \ (37 \leq Z \leq 100) = \left[\sum_{i=0}^{3} C_i Z^i\right]^4 \Big/ \left\{1 + \left[\sum_{i=0}^{3} C_i Z^i\right]^4\right\} \qquad (12')$$

$$\begin{aligned} C_0 &= 0.177650 \\ C_1 &= 0.00298937 \\ C_2 &= 8.91297 \times 10^{-5} \\ C_3 &= -2.67184 \times 10^{-7} \end{aligned} \qquad (17)$$

$$\bar{\omega}_M = (13 \leq Z \leq 100) = 1.29 \times 10^{-9} (Z-13)^4 \qquad (20)$$

Finally, it should be understood that this report is a provisional working document, addressing the requirement for extended-range systematic ω data as input to computation of photon energy-absorption coefficients μ_{en}/ρ as described in Section II, and that corrections, suggestions, and additions, directed to the author, will be welcomed.

VIII. ANNOTATED BIBLIOGRAPHY OF X-RAY FLUORESCENCE YIELD MEASUREMENTS, ANALYSIS, FITS, AND TABLES 1978-1988

78Al01 Allawadhi, K. L., Arora, S. K., and Sood, B. S., Natl. Acad. Sci. Lett. (India) 1, 109-111 (1978)
Average L Shell Fluorescence Yields Following K to L Transfer of Vacancies in Some High Z Elements
(L: high Z)

78Do01 Doyle, B. L., Schiebel, U., McDonald, J. R., and Ellsworth, L. D., Phys. Rev. A, 17, 523-528 (1978)
Charge-State Dependence of the Mean K-Shell Fluorescence Yields of Si^{q+} Ions
(K: Si ions)

79Ah01 Ahmad, I., Z. Phys. A (Germany) 290, 1-5 (1979)
Precision Measurement of K-Shell Fluorescence Yields in Actinide Elements
(K: Np, Pu, Cm, Bk, Cf, Es)

79Ch01 Chen, M. H., Laiman, E., Crasemann, B., Aoyagi, M., and Mark, H., Phys. Rev. A (USA), 19, 2253-2259 (1979).
Relativistic L-Shell Auger and Coster-Kronig Rates and Fluorescence Yields
(Theor.: L_1, L_3: Hg, U, Cm; L_2: Yb, W, Hg, Ra, Th, U, Cm)

79Hr01 Hribar, M., Kodre, A., and Pahor, J., Fizika (Yugoslavia) 11, 109-115 (1979)
The Study of the L-shell Fluorescence Yields of Tin and Antimony
(L: Sn, Sb)

79Kr01 Krause, M. O., J. Phys. and Chem. Ref. Data (USA), 8, 307-327 (1979)
Atomic Radiative and Radiationless Yields for K and L Shells.
(Review, Tables: K: $5 \leq Z \leq 110$; L: $12 \leq Z \leq 110$)

79La01 Langenberg, A. and Van Eck, J., J. Phys. B (GB) 12, 1331-1350 (1979)
An Evaluation of K-Shell Fluorescence Yields; Observation of Outer-Shell Effects
(Review, fit: K: $3 \leq Z \leq 98$)

79Sp01 Spiler, F. and Hribar, M., Fizika (Yugoslavia) 11, 117-120 (1979)
The New Determination of the L-Shell Fluorescence Yield of Krypton
(L: Kr)

79Tu01 Tunnell, T. W., Can, C., and Bhalla, C. P., IEEE Trans. Nucl. Sci. (USA) NS-26, Pt. 2, 1124-1126 (1979)
Theoretical Lifetimes and Fluorescence Yields for Multiply-Ionized Fluorine
(Theor.: K: F ions)

80Bi01 Bissinger, G., Joyce, J. M., Tanis, J. A., and Varghese, S. L., Phys. Lett. A, 77A, 156-158 (1980)
Statistical Scaling of C and O K-Shell Fluorescence Yields
(K: C in CH_4, C_2H_2, C_2H_4, C_2H_6, CO_2, CF_4; O in O_2, CO, CO_2, H_2O)

80Ch01 Chen, M. H., Crasemann, B., and Mark, H., Phys. Rev. A (USA) 21, 436-441 (1980)
Relativistic K-Shell Auger Rates, Level Widths, and Fluorescence Yields
(Theor.: K: 25 elements $18 \leq Z \leq 96$)

80Ch02 Chen, M. H., Crasemann, B., and Mark, H., Phys. Rev. A (USA) 21, 449-453 (1980)
Relativistic M-Shell Radiationless Transitions
(Theor.: M: 8 elements $70 \leq Z \leq 100$)

80Gn01 Gnade, B. E., Braga, R. A., and Fink, R. W., Phys. Rev. C (USA) 21, 2025-2032 (1980)
$L_{2,3}$-Subshell X-Ray Fluorescence and Coster-Kronig Yields at Z = 64 and 67
(L_2, L_3: Gd, Ho)

80Kr01 Krause, M. O., Phys. Rev. A (USA) 22, 1958-1961 (1980)
Average L-Shell Fluorescence, Auger, and Electron Yields
(Review: L: $40 \leq Z \leq 100$)

80Ma01 Marques, M. I., Martins, M. C., and Ferreira, J. G., Port. Phys (Portugal) 11, 9-12 (1980)
The L_1 Subshell Fluorescence Yield of Tl
(L_1: Tl)

80Ni01 Nigam, A. N. and Napalia, R., Proc. Natl. Acad. Sci. India, Section A, 50, 137-144 (1980)
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84Ic01 ICRU Report 37 (1984) (M. J. Berger, Report Committee Chairman)
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89Tr01 Trehan, P. N. (Panjab University, Chandigarh, India), personal communication as part of Indo/U.S. joint project on measurement and analysis of photoionization and fluorescence yield data.

Table 1. ω_K: Comparison of recent fits, tables, $1 \leq Z \leq 110$

Z	Bambynek et al., 1972 fit	Bambynek et al., 1972 most rel. exper.	% diffs exper. from 1972 fit	Krause 1979 adopted table	% diffs 1979 adopted from 1972 fit	Bambynek 1984 fit	% diffs 1984 fit to 1972 fit
1 H	5.18(-6)					2.160(-5)	317%
2 He	4.18(-5)					9.780(-5)	134
3 Li	1.64(-4)					2.928(-4)	78.5
4 Be	4.51(-4)					6.929(-4)	53.6
5 B	.00101			.0017	68.3%	.001409	39.5
6 C	.00198			.0028	41.4	.002575	30.1
7 N	.00351			.0052	48.1	.004349	23.9
8 O	.00579			.0083	43.4	.006909	19.3
9 F	.00902			.013	44.1	.01045	15.9
10 Ne	.0134			.018	34.3	.01519	13.4
11 Na	.0192			.023	19.8	.02133	11.1
12 Mg	.0265			.030	13.3	.02911	9.8
13 Al	.0357	.0380	6.4%	.039	9.2	.03872	8.5
14 Si	.0469	.043	-8.3	.050	6.6	.05037	7.4
15 P	.0603	.060	- .5	.063	4.5	.06422	6.5
16 S	.0760	.082	7.9	.078	2.6	.08038	5.8
17 Cl	.0941	.0955	1.5	.097	3.1	.09892	5.1
18 Ar	.115	.122	6.1	.118	2.6	.1199	4.3
19 K	.138			.140	1.4	.1432	3.8
20 Ca	.163			.163	0	.1687	3.5
21 Sc	.190	.190	0	.188	-1.1	.1962	3.3
22 Ti	.219	.221	.9	.214	-2.3	.2256	3.0
23 V	.249	.253	1.6	.243	-2.4	.2564	3.0
24 Cr	.281	.283	.7	.275	-2.1	.2885	2.7
25 Mn	.314	.313	- .3	.308	-1.9	.3213	2.3
26 Fe	.347	.342	-1.4	.340	-2.0	.3546	2.2
27 Co	.381	.366	-3.9	.373	-2.1	.3880	1.8
28 Ni	.414			.406	-1.9	.4212	1.7
29 Cu	.446	.443	- .7	.440	-1.3	.4538	1.7
30 Zn	.479			.474	-1.0	.4857	1.4
31 Ga	.510	.528	3.5	.507	- .6	.5166	1.3
32 Ge	.540	.554	2.6	.535	- .9	.5464	1.2
33 As	.568	.589	3.6	.562	-1.1	.5748	1.2
34 Se	.596			.589	-1.2	.6019	1.0
35 Br	.622			.618	- .6	.6275	.9
36 Kr	.646	.660	2.2	.643	- .5	.6517	.9
37 Rb	.669	.669	0	.667	- .3	.6744	.8
38 Sr	.691	.702	1.6	.690	- .1	.6956	.7
39 Y	.711			.710	- .1	.7155	.6
40 Zr	.730			.730	0	.7340	.5
41 Nb	.747			.747	0	.7512	.6
42 Mo	.764			.765	.1	.7672	.4
43 Te	.779			.780	.1	.7821	.4
44 Ru	.793			.794	.1	.7958	.4
45 Rh	.806			.808	.2	.8086	.3
46 Pd	.818			.820	.2	.8204	.3
47 Ag	.830	.843	.5	.831	.1	.8313	.2
48 Cd	.840			.843	.4	.8415	.2
49 In	.850			.853	.4	.8508	.1
50 Sn	.859			.862	.3	.8595	.1
51 Sb	.867			.870	.3	.8676	.1
52 Te	.875	.857	-2.1	.877	.2	.8750	0
53 I	.882			.884	.2	.8819	0
54 Xe	.888	.894	.7	.891	.3	.8883	0
55 Cs	.895	.889	- .7	.897	.2	.8942	- .1

Table 1. Continued

Z		Bambynek et al., 1972 fit	Bambynek et al., 1972 most rel. exper.	% diffs exper. from 1972 fit	Krause 1979 adopted table	% diffs 1979 adopted from 1972 fit	Bambynek 1984 fit	% diffs 1984 fit to 1972 fit
56	Ba	.900			.902	.2	.8997	0
57	La	.906			.907	.1	.9047	- .1
58	Ce	.911			.912	.1	.9096	- .2
59	Pr	.915			.917	.2	.9140	- .1
60	Nd	.920			.921	.1	.9181	- .2
61	Pm	.924			.925	.1	.9220	- .2
62	Sm	.927			.929	.2	.9255	- .2
63	Eu	.931	.925	- .6	.932	.1	.9289	- .2
64	Gd	.934			.935	.1	.9320	- .2
65	Tb	.937			.938	.1	.9349	- .2
66	Dy	.940	.943	.3	.941	.1	.9376	- .2
67	Ho	.943			.944	.1	.9401	- .2
68	Er	.945			.947	.2	.9425	- .3
69	Tm	.947			.949	.2	.9447	- .2
70	Yb	.950			.951	.1	.9467	- .3
71	Lu	.952			.953	.1	.9487	- .3
72	Hf	.954			.955	.1	.9505	- .4
73	Ta	.956			.957	.1	.9522	- .4
74	W	.957			.958	.1	.9538	- .3
75	Re	.959			.959	0	.9553	- .4
76	Os	.960			.961	.1	.9567	- .3
77	Ir	.962			.962	0	.9580	- .4
78	Pt	.963	.967	.4	.963	0	.9592	- .4
79	Au	.964			.964	0	.9604	- .4
80	Hg	.966	.958	- .8	.965	- .1	.9615	- .5
81	Tl	.967			.966	- .1	.9625	- .5
82	Pb	.968	.972	.4	.967	- .1	.9634	- .5
83	Bi	.968			.968	0	.9643	- .4
84	Po	.970			.968	- .2	.9652	- .5
85	At	.971			.969	- .2	.9659	- .5
86	Rn	.972			.969	- .3	.9667	- .5
87	Fr	.972			.970	- .2	.9674	- .5
88	Ra	.973			.970	- .3	.9680	- .5
89	Ac	.974			.971	- .3	.9686	- .6
90	Th	.975			.971	- .4	.9691	- .6
91	Pa	.975			.972	- .3	.9696	- .6
92	U	.976	.970	- .6	.972	- .4	.9701	- .6
93	Np	.977			.973	- .4	.9706	- .7
94	Pu	.977			.973	- .4	.9710	- .6
95	Am	.978			.974	- .4	.9713	- .7
96	Cm	.978			.974	- .4	.9717	- .6
97	Bk	.979			.975	- .4	.9720	- .7
98	Cf	.979			.975	- .4	.9722	- .7
99	Es	.980			.975	- .5	.9725	- .8
100	Fm	.980			.976	- .4	.9727	- .7
101	Md	.980			.976	- .4	.9729	- .7
102	No	.981			.976	- .5	.9730	- .8
103	Lw	.981			.977	- .4	.9732	- .8
104		.981			.977	- .4	.9732	- .8
105		.982			.977	- .5	.9733	- .9
106		.982			.978	- .4	.9733	- .9
107		.982			.978	- .4	.9734	- .9
108		.983			.978	- .5	.9733	-1.0
109		.983			.978	- .5	.9733	-1.0
110		.983			.979	- .4	.9732	-1.0

Table 2. Summary and analysis of Cohen (87Co01) $\bar{\omega}_L$ review, fits, and tabulations, including ECPSSR (Energy loss, Coulomb deflection, Perturbed Stationary State, Relativistic effects)

Z	Bambynek et al., 1972 $\bar{\omega}_L$ table	Bambynek et al., 1972 $\bar{\omega}_L$ fit	% diff. fit from table	Mitchell & Barfoot 1981 $\bar{\omega}_L$ table	Mitchell & Barfoot 1981 $\bar{\omega}_L$ fit	% diff. fit from table	Cohen 1987 ECPSSR $\bar{\omega}_L$ table	Cohen 1987 ECPSSR $\bar{\omega}_L$ fit	% diff. fit from table
23 V	.00235	.00588	+150.2%	.0038	.0154	+305.%			
24 Cr									
25 Mn	.00295	.00685	132.2	.0052	.0170	+227.			
26 Fe									
27 Co									
28 Ni				.0081	.0201	+148.	.0092	.0111	+20.7%
29 Cu	.0056	.00951	69.8	.0093	.0213	129.	.0105	.0121	15.2
30 Zn				.011	.0226	105.	.0117	.0132	12.8
31 Ga	.0064	.0113	76.6	.012	.0240	100.	.0131	.0145	10.7
32 Ge				.014	.0255	82.1	.0145	.0158	9.0
33 As				.015	.0271	80.7	.0161	.0172	6.8
34 Se				.017	.0289	70.0	.0177	.0188	6.2
35 Br				.019	.0308	62.1	.0198	.0204	3.0
36 Kr				.022	.0329	49.5	.0219	.0222	1.4
37 Rb	.010	.0192	92.0	.024	.0351	46.3	.0241	.0242	.42
38 Sr				.027	.0375	38.9	.0262	.0263	.38
39 Y	.0315	.0229	- 27.3	.030	.0401	33.7	.0288	.0285	- 1.0
40 Zr				.033	.0428	29.7	.0313	.0309	- 6.4
41 Nb				.036	.0458	27.2	.0344	.0335	- 2.6
42 Mo				.040	.0489	22.3	.0374	.0363	- 2.9
43 Te				.043	.0522	21.4	.0406	.0393	- 3.2
44 Ru				.047	.0558	18.7	.0438	.0425	- 3.0
45 Rh				.052	.0596	14.6	.0471	.0459	- 2.5
46 Pd				.056	.0637	13.8	.0503	.0495	- 1.6
47 Ag	.0518	.0458	- 11.6	.061	.0679	11.3	.0544	.0534	- 1.8
48 Cd				.066	.0726	10.0	.0584	.0575	- 1.5
49 In				.071	.0774	9.0	.0629	.0618	- 1.7
50 Sn				.077	.0825	7.1	.0673	.0665	- 1.2
51 Sb				.082	.0879	7.2	.0724	.0714	- 1.4
52 Te				.089	.0936	5.2	.0774	.0765	- 1.2
53 I				.096	.0996	3.8	.0828	.0820	- .97
54 Xe	.107	.0804	- 24.9	.102	.106	3.9	.0882	.0877	- .57
55 Cs	.089	.0867	- 2.6	.110	.113	2.7	.102	.0938	- 8.04
56 Ba	.093	.0934	+ .43	.117	.119	1.7	.101	.100	- .99
57 La	.101	.101	0	.125	.127	1.6	.108	.107	- .93
58 Ce				.133	.134	.75	.115	.114	- .87
59 Pr	.123	.116	- 5.7	.141	.142	.71	.123	.121	- 1.63

Table 2. Continued

Z	Bambynek et al., 1972 $\bar{\omega}_L$ table	Bambynek et al., 1972 $\bar{\omega}_L$ fit	% diff. fit from table	Mitchell & Barfoot 1981 $\bar{\omega}_L$ table	Mitchell & Barfoot 1981 $\bar{\omega}_L$ fit	% diff. fit from table	Cohen 1987 ECPSSR $\bar{\omega}_L$ table	Cohen 1987 ECPSSR $\bar{\omega}_L$ fit	% diff. fit from table
60 Nd	.131	.124	- 5.3	.150	.150	0	.130	.129	- .77
61 Pm				.158	.159	.63	.138	.137	- .73
62 Sm				.168	.168	0	.145	.145	0
63 Eu	.142	.151	+ 6.3	.177	.177	0	.154	.153	- .65
64 Gd				.187	.187	0	.162	.163	- .62
65 Tb	.194	.172	-11.3	.197	.196	- .51	.172	.172	0
66 Dy	.14	.182	+30.0	.207	.206	- .48	.181	.182	- .55
67 Ho				.217	.217	0	.191	.192	- .52
68 Er				.228	.227	- .44	.201	.202	- .50
69 Tm				.239	.238	- .42	.210	.212	+0.95
70 Yb				.250	.249	- .40	.220	.223	1.36
71 Lu				.261	.261	0	.231	.234	1.30
72 Hf				.272	.272	0	.242	.245	1.24
73 Ta	.225	.266	+18.2	.284	.284	0	.255	.257	.78
74 W				.296	.296	0	.267	.269	.75
75 Re				.308	.308	0	.280	.281	.36
76 Os				.320	.320	0	.293	.293	0
77 Ir	.30	.320	6.7	.332	.332	0	.305	.305	0
78 Pt	.32	.334	4.4	.344	.344	0	.318	.318	0
79 Au	.398	.348	-12.6	.356	.357	+ .28	.332	.331	- .30
80 Hg	.38	.362	- 4.74	.369	.369	0	.345	.343	- .58
81 Tl	.43	.376	-12.6	.381	.382	+ .26	.359	.356	- .84
82 Pb	.36	.390	8.3	.393	.394	.25	.372	.369	- .81
83 Bi	.40	.403	.75	.406	.406	0	.385	.382	- .78
84 Po							.398	.395	- .75
85 At							.411	.409	- .49
86 Rn							.423	.422	- .24
87 Fr							.436	.435	- .23
88 Ra	.451	.472	4.66				.448	.448	0
89 Ac							.461	.461	0
90 Th	.488	.498	2.05				.475	.474	- .21
91 Pa	.51	.511	.20				.487	.486	- .21
92 U	.51	.524	2.75	.515	.514	- .19	.499	.499	0
93 Np	.575	.537	- 6.61				.510	.511	+ .20
94 Pu	.581	.549	- 5.51				.522	.524	.38
95 Am							.535	.536	19
96 Cm	.531	.572	+ 7.72				.547	.548	18
97 Bk								.560	
98 Cf								.572	
99 Es								.583	
100 Fm								.595	

Table 3. Analysis of ω_M data

Z	Measurements						Theory		Fit
	Lay 1934	Jaffe 1954	Jopson et al. 1965	Konstantinov & Sazonova 1968	Hribar et al. 1982	Shatendra et al. 1984	Chen et al. (McGuire recipe)	Sarkar et al. 1981 (derived Chen 1980)	Burhop 1955 formula, renormal.
64 Gd								.0072	.0087
66 Dy								.0095	.0102
67 Ho								.0110	.0110
70 Yb							.0128	.0154	.0136
72 Hf								.0190	.0156
73 Ta								.0209	.0167
74 W							.0194	.0220	.0179
76 Os			.013±.003						.0203
78 Pt								.0257	.0230
79 Au			.024±.005	.023±.001		.025±.004		.0268	.0245
80 Hg							.0274		.0260
82 Pb			.026±.005	.029±.002	.032±.003	.028±.004			.0292
83 Bi		.037±.007	.030±.006	.035±.002			.0318		.0310
88 Ra							.0400		.0408
90 Th						.044±.004			.0453
92 U	.06					.051±.005	.0470		.0502
96 Cm							.0520		.0612
100 Fm							.0578		.0739

Table 4. Fluorescence yield values ω_K, $\bar{\omega}_L$, and $\bar{\omega}_M$ for $1 \leq Z \leq 100$, generated from fitting functions recommended in this report.

Z	ω_K	$\bar{\omega}_L$	$\bar{\omega}_M$
1 H	2.160(-5)		
2 He	9.780(-5)		
3 Li	2.928(-4)	1.39(-6)	
4 Be	6.929(-4)	4.25(-6)	
5 B	.001409	1.01(-5)	
6 C	.002575	2.05(-5)	
7 N	.004349	3.74(-5)	
8 O	.006909	6.28(-5)	
9 F	.01045	9.93(-5)	
10 Ne	.01519	1.50(-4)	
11 Na	.02133	2.17(-4)	
12 Mg	.02911	3.04(-4)	
13 Al	.03872	4.15(-4)	
14 Si	.05037	5.53(-4)	1.29(-9)
15 P	.06422	7.24(-4)	2.06(-8)
16 S	.08038	9.30(-4)	1.04(-7)
17 Cl	.09892	.00118	3.30(-7)
18 Ar	.1199	.00147	8.06(-7)
19 K	.1432	.00181	1.67(-6)
20 Ca	.1687	.00221	3.10(-6)
21 Sc	.1962	.00268	5.28(-6)
22 Ti	.2256	.00321	8.46(-6)
23 V	.2564	.00381	1.29(-5)
24 Cr	.2885	.00450	1.89(-5)
25 Mn	.3213	.00527	2.67(-5)
26 Fe	.3546	.00614	3.68(-5)
27 Co	.3880	.00711	4.96(-5)
28 Ni	.4212	.00819	6.53(-5)
29 Cu	.4538	.00939	8.45(-5)
30 Zn	.4857	.0107	1.08(-4)
31 Ga	.5166	.0122	1.35(-4)
32 Ge	.5464	.0138	1.68(-4)
33 As	.5748	.0155	2.06(-4)
34 Se	.6019	.0174	2.51(-4)
35 Br	.6275	.0195	3.02(-4)
36 Kr	.6517	.0218	3.61(-4)
37 Rb	.6744	.0242	4.28(-4)
38 Sr	.6956	.0263	5.04(-4)
39 Y	.7155	.0285	5.90(-4)
40 Zr	.7340	.0309	6.86(-4)
41 Nb	.7512	.0335	7.93(-4)
42 Mo	.7672	.0363	9.12(-4)
43 Te	.7821	.0393	.00104
44 Ru	.7958	.0425	.00119
45 Rh	.8086	.0459	.00135
46 Pd	.8204	.0495	.00153
47 Ag	.8313	.0534	.00172
48 Cd	.8415	.0575	.00193
49 In	.8508	.0618	.00217

Table 4. Continued

Z	ω_K	$\bar{\omega}_L$	$\bar{\omega}_M$
50 Sn	.8595	.0665	.00242
51 Sb	.8676	.0714	.00269
52 Te	.8750	.0765	.00298
53 I	.8819	.0820	.00330
54 Xe	.8883	.0877	.00365
55 Cs	.8942	.0938	.00401
56 Ba	.8997	.100	.00441
57 La	.9049	.107	.00484
58 Ce	.9096	.114	.00529
59 Pr	.9140	.121	.00578
60 Nd	.9181	.129	.00629
61 Pm	.9220	.137	.00685
62 Sm	.9255	.145	.00744
63 Eu	.9289	.153	.00806
64 Gd	.9320	.163	.00873
65 Tb	.9349	.172	.00943
66 Dy	.9376	.182	.0102
67 Ho	.9401	.192	.0110
68 Er	.9425	.202	.0118
69 Tm	.9447	.212	.0127
70 Yb	.9467	.223	.0136
71 Lu	.9487	.234	.0146
72 Hf	.9505	.245	.0156
73 Ta	.9522	.257	.0167
74 W	.9538	.269	.0179
75 Re	.9553	.281	.0191
76 Os	.9567	.293	.0203
77 Ir	.9580	.305	.0216
78 Pt	.9592	.318	.0230
79 Au	.9604	.331	.0245
80 Hg	.9615	.343	.0260
81 Tl	.9625	.356	.0275
82 Pb	.9634	.369	.0292
83 Bi	.9643	.382	.0310
84 Po	.9652	.395	.0328
85 At	.9659	.409	.0347
86 Rn	.9667	.422	.0366
87 Fr	.9674	.435	.0387
88 Ra	.9680	.448	.0408
89 Ac	.9686	.461	.0430
90 Th	.9691	.474	.0453
91 Pa	.9696	.486	.0477
92 U	.9701	.499	.0502
93 Np	.9706	.511	.0528
94 Pu	.9710	.524	.0555
95 Am	.9713	.536	.0583
96 Cm	.9717	.548	.0612
97 Bk	.9720	.560	.0642
98 Cf	.9722	.572	.0673
99 Es	.9725	.583	.0706
100 Fm	.9727	.595	.0739

NBS-114A (REV. 2-8C)

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report reviews x-ray fluorescence yield experimental and theoretical information beyond that available in earlier extensive reviews by Fink et al., (1966), Bambynek et al. (1972), and by Krause (1979). An annotated bibliography 1978-1988 is included. Tables and fits of the K shell fluorescence yield ω_K, and the average L and M shell fluorescence yields $\bar{\omega}_L$ and $\bar{\omega}_M$, for use in computing photon energy-absorption coefficients μ_{en}/ρ, are presented.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Auger effect; energy-absorption coefficient; fluorescence yield; ionization; photon; radiationless transitions; vacancies; x-ray.

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