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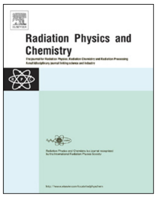

Updated database, new empirical and theoretical values of average L shell fluorescence yields of elements with $23 \leq Z \leq 96$

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ABSTRACT

In this paper, a summary of existing experimental data published in the period of time between 1954 and 2015 is reviewed and presented in a tabular form for average L shell fluorescence yields taken from different sources. First, a critical examination of these data using the *weighted average values* ϖ_{L-W} is presented. Then, an interpolation using the well-known analytical function $(\varpi_{L-W}/(1-\varpi_{L-W}))^{1/4}$ as a function of the atomic number Z is performed to deduce a new empirical average L shell fluorescence yields for elements in the range $23 \leq Z \leq 96$. New theoretical calculations based on the configuration mixing Dirac-Fock method were performed for a few elements and are presented in this work. The results are compared with other theoretical, experimental and empirical values reported in the literature and a reasonable agreement has been obtained.

1. Introduction

The analytical methods based on X-ray fluorescence have great importance for a number of practical applications in a variety of fields including atomic physics, X-ray fluorescence surface chemical analysis, medical research and treatments (such as cancer therapy) and industrial irradiation processing. Fluorescence yields are among the fundamental atomic physics parameters, because they are needed for the quantitative analysis of materials, as well as the determination of quantities such as ionization and excitation cross sections from the detected spectra. Therefore, they are also important for the computation of x-ray production cross-sections (Sampaio et al., 2015; Madeira et al., 2015). This paper focus on the average L shell fluorescence yields ϖ_L-and the deduction and improvement of their empirical values for a number of elements. Several attempts were made for measuring and calculating the L-shell fluorescence yields using a theoretical model, or by fitting the experimental data (empirical and semi-empirical formulae) for a wide range of elements. Chen et al. (1981) made theoretical calculations based on the relativistic DHS (Dirac-Hartree-Slater) model for L-subshell Coster-Kronig transitions, f_{ij} (ij = 12, 13 and 23), and fluorescence yields, $\omega_i(i = 1,2,3)$, for 25 elements in the atomic range $18 \leq Z \leq 96$. Puri et al. (1993) compiled the ω_i, f_{ij} (ij = 12, 13 and 23), and $\varpi_L$values for all elements in the atomic number range $25 \leq Z \leq 96$ using the DHS model. Later, Puri and coworkers published a several papers about the measurement and calculation of atomic parameters, in particular: X-ray relative intensities (Kumar et al. (2010); Puri (2014)), Li (i = 1–3) X-ray fluorescence and -Coster-Kronig yields (Puri and Singh (2006), Chauhan et al. (2008), Kumar and Puri (2010), (Kaur et al. (2017a)), X-ray fluorescence (XRF) and production (XRP) cross section (Puri et al. (1995), Chauhan et al. (2008), Kaur et al. (2016; 2017b)). Based on the calculation of Puri et al. (1993), average L-shell fluoresence yield (ϖ_L), average L-shell Auger yields (a_L) and the total L-

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shell x-ray fluorescence cross sections (σ_L^X) at 30 keV were calculated theoretically by Öz et al. (1999) for the elements with $25 \le Z \le 101$. Mittal et al. (1996) presented the optimum values of $\bar{\omega}_L$for all the elements in the atomic region $25 \le Z \le 95$ using polynomial and cubic form fits in the regions $25 \le Z \le 39$ and $40 \le Z \le 95$, respectively. L X-ray fuorescence cross-sections for elements $40 \le Z \le 92$ at energies 2–116 keV have been generated from an empirical relation fited to two sets of available semi-empirical and theoretical cross-sectional values by Mittal et al. (2001) using the computer program 'LCSGEN'. Kaur and Mittal (2014a, 2014b) used the AMSFYLD and MFCKYLD codes to calculate the average M-shell fluorescence yield, M sub-shell fluorescence and Coster-Kronig yields for elements with Z in the range of $60 \le Z \le 90$, $57 \le Z \le 90$ and $67 \le Z \le 90$ respectively. These calculations take into account the non-relativistic HFS values of McGuire (1972) and the relativistic Dirac-Hartree-Slater (DHS) values reported by Chen et al. (1980, 1983). Recently, the same research groupe (Bansal et al. (2017, 2018)) measured the L and M sub-shell fluorescence cross-section for elements Z = 62–67 and Z = 78–92 respectively, at tuned synchrotron photon energies.

Important works were published for measured and calculated values of the L-subshell Coster-Kronig transitions and fluorescence yields for a wide range of elements in a tabular form. Fink et al. (1966) reviewed the experimental ω_i and f_{ij}data published before 1966. Bambynek et al. (1972) presented, in a review article, a collection of the experimental values of $\bar{\omega}_L$ for elements in the region $23 \le Z \le 96$ and L-subshell fluorescence yields from xenon to curium ($54 \le Z \le 96$) and the Coster-Kronig transitions from barium to curium. These tables contain 83 values of average L-shell fluorescence yields. Krause (1979) calculated the semi-empirical fitted values of the L subshell fluorescence yields and the Coster-Kronig transitions using all experimental data published before 1979 for the elements in the atomic range of $12 \le Z \le 110$. Hubbell et al. (1994) compiled more recent experimental values in a table regrouping the data published in the period 1978 to 1993 (the table has 107 values for $\bar{\omega}_L$) for elements with $26 \le Z \le 92$, which were obtained from a semi-empirical relation including the available experimental data. Campbell (2003) compiled the more recent experimental values, obtained in the period of 1968–2002, and published the reassembled data for the elements with $39 \le Z \le 96$ in a table form. In 2014 our research group (Kahoul et al. (2014)) interpolated the weighted and unweighted mean values of the experimental data by using the analytical function $(\bar{\omega}_M/(1-\bar{\omega}_M))^{1/4}$ as function of the atomic number (Z) to deduce the empirical average M-shell fluorescence yield in the atomic range of $70 \le Z \le 92$. In the same paper we have also employed the famous formula $\bar{\omega}_M = A\times (Z-13)^4$to generalize the average M-shell fluorescence yield for elements with $19 \le Z \le 100$. Recentlly the same scientific group (Sahnoune et al. (2016)) presented a summary of experimental data for the L_i subshell fluorescence yields in a tabular form. These data consists of about 1333 experimental values (382 for ω_{L1}, 488 for $\omega_{L2}$and 463 for ω_{L3}). Also, these experimental data were used to determine the empirical L_i subshell fluorescence yields of elements in the atomic range $40 \le Z \le 96$ for ω_{L1} ω_{L2}, and $23 \le Z \le 96$ for ω_{L3} emploing a polynomial interpolation. For the empirical formulae, Wentzel (1927) gave the first relation for the approximation of the K shell fluorescence yields as a function of Z, namely ($\omega_K = 10^{-6}Z^4/(1+10^{-6}Z^4)$). Based on the Wentzel equation, Broll (1986) proposed the empirical formula $\omega_{L3} = (1 + b/Z^4)^{-1}$ for the elements with $30 \le Z \le 90$, with $b= 9\times 10^7$for $30 \le Z \le 70$ and $b= (9-0.1\times(Z-70))\times 10^7$ for $70 \le Z \le 90$. Mitchell and Barfoot (1981) used the well-known formula $(\bar{\omega}_L/(1-\bar{\omega}_L))^{1/4} = \sum_{i=1}^{3} a_i Z^i$to calculate average L shell fluorescence yields for selected targets between $23 \le Z \le 96$ with parameters a_i($a_0 = 3.26968\times10^{-1}$, $a_1 = -2.42879\times10^{-3}$, $a_2 = 1.7166\times10^{-4}$ and $a_3 = -6.96583\times10^{-7}$). In 1987, Cohen (1987) used the same formula and the best available data sets to produce a consistent and reliable set of average L shell fluorescence yields for all elements for $_{28}$Ni to $_{96}$Cm (with: $a_0 = 1.7765\times10^{-1}$, $a_1 = 2.98937\times10^{-3}$, $a_2 = 8.91297\times10^{-5}$ and $a_3 = -2.67184\times10^{-7}$). In a recent paper (Aylikçi et al. (2015)), our research group presente the semi-empirical and empirical L-subshell Coster-Kronig transition (f_{12}, f_{13}, f_{23}) and fluorescence yield (ω_{Li} , i= 1, 2, 3) values for the elements with the atomic number $50 \le Z \le 92$. The same research group (Bendjedi et al. (2015) used the ratio of the empirical x-ray production cross section to the ionization cross section $\sigma_{emp}^X/\sigma_{emp}^I$by proton impact and the formula $(\bar{\omega}_L/(1-\bar{\omega}_L))^{1/4} = a + bZ$ with $a= -0.02177$ and $b= 0.01073$to deduce the empirical average L-shell fluorescence yields for element from zirconium to uranium. In this study, a summary of the experimental data of the average L-shell fluorescence yields that are taken directly from different sources published in the period 1954 to 2015 is presented in a tabular form for elements in the region $23 \le Z \le 96$. We added the weighted average values ($\bar{\omega}_{L-W}$) to these data consisting of about 316 experimental values. Then, using the weighted-mean values of these experimental data and $(\bar{\omega}_L/(1-\bar{\omega}_L))^{1/4} = \sum_i b_i Z^i$, we deduced the empirical average L-shell fluorescence yields of elements in the range $23 \le Z \le 96$. New theoretical calculations based on the configuration mixing Dirac-Fock method were performed for a few elements and are presented in this work. Finally, the results were presented in a tabular form and compared with theoretical, experimental and other semi-empirical fluorescence yield values.

2. Survey on 1994–2015 experimental works

From 1994 until 2015, an important number of experimental measurements for the L shell fluorescence yields ($\bar{\omega}_L$) have been performed but no review articles are published concerning databases of experimental $\bar{\omega}_L$. Several authors have deduced $\bar{\omega}_L$ values using different methods; these methods vary according to the ionization process, the target material, the detectors, etc. In 1994, Rao et al. (1994) measured the total L X-ray fluorescence cross section for the elements $_{51}$Sb, $_{50}$Sn, $_{49}$In, $_{48}$Cd, $_{47}$Ag and $_{46}$Pd excited by 6.47, 7.57 and 8.12 keV photons using an X-ray tube with a modified secondary exciter system. These values have been further used to deduce the values of the average L-shell fluorescence yields. Average L-shell fluorescence yields for $_{60}$Nb, $_{70}$Yb, $_{80}$Hg and $_{90}$Th were measured by Allawadhi et al. (1996) using an experimental system consisting of a double reflection annular source and secondary target systems to produce different excitation energies. Ertuğrul (1996) proposed experimental values of average L-shell fluorescence yields of lanthanides such as $_{57}$La, $_{58}$Ce, $_{59}$Pr, $_{60}$Nd, $_{62}$Sm, $_{63}$Eu, $_{64}$Gd, $_{65}$Tb, $_{66}$Dy, $_{67}$Ho and $_{68}$Er by exciting the elemental targets with 59.4 keV photons from a ^{241}Am source. In fact this radioisotope has been widely used in measurements of atomic parameters with radioactive source for that excitation energy: The L-shell fluorescence yields of seven elements in the atomic range $65 \le Z \le 74$ ($_{65}$Tb, $_{66}$Dy, $_{67}$Ho, $_{68}$Er, $_{70}$Yb, $_{73}$Ta and $_{74}$W) were measured by Şimşek et al. (1998) using a Ge(Li) detector, the targets were excited using 59.5 keV γ-rays from an Am-241 radioactive source of strength 100 mCi. Şimşek et al. (1999a,b) also investigated the L-shell fluorescence yields for $_{56}$Ba, $_{57}$La, $_{58}$Ce, $_{59}$Pr, $_{60}$Nd, $_{62}$Sm and $_{64}$Gd elements using this radioactive source. The same group < comment message = The citation "Simsek et al., 1999a" has been changed to match the author name/date in the reference list. Please check here and in subsequent occurrences. > (< / comment > < comment message = The citations "Simsek et al., 1999a" has been changed to match the date in the reference list. Please check here and in subsequent occurrences. > < /comment > Şimşek et al., 1999a) measured the $\bar{\omega}_L$ for element in the atomic range $79 \le Z \le 92$ ($_{79}$Au, $_{80}$Hg, $_{81}$Tl, $_{82}$Pb, $_{83}$Bi, $_{90}$Th and $_{92}$U). Durak and Özdemir (2000) reported the results of the measurement of all elements covering the range of atomic numbers $55 \le Z \le 68$ ($_{55}$Cs, $_{56}$Ba, $_{57}$La, $_{58}$Ce, $_{59}$Pr, $_{60}$Nd, $_{62}$Sm, $_{65}$Tb, $_{66}$Dy, $_{67}$Ho and $_{68}$Er). Lα, Lβ, Lγ and Lι X-ray production cross-sections for elements in the atomic range $70 \le Z \le 92$ ($_{70}$Yb, $_{72}$Hf, $_{74}$W, $_{76}$Os, $_{80}$Hg, $_{81}$Tl, $_{82}$Pb, $_{90}$Th and $_{92}$U) were measured by Özdemir and Durak (2000) using a filtred source. Then, the average L-shell fluorescence yields had been calculated using the experimental

L-shell cross-section values and the photoionization cross-section values calculated from the table of Scofield (1974) by authors (Özdemir and Durak, 2000). Söğüt et al. (2003) determined the average L-shell fluorescence yields of $_{90}$Th and $_{92}$U using the x-ray production cross section measured also with a ^{241}Am source and a Si(Li) detector. Küçükönder et al. (2004) measured the average L-X-ray fluorescence yields in heavy elements such as $_{72}$Hf, $_{73}$Ta, $_{74}$W, $_{75}$Re, $_{78}$Pt, $_{79}$Au, $_{80}$Hg, $_{81}$Tl, $_{82}$Pb, $_{83}$Bi, $_{90}$Th and $_{92}$U with the same system. Cengiz et al. (2010) measured the average L-shell fluorescence yields of elements $_{74}$W, $_{75}$Re, $_{76}$Os and $_{78}$Pt where the L X-rays were counted by an Ultra-LEGe detector with a resolution of 150 eV at 5.9 keV. Durdu and Kucukonder (2012) measured the $\varpi_L$for $_{62}$Sm and $_{68}$Eu. Aksoy et al. (2012) presented experimental average L-shell fluorescence yields for $_{73}$Ta and $_{74}$W by exciting the pure elementals and their compounds targets with a ^{241}Am annular source and detected using an Ultra-LEGe detector and with resolution of 150 eV at 5.9 keV. The average L-shell fluorescence yields of some rare earth elements ($_{59}$Pr, $_{62}$Sm, $_{64}$Gd, $_{66}$Dy, $_{67}$Ho and $_{70}$Yb) were measured by Punchithay and Balakrishna (2013) using a HPGe detector. The average L-shell fluorescence yields for plomb ($_{82}$Pb) were measured by Doğan et al. (2015). Other types of radioactive isotopes have been used as excitation sources aswell: Ertuğrul (2002) obtained the average L-shell fluorescence yields for elements $_{40}$Zr, $_{41}$Nb, $_{42}$Mo, $_{46}$Pd, $_{47}$Ag, $_{48}$Cd, $_{49}$In, $_{50}$Sn, $_{51}$Sb, $_{52}$Te, $_{53}$I and $_{55}$Cs from measurements of x-ray production cross section at 5.96 keV incident photons using a ^{55}Fe annular source with 50 mCi. Apaydin et al. (2008) measured the average L-shell fluorescence yields of elements in the region $75 \le Z \le 92$ ($_{75}$Re, $_{76}$Os, $_{77}$Ir, $_{78}$Pt, $_{79}$Au, $_{80}$Hg, $_{81}$Tl, $_{82}$Pb, $_{83}$Bi, $_{90}$Th and $_{92}$U) using excitation energy of 123.6 keV with a ^{57}Co annular source.

3. Data analysis

The present database for the average L-shell fluorecence yields were taken from the referenced papers and compilations:

- Bambynek et al. (1972), compilation of 83 experimental data of average L-shell fluorescence yields for elements in the region $23 \le Z \le 96$ published in the period 1934 to 1972. These tables contain 25 values without associated errors. We have excluded all values that the errors were not reported in the paper.
- Hubbell et al. (1994), regrouped more recent experimental from iron to uranium ($26 \le Z \le 92$); a total of 107 average fluorescence yields are then collected from the literature covering the period 1978 to 1993.
- Six papers (Budick and Derman (1972); Nix et al. (1972); Yeluri et al. (1972), Wood et al. (1972), Weksler and de Pinho (1973) and Hribar et al. (1977)) are not cited neither by Bambynek et al. (1972) nor by Hubbell et al. (1994), published in the period 1972 to 1978 (about 14 values).
- Own compilation (135 values), gathering the data published from 1994 to 2015 (Rao et al. (1994); Allawadhi et al. (1996); Ertuğrul (1996); Şimşek et al. (1998, 1999a,b, 1999a); Durak and Özdemir (2000); Özdemir and Durak (2000); Ertuğrul (2002); Söğüt et al. (2003); Küçükönder et al. (2004); Apaydin et al. (2008); Cengiz et al. (2010); Durdu and Kucukonder (2012); Aksoy et al. (2012); Punchithay and Balakrishna (2013); Doğan et al. (2015)).

These reported values were taken in a three to fourth-digit format with their associated errors. Table 1 give a summary of the compiled database of average L-shell fluorescence yields for elements from $_{23}$V to $_{96}$Cm. In the same table it has been presented the references from which databases were extracted. In the cases where we have N measurments $(\varpi_L)_1(\varpi_L)_2(\varpi_L)_3$, …, $(\varpi_L)_N$ with uncertaities $\Delta(\varpi_L)_1$, $\Delta(\varpi_L)_2$, $\Delta(\varpi_L)_3$, …., $\Delta(\varpi_L)_N$of average L-shell fluorescence yield for a given element $_Z$X, the *weighted average values* given by the following formula:

Table 1
The summary of the experimental average L-shell fluorescence yields for elements from $_{23}$V to $_{96}$Cm, the *weighted average value* (ϖ_{L-W}) and the uncertainty on ϖ_{L-W}.

Z	$\varpi_L \pm \Delta(\varpi_L)$	References	ϖ_{L-W}
23, V	0.00235 ± 0.00025	(Konstantinov and Perepelkin, 1960)	0.0024 ± 0.0003
25, Mn	0.00295 ± 0.0004	(Konstantinov and Sazonova, 1965)	0.0030 ± 0.0004
26, Fe	0.0063 ± 0.0010	McNeir et al. (1991)	0.0063 ± 0.0010
28, Ni	0.0083 ± 0.0016	Duggan et al. (1985)	0.0088 ± 0.0011
	0.0091 ± 0.0014	McNeir et al. (1991)	
29, Cu	0.0098 ± 0.0019	Duggan et al. (1985)	0.0103 ± 0.0009
	0.0105 ± 0.0010	McNeir et al. (1991)	
30, Zn	0.0117 ± 0.0018	McNeir et al. (1991)	0.0117 ± 0.0018
31, Ga	0.0064 ± 0.0004	(Konstantinov and Perepelkin, 1960)	0.0067 ± 0.004
	0.0129 ± 0.0019	McNeir et al. (1991)	
32, Ge	0.0139 ± 0.0021	McNeir et al. (1991)	0.0139 ± 0.0021
33, As	0.0156 ± 0.0023	Duggan et al. (1985)	0.0156 ± 0.0023
36, Kr	0.0210 ± 0.002	(Spiler and Hribar, 1979)	0.0210 ± 0.0020
37, Rb	0.0110 ± 0.001	Hohmuth et al. (1963)	0.0113 ± 0.0009
	0.0090 ± 0.002	Hohmuth et al. (1963)	
	0.0186 ± 0.0028	Duggan et al. (1985)	
38, Sr	0.0213 ± 0.0032	Duggan et al. (1985)	0.0213 ± 0.0032
39, Y	0.0315 ± 0.0028	(Bailey and Swedlund, 1967)	0.0289 ± 0.0022
	0.0246 ± 0.0036	Sera et al. (1980)	
40, Zr	0.0282 ± 0.0014	Singh et al. (1983)	0.0281 ± 0.0013
	0.033 ± 0.0049	Duggan et al. (1985)	
	0.026 ± 0.003	(Ertuğrul, 2002)	
41, Nb	0.029 ± 0.0014	Singh et al. (1983)	0.0307 ± 0.0012
	0.037 ± 0.003	Garg et al. (1992)	
	0.032 ± 0.003	(Ertuğrul, 2002)	
42, Mo	0.0316 ± 0.0016	Singh et al. (1983)	0.0334 ± 0.0013
	0.0380 ± 0.003	Garg et al. (1992)	
	0.035 ± 0.003	(Ertuğrul, 2002)	
45, Rh	0.051 ± 0.005	Garg et al. (1992)	0.0510 ± 0.005
46, Pd	0.039 ± 0.007	Duggan et al. (1985)	0.0501 ± 0.0022
	0.054 ± 0.005	Garg et al. (1992)	
	0.057 ± 0.006	Rao et al. (1994)	
	0.049 ± 0.003	(Ertuğrul, 2002)	
47, Ag	0.029 ± 0.003	Bertolini et al. (1954)	0.0496 ± 0.0011
	0.047 ± 0.002	Bertrand et al. (1959)	
	0.0659 ± 0.0037	(Bailey and Swedlund, 1967)	
	0.046 ± 0.003	Budick and Derman (1972)	
	0.0556 ± 0.002	Singh et al. (1983)	
	0.057 ± 0.005	Garg et al. (1992)	
	0.061 ± 0.006	Rao et al. (1994)	
	0.051 ± 0.005	(Ertuğrul, 2002)	
48, Cd	0.425 ± 0.0064	Nix et al. (1972)	0.0802 ± 0.0015
	0.0569 ± 0.002	Singh et al. (1983)	
	0.066 ± 0.005	Garg et al. (1992)	
	0.067 ± 0.005	Rao et al. (1994)	
	0.056 ± 0.004	(Ertuğrul, 2002)	
49, In	0.0571 ± 0.0029	Singh et al. (1983)	0.0706 ± 0.0015
	0.075 ± 0.005	Garg et al. (1992)	
	0.077 ± 0.002	Rao et al. (1994)	
	0.065 ± 0.006	(Ertuğrul, 2002)	
50, Sn	0.081 ± 0.012	Sera et al. (1980)	0.0786 ± 0.0018
	0.079 ± 0.006	Garg et al. (1992)	
	0.080 ± 0.002	Rao et al. (1994)	
	0.069 ± 0.005	(Ertuğrul, 2002)	
51, Sb	0.083 ± 0.006	Garg et al. (1992)	0.0833 ± 0.0018
	0.084 ± 0.002	Rao et al. (1994)	
	0.075 ± 0.007	(Ertuğrul, 2002)	
52, Te	0.073 ± 0.007	Budick and Derman (1972)	0.0813 ± 0.0040
	0.093 ± 0.007	Garg et al. (1992)	
	0.078 ± 0.007	(Ertuğrul, 2002)	
53, I	0.077 ± 0.004	Singh et al. (1983)	0.0792 ± 0.0035
	0.086 ± 0.007	(Ertuğrul, 2002)	
54, Xe	0.103 ± 0.01	Fink and Robinson (1955)	0.1010 ± 0.0028
	0.11 ± 0.01	Hohmuth and Winter (1964)	
	0.100 ± 0.003	Hribar et al. (1977)	
55, Cs	0.089 ± 0.013	Nix et al. (1972)	0.0948 ± 0.0027

(*continued on next page*)

Table 1 (*continued*)

Z	$\bar{\omega}_L \pm \Delta(\bar{\omega}_L)$	References	$\bar{\omega}_{L-W}$
	0.096 ± 0.003	Durak and Özdemir (2000)	
	0.090 ± 0.007	(Ertuğrul, 2002)	
56, Ba	0.093 ± 0.012	Nix et al. (1972)	0.1071 ± 0.0022
	0.110 ± 0.003	Singh et al. (1990)	
	0.112 ± 0.007	(Simsek et al., 1999a,b)	
	0.102 ± 0.004	Durak and Özdemir (2000)	
57, La	0.092 ± 0.007	Hohmuth et al. (1963)	0.1123 ± 0.0020
	0.110 ± 0.015	Nix et al. (1972)	
	0.118 ± 0.003	Singh et al. (1990)	
	0.108 ± 0.008	Mann et al. (1990)	
	0.110 ± 0.009	(Ertuğrul, 1996)	
	0.135 ± 0.009	(Simsek et al., 1999a,b)	
	0.106 ± 0.004	Durak and Özdemir (2000)	
58, Ce	0.110 ± 0.015	Nix et al. (1972)	0.1201 ± 0.0025
	0.123 ± 0.017	Nix et al. (1972)	
	0.121 ± 0.004	Singh et al. (1990)	
	0.108 ± 0.008	Mann et al. (1990)	
	0.119 ± 0.009	(Ertuğrul, 1996)	
	0.141 ± 0.007	(Simsek et al., 1999a,b)	
	0.114 ± 0.005	Durak and Özdemir (2000)	
59, Pr	0.132 ± 0.004	Singh et al. (1990)	0.1296 ± 0.0026
	0.127 ± 0.009	Mann et al. (1990)	
	0.125 ± 0.009	(Ertuğrul, 1996)	
	0.145 ± 0.012	(Simsek et al., 1999a,b)	
	0.123 ± 0.005	Durak and Özdemir (2000)	
	0.142 ± 0.011	(Punchithay and Balakrishna, 2013)	
60, Nd	0.143 ± 0.004	Singh et al. (1990)	0.1333 ± 0.0017
	0.131 ± 0.009	Mann et al. (1990)	
	0.128 ± 0.006	Allawadhi et al. (1996)	
	0.134 ± 0.007	Allawadhi et al. (1996)	
	0.129 ± 0.006	Allawadhi et al. (1996)	
	0.131 ± 0.006	Allawadhi et al. (1996)	
	0.137 ± 0.007	Allawadhi et al. (1996)	
	0.134 ± 0.007	Allawadhi et al. (1996)	
	0.125 ± 0.006	Allawadhi et al. (1996)	
	0.131 ± 0.006	Allawadhi et al. (1996)	
	0.123 ± 0.006	Allawadhi et al. (1996)	
	0.132 ± 0.008	(Ertuğrul, 1996)	
	0.161 ± 0.008	(Simsek et al., 1999a,b)	
	0.127 ± 0.006	Durak and Özdemir (2000)	
61, Pm	0.131 ± 0.017	Nix et al. (1972)	0.1310 ± 0.0170
62, Sm	0.161 ± 0.005	Singh et al. (1990)	0.1481 ± 0.0023
	0.149 ± 0.010	Mann et al. (1990)	
	0.144 ± 0.005	Stotzel et al. (1992)	
	0.146 ± 0.010	(Ertuğrul, 1996)	
	0.174 ± 0.012	(Simsek et al., 1999a,b)	
	0.142 ± 0.005	Durak and Özdemir (2000)	
	0.143 ± 0.007	(Durdu and Küçükönder, 2012)	
	0.137 ± 0.008	(Durdu and Küçükönder, 2012)	
	0.149 ± 0.012	(Punchithay and Balakrishna, 2013)	
63, Eu	0.126 ± 0.010	Wood et al. (1972)	0.1536 ± 0.0033
	0.145 ± 0.013	Wood et al. (1972)	
	0.164 ± 0.005	Singh et al. (1990)	
	0.148 ± 0.010	Mann et al. (1990)	
	0.150 ± 0.012	(Ertuğrul, 1996)	
	0.153 ± 0.007	(Durdu and Küçükönder, 2012)	
64,Gd	0.142 ± 0.023	Nix et al. (1972)	0.1750 ± 0.0036
	0.184 ± 0.005	Singh et al. (1990)	
	0.165 ± 0.010	Mann et al. (1990)	
	0.161 ± 0.013	(Ertuğrul, 1996)	
	0.170 ± 0.009	(Simsek et al., 1999a,b)	
	0.167 ± 0.012	(Punchithay and Balakrishna, 2013)	
65, Tb	0.194 ± 0.027	(Nix et al., 1972)	0.1794 ± 0.0033
	0.192 ± 0.006	Singh et al. (1990)	
	0.168 ± 0.010	Mann et al. (1990)	
	0.175 ± 0.014	(Ertuğrul, 1996)	
	0.182 ± 0.010	(Şimşek et al., 1998)	
	0.173 ± 0.005	Durak and Özdemir (2000)	

Table 1 (*continued*)

Z	$\bar{\omega}_L \pm \Delta(\bar{\omega}_L)$	References	$\bar{\omega}_{L-W}$
66, Dy	0.14 ± 0.02	(Zimmerli and Flammersfeld, 1963)	0.1847 ± 0.0033
	0.194 ± 0.027	Nix et al. (1972)	
	0.199 ± 0.006	Singh et al. (1990)	
	0.175 ± 0.010	Mann et al. (1990)	
	0.174 ± 0.009	(Ertuğrul, 1996)	
	0.190 ± 0.009	(Şimşek et al., 1998)	
	0.179 ± 0.007	Durak and Özdemir (2000)	
	0.182 ± 0.012	(Punchithay and Balakrishna, 2013)	
67, Ho	0.267 ± 0.010	Bhan et al. (1986)	0.2101 ± 0.0033
	0.217 ± 0.006	Singh et al. (1990)	
	0.193 ± 0.010	Mann et al. (1990)	
	0.191 ± 0.014	(Ertuğrul, 1996)	
	0.200 ± 0.010	(Şimşek et al., 1998)	
	0.197 ± 0.007	Durak and Özdemir (2000)	
	0.195 ± 0.011	(Punchithay and Balakrishna, 2013)	
68, Er	0.223 ± 0.007	Singh et al. (1990)	0.2093 ± 0.0035
	0.205 ± 0.010	Mann et al. (1990)	
	0.207 ± 0.014	(Ertuğrul, 1996)	
	0.208 ± 0.006	(Şimşek et al., 1998)	
	0.200 ± 0.007	Durak and Özdemir (2000)	
69, Tm	0.228 ± 0.007	Singh et al. (1990)	0.2280 ± 0.0070
70, Yb	0.239 ± 0.009	Singh et al. (1990)	0.2277 ± 0.0030
	0.228 ± 0.010	Mann et al. (1990)	
	0.224 ± 0.011	Allawadhi et al. (1996)	
	0.219 ± 0.011	Allawadhi et al. (1996)	
	0.210 ± 0.010	Allawadhi et al. (1996)	
	0.229 ± 0.011	Allawadhi et al. (1996)	
	0.227 ± 0.011	Allawadhi et al. (1996)	
	0.233 ± 0.011	Allawadhi et al. (1996)	
	0.235 ± 0.008	(Şimşek et al., 1998)	
	0.223 ± 0.009	Özdemir and Durak (2000)	
	0.232 ± 0.011	(Punchithay and Balakrishna, 2013)	
71,Lu	0.29 ± 0.05	Gizon et al. (1968)	0.2430 ± 0.0057
	0.246 ± 0.007	Singh et al. (1990)	
	0.235 ± 0.010	Mann et al. (1990)	
72, Hf	0.255 ± 0.007	Singh et al. (1990)	0.2513 ± 0.0043
	0.245 ± 0.006	Özdemir and Durak (2000)	
	0.266 ± 0.012	(Küçükönder et al., 2004)	
73, Ta	0.225 ± 0.01	Rao and Crasemann (1966)	0.2657 ± 0.0036
	0.280 ± 0.020	Singh et al. (1985)	
	0.273 ± 0.008	Shatendra et al. (1985)	
	0.316 ± 0.013	Bhan et al. (1986)	
	0.274 ± 0.008	Singh et al. (1990)	
	0.254 ± 0.012	Mann et al. (1990)	
	0.252 ± 0.011	(Şimşek et al., 1998)	
	0.277 ± 0.012	(Küçükönder et al., 2004)	
	0.256 ± 0.013	Aksoy et al. (2012)	
74, W	0.290 ± 0.020	Singh et al. (1985)	0.2749 ± 0.0033
	0.296 ± 0.021	Shatendra et al. (1985)	
	0.285 ± 0.008	Singh et al. (1990)	
	0.272 ± 0.013	Mann et al. (1990)	
	0.283 ± 0.018	(Şimşek et al., 1998)	
	0.269 ± 0.005	Özdemir and Durak (2000)	
	0.316 ± 0.015	(Küçükönder et al., 2004)	
	0.245 ± 0.012	Cengiz et al. (2010)	
	0.276 ± 0.010	Aksoy et al. (2012)	
75, Re	0.286 ± 0.008	Singh et al. (1990)	0.2772 ± 0.0058
	0.324 ± 0.017	(Küçükönder et al., 2004)	
	0.235 ± 0.014	Apaydin et al. (2008)	
	0.263 ± 0.013	Cengiz et al. (2010)	
76, Os	0.293 ± 0.006	Özdemir and Durak (2000)	0.2851 ± 0.0052
	0.252 ± 0.015	Apaydin et al. (2008)	
	0.271 ± 0.014	Cengiz et al. (2010)	
77, Ir	0.30 ± 0.04	Wilken (1968)	0.3040 ± 0.0081
	0.326 ± 0.010	Singh et al. (1990)	
	0.255 ± 0.015	Apaydin et al. (2008)	
78, Pt	0.32 ± 0.02	Jopson et al. (1962)	0.3157 ± 0.0065
	0.328 ± 0.010	Singh et al. (1990)	
	0.371 ± 0.020	(Küçükönder et al., 2004)	
	0.258 ± 0.015	Apaydin et al. (2008)	

(*continued on next page*)

Table 1 (*continued*)

Z	$\varpi_L \pm \Delta(\varpi_L)$	References	ϖ_{L-W}
	0.312 ± 0.016	Cengiz et al. (2010)	
79, Au	0.374 ± 0.018	Jopson et al. (1963)	0.3528 ± 0.0049
	0.430 ± 0.012	(Di Lazzaro, 1965)	
	0.360 ± 0.020	Singh et al. (1985)	
	0.336 ± 0.023	Shatendra et al. (1985)	
	0.345 ± 0.014	Bhan et al. (1986)	
	0.330 ± 0.010	Singh et al. (1990)	
	0.338 ± 0.016	Mann et al. (1990)	
	0.325 ± 0.016	(Simsek et al., 1999a,b)	
	0.387 ± 0.022	(Küçükönder et al., 2004)	
	0.272 ± 0.019	Apaydin et al. (2008)	
80, Hg	0.24 ± 0.04	Jaffe (1954)	0.3446 ± 0.0039
	0.371 ± 0.035	(Haynes and Achor, 1955)	
	0.34 ± 0.04	(Schmied and Fink, 1957)	
	0.410 ± 0.04	Nall et al. (1960)	
	0.40 ± 0.05	Rao and Crasemann (1965)	
	0.39 ± 0.06	Rao and Crasemann (1965)	
	0.40 ± 0.04	(Kloppenburg, 1969)	
	0.380 ± 0.020	Singh et al. (1985)	
	0.323 ± 0.020	(Shatendra et al. (1985))	
	0.346 ± 0.017	Mann et al. (1990)	
	0.351 ± 0.017	Allawadhi et al. (1996)	
	0.335 ± 0.017	Allawadhi et al. (1996)	
	0.346 ± 0.017	Allawadhi et al. (1996)	
	0.356 ± 0.017	Allawadhi et al. (1996)	
	0.362 ± 0.018	Allawadhi et al. (1996)	
	0.342 ± 0.017	Allawadhi et al. (1996)	
	0.352 ± 0.017	Allawadhi et al. (1996)	
	0.353 ± 0.014	(Simsek et al., 1999a,b)	
	0.343 ± 0.007	Özdemir and Durak (2000)	
	0.311 ± 0.020	(Küçükönder et al., 2004)	
	0.292 ± 0.020	Apaydin et al. (2008)	
81, Tl	0.50 ± 0.02	Burde and Cohen (1956)	0.3636 ± 0.0043
	0.48 ± 0.03	Risch (1958)	
	0.41 ± 0.04	Ramaswamy (1962)	
	0.390 ± 0.030	Singh et al. (1985)	
	0.337 ± 0.023	Shatendra et al. (1985)	
	0.365 ± 0.015	Bhan et al. (1986)	
	0.354 ± 0.010	Singh et al. (1990)	
	0.349 ± 0.017	Mann et al. (1990)	
	0.365 ± 0.019	(Simsek et al., 1999a,b)	
	0.356 ± 0.007	Özdemir and Durak (2000)	
	0.329 ± 0.020	(Küçükönder et al., 2004)	
	0.314 ± 0.022	Apaydin et al. (2008)	
82, Pb	0.39 ± 0.02	Patronis et al. (1957)	0.3707 ± 0.0045
	0.36 ± 0.02	Jopson et al. (1962)	
	0.297 ± 0.030	(Rao, 1968)	
	0.34 ± 0.030	Yeluri et al. (1972)	
	0.45 ± 0.040	Yeluri et al. (1972)	
	0.380 ± 0.030	Singh et al. (1985)	
	0.391 ± 0.027	Shatendra et al. (1985)	
	0.395 ± 0.019	Bhan et al. (1986)	
	0.374 ± 0.010	Singh et al. (1990)	
	0.361 ± 0.018	Mann et al. (1990)	
	0.378 ± 0.022	(Simsek et al., 1999a,b)	
	0.369 ± 0.008	Özdemir and Durak (2000)	
	0.399 ± 0.024	(Küçükönder et al., 2004)	
	0.345 ± 0.029	Apaydin et al. (2008)	
	0.346 ± 0.019	(Doğan et al., 2015)	
83, Bi	0.51 ± 0.03	Burde and Cohen (1956)	0.3822 ± 0.005
	0.38 ± 0.02	(Fink, 1957)	
	0.38 ± 0.04	(Lee and thesis, 1958)	
	0.330 ± 0.016	(Freund and Fink, 1969)	
	0.410 ± 0.023	Shatendra et al. (1985)	
	0.411 ± 0.015	(Bhan et al., 1986)	
	0.374 ± 0.010	Singh et al. (1990)	
	0.367 ± 0.017	Mann et al. (1990)	
	0.391 ± 0.013	(Simsek et al., 1999a,b)	
	0.394 ± 0.020	(Küçükönder et al., 2004)	
	0.369 ± 0.031	Apaydin et al. (2008)	
	0.364 ± 0.02	Weksler and de Pinho (1973)	
88, Ra	0.48 ± 0.012	(Halley and Engelkemeir, 1964)	0.4714 ± 0.0109
	0.40 ± 0.03	Gil et al. (1965)	
	0.52 ± 0.05	Booth et al. (1956)	
90, Th	0.488 ± 0.008	(Halley and Engelkemeir, 1964)	0.4759 ± 0.0043
	0.490 ± 0.015	Singh et al. (1985)	
	0.407 ± 0.017	Shatendra et al. (1985)	
	0.456 ± 0.023	Bhan et al. (1986)	
	0.473 ± 0.010	Singh et al. (1990)	
	0.473 ± 0.024	Allawadhi et al. (1996)	
	0.499 ± 0.025	Allawadhi et al. (1996)	
	0.481 ± 0.024	Allawadhi et al. (1996)	
	0.453 ± 0.023	Allawadhi et al. (1996)	
	0.491 ± 0.024	Allawadhi et al. (1996)	
	0.483 ± 0.024	Allawadhi et al. (1996)	
	0.472 ± 0.025	(Simsek et al., 1999a,b)	
	0.474 ± 0.013	Özdemir and Durak (2000)	
	0.530 ± 0.031	(Küçükönder et al., 2004)	
	0.451 ± 0.036	Apaydin et al. (2008)	
91, Pa	0.52 ± 0.03	Adamson et al. (1962)	0.5128 ± 0.0240
	0.50 ± 0.04	(Boyer and Barat, 1968)	
92, U	0.478 ± 0.009	(Halley and Engelkemeir, 1964)	0.4839 ± 0.0047
	0.603 ± 0.04	(Di Lazzaro, 1965)	
	0.570 ± 0.019	Byrne et al. (1968)	
	0.42 ± 0.01	Salgueiro et al. (1968)	
	0.53 ± 0.06	Zender et al. (1969)	
	0.600 ± 0.04	Singh et al. (1985)	
	0.609 ± 0.042	Shatendra et al. (1985)	
	0.492 ± 0.025	(Bhan et al., 1986)	
	0.489 ± 0.010	Singh et al. (1990)	
	0.514 ± 0.038	(Simsek et al., 1999a,b)	
	0.499 ± 0.018	Özdemir and Durak (2000)	
	0.546 ± 0.033	(Söğüt et al., 2003)	
	0.546 ± 0.033	(Küçükönder et al., 2004)	
	0.481 ± 0.038	Apaydin et al. (2008)	
93, Np	0.66 ± 0.08	(Akalaev et al., 1964)	0.49746 ± 0.0096
	0.49 ± 0.01	Salgueiro et al. (1961)	
	0.576 ± 0.04	Weksler and de Pinho (1973)	
94, Pu	0.540 ± 0.009	(Halley and Engelkemeir, 1964)	0.5524 ± 0.0067
	0.73 ± 0.10	(Akalaev et al., 1964)	
	0.566 ± 0.010	Byrne et al. (1968)	
96, Cm	0.531 ± 0.010	(Halley and Engelkemeir, 1964)	0.5310 ± 0.010

$$\varpi_{L-W} = \left(\sum_{j=1}^{N} (\Delta(\varpi_L)_j)^{-2}\right)^{-1} \sum_{j=1}^{N} \left[\frac{(\varpi_L)_j}{(\Delta(\varpi_L)_j)^{2}}\right] \quad (1)$$

Where the uncertainty on $\varpi_{L-W}$is:

$$\left(\sum_{j=1}^{N} (\Delta(\varpi_L)_j)^{-2}\right)^{-\frac{1}{2}} \quad (2)$$

These *weighted average values* and the uncertainty on ϖ_{L-W}have been also added in the same table. We have rejected the cited experimental results where uncertainties were not reported. It is worth noting that in our database, all the measurements values for the average L shell fluorescence yields (ϖ_L) have been obtained in photoionization experiments. Only the three experiments of Sera at al. (1980), Duggan et al. (1985) and McNeir et al. (1991) were established by proton impact. Comparison between values shows that there are significant differences between the fluorescence yields obtained in both methods, but the number of data values in not sufficient to make a meaningful analysis. The immediate difference in the ionization mechanism is the presence of Coulomb interaction proton-atom experiments. It is expected that this might produce primary and spectator hole distributions

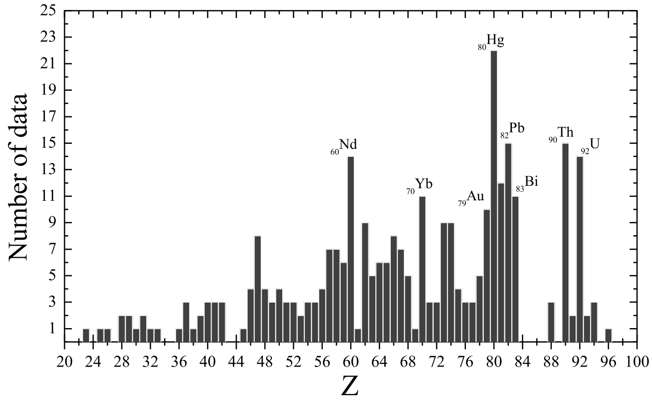

Fig. 1. Distribution of the number of the experimental average L-shell fluorescence yields as a function of atomic number Z.

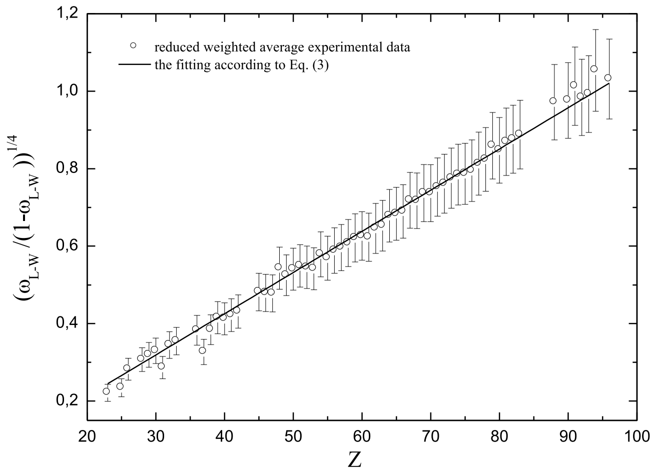

Fig. 2. The distribution of the reduced experimental data ($(\varpi_{L-W}/(1-\varpi_{L-W}))^{1/4}$) as a function of atomic number Z for the Z-group $23 \le Z \le 96$. The curve is the fitting according to formula (3).

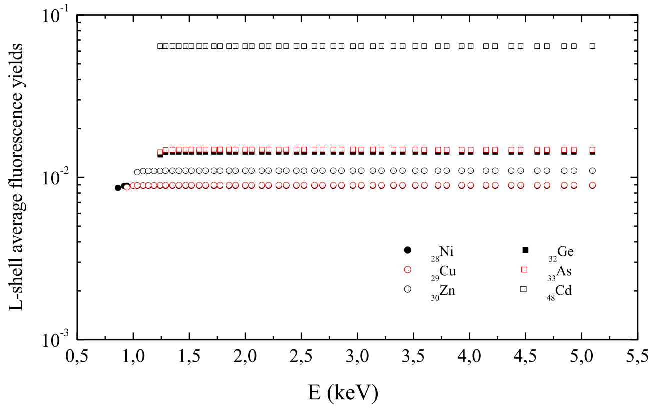

Fig. 3. Energy-dependence of the L-shell average fluorescence yields between ~1 and ~5 keV computed for a few elements with the mcdfgme code developed by Desclaux (1975) and Indelicato (1995).

different from photoionization process. However, as far as we know, there is not enough data to clarify this statement and further theoretical and experimental study will be needed. Therefore, both photon or proton experiments are used in the data fitting.

Fig. 1 gives the distribution of these experimental data according to their target atomic number. The examination of the figure requires some comments, namely:

- Nearly all the targets from $_{23}$V to $_{96}$Cm are covered except some isolated cases with no data or less than two data.
- The most exploited targets are in the region $56 \le Z \le 83$ and comport an important number of data such as $_{57}$La, $_{58}$Ce, $_{60}$Nd, $_{62}$Sm, $_{66}$Dy, $_{67}$Ho, $_{70}$Yb, $_{73}$Ta, $_{74}$W, $_{79}$Au, $_{80}$Hg, $_{81}$Tl, $_{82}$Pb and $_{83}$Bi. It has been observed also that the two elements $_{90}$Th and $_{92}$U have an important number of data.
- Data for the elements $_{24}$Cr, $_{27}$Co, $_{34}$Se, $_{35}$Br, $_{43}$Tc, $_{44}$Ru, $_{84}$Po, $_{85}$At, $_{86}$Rn, $_{87}$Fr, $_{89}$Ac and $_{95}$Am are not yet reported due to the fact that they are difficult to handle, being radioactive elements or not readily available.

Consequently, it has been investigated and regrouped a large number of database composed of 316 experimental values. It should be clearly pointed out that these huge numbers of data for the calculation of empirical average L-shell fluorescence yield values are used for the first time.

4. Calculation procedure of empirical average L-shell fluorescence yield ($\varpi_{L\text{-}emp}$)

In this study, new parameters were presented for the calculation of the L-shell fluorescence yields for targets from $_{23}$V to $_{96}$Cm. The *weighted average values* ϖ_{L-W} were used to calculate the empirical L-shell fluorescence yields (the last column from Table 1). Taking into account the approximation $(\omega/(1-\omega))^{1/4} = \sum_n b_n Z^n$ (see: Wentzel (1927); Burhop (1955); Fink et al. (1966); Bambynek et al. (1972); Mitchell and Barfoot (1981); Broll (1986); Hubbell et al. (1994); Küp Aylikçi et al. (2011); Kahoul et al. (2012, 2014); Aylikçi et al. (2015); Bendjedi et al. (2015); Sahnoune et al. (2016)) the reduced *weighted average value* $(\omega_{L-W}/(1-\omega_{L-W}))^{1/4}$, is presented as function of Z and plotted in Fig. 2 (dots) with respect to atomic number Z. Since the distribution of experimental values is linear, in order to determine a reliable empirical L-shell fluorescence yields, based on the Wentzel (1927) and Broll (1986) equation's, we propose a linear function for the interpolation (with: $b_0 = 0$). So, the analytical function used for the fitting is the following:

$$(\varpi_{LL-W}/(1-\varpi_{LL-W}))^{1/4} = b_1 \times Z \tag{3}$$

For the determination of empirical average L-shell fluorescence yields, formula (3) can be rewritten as:

$$(\varpi_L)_{L-emp} = \left(\frac{Z^4}{B+Z^4}\right) \tag{4}$$

with: $B = (b_1)^{-4} = (7.816296 \pm 0.1119) \times 10^7$

The deviation of the calculated empirical average L-shell fluorescence yield $(\varpi_L)_{L-emp}$values from the corresponding weighted experimental values is expressed in terms of the *root-mean-square error*(ε_{RMS}). It is calculated using the expression (Küp Aylikçi et al., 2011):

$$\varepsilon_{RMS} = \left[\sum_{j=1}^{N}\frac{1}{N}\left(\frac{(\varpi_L)_{L-W}-(\varpi_L)_{L-emp}}{(\varpi_L)_{L-emp}}\right)^2\right]^{\frac{1}{2}} \tag{5}$$

Where N is the number of weighted experimental data for each element (in this case N = 1).

5. Calculation procedure in the configuration mixing Dirac-Fock approach

Although the average fluorescence yield of a shell is generally presented as a constant, the reality is that it depends on the excitation source (eg, protons, electrons or γ radiation) and its energy. The average yield of the L (or any other) shell is defined as,

Table 2
Empirical and theoretical (this work), theoretical, fitted and experimental (other works) average L-shell fluorescence yields for all elements in the region $23 \le Z \le 96$.

Z-element	This work			Other works					
				Theo.	Fitt.				Exp.
	Emp.	ε_{RMS}(%)	mcdfgme	Chen et al. (1981)	Puri et al. (1993)	Hubbell et al. (1994)	Öz et al. (1999)	Bendjedi et al. (2015)	
Z = 23, V	0.0036	32.73	–	–	–	–	–	–	–
Z = 24, Cr	0.0042	–	–	–	–	–	–	–	–
Z = 25, Mn	0.0050	39.67	–	–	0.0037	–	0.0039	–	–
Z = 26, Fe	0.0058	8.39	–	–	0.0053	0.0064	0.0052	–	0.0063[a]
Z = 27, Co	0.0068	–	–	–	0.0069	–	0.0069	–	–
Z = 28, Ni	0.0078	12.79	0.0088	–	0.0085	0.0088	0.0086	–	0.0091[a]
Z = 29, Cu	0.0090	14.86	0.0088	–	0.0101	0.0100	0.010	–	0.0105[a]
Z = 30, Zn	0.0103	14.07	0.0108	–	0.0103	0.0113	0.011	–	0.0117[a]
Z = 31, Ga	0.0117	42.62	–	–	0.0122	0.0128	0.012	–	0.0129[a]
Z = 32, Ge	0.0132	5.00	0.0143	–	0.0141	0.0141	0.014	–	0.0139[a]
Z = 33, As	0.0149	4.38	0.0149	–	0.0160	0.0156	0.016	–	0.0156[b]
Z = 34, Se	0.0168	–	–	–	0.0180	–	0.018	–	–
Z = 35, Br	0.0188	–	–	–	0.0199	–	0.020	–	–
Z = 36, Kr	0.0210	0.17	–	–	0.0209	0.0211	0.021	–	–
Z = 37, Rb	0.0234	51.74	–	–	0.0234	0.0232	0.023	–	0.0186[b]
Z = 38, Sr	0.0260	18.03	–	–	0.0260	0.0256	0.026	–	0.0213[b]
Z = 39, Y	0.0287	0.53	–	–	0.0289	0.0282	0.029	–	–
Z = 40, Zr	0.0317	11.39	–	–	0.0319	0.0310	0.031	0.0268	0.033[b]
Z = 41, Nb	0.0349	12.01	–	–	0.0350	0.0342	0.035	0.0297	0.032[c]
Z = 42, Mo	0.0383	12.76	–	–	0.0384	0.0376	0.038	0.0327	0.035[c]
Z = 43, Tc	0.0419	–	–	–	0.0420	–	0.042	0.0360	–
Z = 44, Ru	0.0458	–	–	–	0.0459	–	0.046	0.0395	–
Z = 45, Rh	0.0498	2.31	–	–	0.0499	0.0499	0.049	0.0432	–
Z = 46, Pd	0.0542	7.53	–	–	0.0543	0.0547	0.053	0.0472	0.049[c]
Z = 47, Ag	0.0588	15.59	–	–	0.0589	0.0599	0.058	0.0514	0.051[c]
Z = 48, Cd	0.0636	26.11	0.0635	–	0.0637	0.0656	0.063	0.0559	0.056[c]
Z = 49, In	0.0687	2.78	–	–	0.0689	0.0717	0.068	0.0606	0.065[c]
Z = 50, Sn	0.0740	6.16	–	–	0.0743	0.0782	0.073	0.0656	0.069[c]
Z = 51, Sb	0.0797	4.57	–	–	0.0800	0.0852	0.079	0.0708	0.075[c]
Z = 52, Te	0.0855	4.96	–	–	0.0860	0.0934	0.081	0.0763	0.078[c]
Z = 53, I	0.0917	13.62	–	–	0.0923	0.0960	0.091	0.0821	0.086[c]
Z = 54, Xe	0.0981	2.94	–	–	0.0989	–	0.097	0.0882	–
Z = 55, Cs	0.1048	9.54	–	–	0.1058	–	0.104	0.0945	0.090[c]
Z = 56, Ba	0.1118	4.17	–	0.114	0.113	0.110	0.111	0.1011	0.102[d]
Z = 57, La	0.1190	5.62	–	0.121	0.1204	0.116	0.119	0.1080	0.106[d]
Z = 58, Ce	0.1265	5.04	–	0.129	0.1282	0.123	0.127	0.1151	0.114[d]
Z = 59, Pr	0.1342	3.44	–	0.138	0.1363	0.130	0.127	0.1225	0.123[d]
Z = 60, Nd	0.1422	6.28	–	0.146	0.1447	0.138	0.140	0.1302	0.127[d]
Z = 61, Pm	0.1505	12.95	–	0.155	0.1533	–	0.156	0.1382	–
Z = 62, Sm	0.1590	6.85	–	0.164	0.1623	0.155	0.162	0.1464	0.142[d]
Z = 63, Eu	0.1677	8.43	–	0.173	0.1715	0.165	0.171	0.1548	0.164[e]
Z = 64, Gd	0.1767	0.97	–	0.184	0.1810	0.174	0.181	0.1635	0.184[e]
Z = 65, Tb	0.1859	3.51	–	0.194	0.1907	0.184	0.191	0.1725	0.192[e]
Z = 66, Dy	0.1953	5.45	–	0.204	0.2007	0.194	0.201	0.1817	0.199[e]
Z = 67, Ho	0.2050	2.5	–	0.214	0.2109	0.205	0.212	0.1911	0.217[e]
Z = 68, Er	0.2148	2.56	–	0.223	0.2213	0.215	0.222	0.2007	0.223[e]
Z = 69,Tm	0.2248	1.42	–	0.231	0.2320	0.226	0.232	0.2105	0.228[e]
Z = 70, Yb	0.2350	3.1	–	0.241	0.2428	0.236	0.243	0.2205	0.239[e]
Z = 71,Lu	0.2453	0.96		0.252	0.2538	0.247	0.255	0.2307	0.246[e]
Z = 72, Hf	0.2559	1.78		0.264	0.2650	0.258	0.266	0.2411	0.255[e]
Z = 73, Ta	0.2665	0.30		0.277	0.2764	0.269	0.277	0.2517	0.274[e]
Z = 74, W	0.2773	0.85		0.290	0.2878	0.280	0.289	0.2624	0.285[e]
Z = 75, Re	0.2882	3.80		0.301	0.2994	0.292	0.296	0.2732	0.286[e]
Z = 76, Os	0.2991	4.70		0.312	0.3111	–	0.309	0.2841	–
Z = 77, Ir	0.3102	2.01		0.322	0.3229	0.314	0.320	0.2952	0.326[e]
Z = 78, Pt	0.3214	1.77		0.332	0.3347	0.326	0.331	0.3063	0.328[e]
Z = 79, Au	0.3326	6.08		0.342	0.3465	0.337	0.342	0.3175	0.330[e]
Z = 80, Hg	0.3438	0.22		0.352	0.3584	0.348	0.354	0.3288	0.292[f]
Z = 81, Tl	0.3551	2.38		0.363	0.3702	0.360	0.365	0.3402	0.314[f]
Z = 82, Pb	0.3665	1.16		0.374	0.3820	0.371	0.377	0.3516	0.345[f]
Z = 83, Bi	0.3778	1.49		0.385	0.3937	0.383	0.389	0.3630	0.369[f]
Z = 84, Po	0.3891	–		0.397	0.4053	–	0.401	0.3744	–

(*continued on next page*)

Table 2 (*continued*)

Z-element	This work		Other works					
			Theo.	Fitt.				Exp.
	Emp.	ε_{RMS} (%)	Chen et al. (1981)	Puri et al. (1993)	Hubbell et al. (1994)	Öz et al. (1999)	Bendjedi et al. (2015)	
Z = 85, At	0.4004	–	0.409	0.4167	–	0.414	0.3858	–
Z = 86, Rn	0.4117	–	0.422	0.4280	–	0.424	0.3972	–
Z = 87, Fr	0.4230	–	0.434	0.4392	–	0.437	0.4086	–
Z = 88, Ra	0.4341	8.58	0.446	0.4501	–	0.448	0.4200	–
Z = 89, Ac	0.4453	–	0.458	0.4607	–	0.460	0.4313	–
Z = 90, Th	0.4563	4.29	0.470	0.4711	0.468	0.472	0.4426	0.451[f]
Z = 91, Pa	0.4673	9.73	0.481	0.4811	–	0.482	0.4537	–
Z = 92, U	0.4782	1.19	0.492	0.4908	0.495	0.493	0.4648	0.481[f]
Z = 93, Np	0.4890	0.73	–	0.500	–	–	–	–
Z = 94, Pu	0.4997	10.54	–	0.5089	–	–	–	–
Z = 95, Am	0.5103	–	–	0.5173	–	–	–	–
Z = 96, Cm	0.5208	1.97	–	0.5251	–	–	–	–

[a] (McNeir et al., 1991).
[b] (Duggan et al., 1985).
[c] (Ertuğrul, 2002).
[d] (Durak and Özdemir, 2000).
[e] (Singh et al., 1990).
[f] (Apaydin et al., 2008).

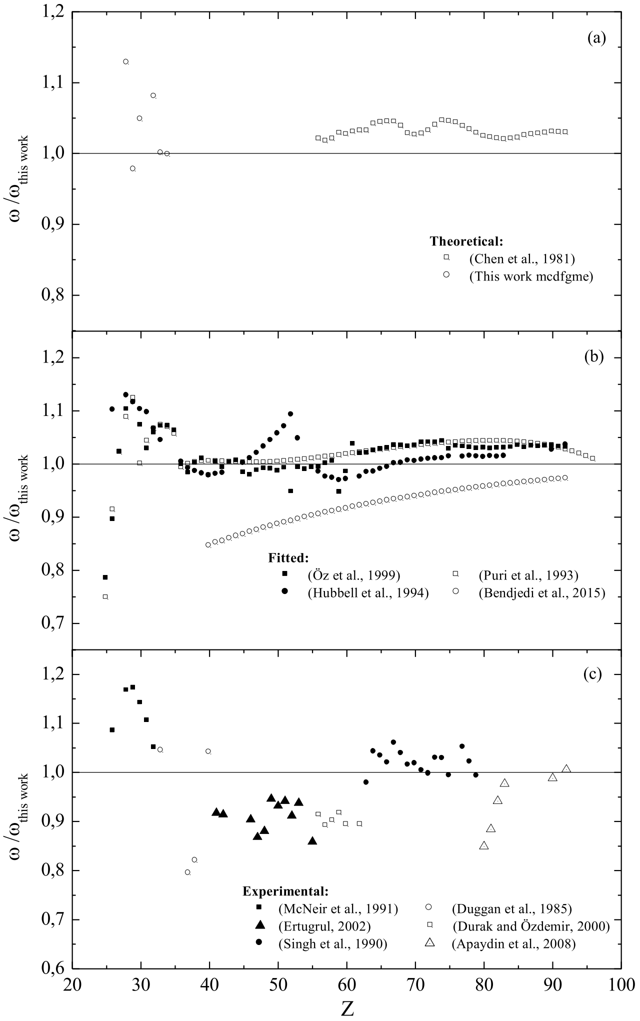

Fig. 4. Ratio to the present calculation of our theoretical values using the mcdfgme code, the theoretical values of Chen et al. (1981), the fitted results of Puri et al. (1993), Hubbell et al. (1994), Öz et al. (1999), Bendjedi et al. (2015) and the experimental measurments of McNeir et al. (1991), Duggan et al. (1985), Ertuğrul (2002), Durak and Özdemir (2000), Singh et al. (1990), Apaydin et al. (2008).

$$\bar{\omega}_L = \frac{\sum_i \sigma_i^X}{\sum_i \sigma_i^I} \tag{6}$$

where σ_i^I (i = 1, 2, 3) are the L subshells ionization cross-sections, and σ_i^X are the respective subshell x-ray production cross section, defined by,

$$\sigma_1^X = \omega_1 \sigma_1^I \tag{7a}$$

$$\sigma_2^X = \omega_2 [\sigma_2^I + f_{12}\sigma_1^I] \tag{7b}$$

$$\sigma_3^X = \omega_3 [\sigma_3^I + f_{23}\sigma_2^I + (f_{12}f_{23} + f_{13})\sigma_1^I] \tag{7c}$$

where ω_i are the L subshell fluorescence yields, and f_{ij} are the L shell Coster-Kronig coefficients.

The first terms of equation (7) describe the direct ionization of the subshell i, and the remaining terms the vacancy propagation within the L subshells. These equations do not include a term describing the propagation of a primary vacancy created in the K shell to the L subshells. Therefore, they assume that the energy of the incident radiation is below the K-shell edge for a given element.

The results presented here for six elements ($_{28}$Ni, $_{29}$Cu, $_{30}$Zn, $_{32}$Ge, $_{33}$As and $_{48}$Cd) are obtained from subshell fluorescence yields and Coster-Kronig coefficients derived from radiative and radiationless rates calculated with the mcdfgme code developed by Desclaux (1975) and Indelicato (1995). Photoionization cross-sections were also computed using the same code, making these results consistent in what concerns the physical model used for the different quantities envolved in Eq. (7). For further details on the calculation method we refer the reader to Sampaio et al. (2016). Only a limited number of elements are presented here since these calculations are very time-consuming.

To understand the energy-dependence of the average fluorescence yield, the subshell photoionization cross-sections and x-ray production cross-sections were calculated for the energy range between ≤1 keV and ≥5 keV, which is below the K shell edge of all elements considered. Calculations were done in a grid of 95 energy points corresponding to all tabulated L subshell edges in that range. Fig. 3 clearly shows that above the L_1 edge the average fluorescence yield remains essentially constant. Variations in the L-shell average fluorescence yield above the L_1 edge are of the order of 10^{-5}. Thus, the values in Table 2 are with four significant figures.

6. Results and discussion

The present calculation of empirical average L-hell fluorescence yields for all elements in the region 23 ≤ Z ≤ 96 and the theoretical values for six elements ($_{28}$Ni, $_{29}$Cu, $_{30}$Zn, $_{32}$Ge, $_{33}$As and $_{48}$Cd) using the mcdfgme code are listed in Table 2. The interpolation errors (ε_{RMS}) on the empirical results are also listed in Table 2. Because the experimental data for the elements $_{24}$Cr, $_{27}$Co, $_{34}$Se, $_{35}$Br, $_{43}$Tc, $_{44}$Ru, $_{84}$Po, $_{85}$At, $_{86}$Rn, $_{87}$Fr, $_{89}$Ac and $_{95}$Am are not yet reported the values of ε_{RMS} for these elements are not added. The theoretical values of Chen et al. (1981), the fitted results of Puri et al. (1993), Hubbell et al. (1994), Öz et al. (1999), Bendjedi et al. (2015), and the experimental measurments of McNeir et al. (1991), Duggan et al. (1985), Ertuğrul (2002), Durak and Özdemir (2000), Singh et al. (1990), Apaydin et al. (2008) are also added in the same table. To well compare our empirical average fluorescence yields and these theoretical, fitted and experimental values, ratio to the present calculation of all values of ϖ_{L-emp} are plotted in Fig. 4 ((a): theoretical, (b): fitted, (c): experimental) as a function of atomic number. Generally, it can be seen that the present empirical average L-shell fluorescence yields, calculated using formula (4), are in agreement with the theoretical, fitted and experimental values for all elements in the range of 23 ≤ Z ≤ 96. The current results are compatible with the experimental values of McNeir et al. (1991), Duggan et al. (1985), Ertuğrul (2002), Durak and Özdemir (2000), Singh et al. (1990), Apaydin et al. (2008) but a significant variations are observed for the average L shell fluorescence yields of the elements $_{37}$Rb, $_{38}$Sr, $_{80}$Hg and $_{81}$Tl investigated by Duggan et al. (1985) and Apaydin et al. (2008). In addition, our data of ϖ_{L-emp} differ by only a few percent from those of theoretical values of Chen et al. (1981) over the whole range of atomic number and the agrument varies from 1.69% to 4.59%. Where the relative difference -RD- between the obtained empirical values and the other calculation were calculated using the equation $\mathrm{RD}\left(\%\right) = |(\omega - \omega_{emp})/\omega_{emp}| \times 100$. Also, from Fig. 4, it can be seen that our empirical L-shell fluorescence yields agree quite well with fitted values of Puri et al. (1993), Hubbell et al. (1994), Öz et al. (1999), Bendjedi et al. (2015). Within the error range for these calculations, the agrument varies from 0.065% to 12.78% for Puri et al. (1993), 0.016%–12.78% for Hubbell et al. (1994), 0.015%–11.51% for Öz et al. (1999) and 2.81%–15.50% for Bendjedi et al. (2015) except the iron ($_{26}$Fe). A disagreement of 25.19% and 21.57% was observed when comparing to Puri et al. (1993) values and of Öz et al. (1999) respectivelly. Our empirical and theoretical average L-shell fluorescence yield values are compared with each other in the same figure (Fig. 4 (a)) by plotting the ratio $\varpi_{L-theo}/\varpi_{L-emp}$ for six elements ($_{28}$Ni, $_{29}$Cu, $_{30}$Zn, $_{32}$Ge, $_{33}$As and $_{48}$Cd). It is clear from Fig. 4 (a) that the theoretical results based on the mcdfgme code for $_{28}$Ni, $_{30}$Zn and $_{32}$Ge are higher by 4.85–12.82% than the empirical calculation (12.82% for $_{28}$Ni, 4.85% for $_{30}$Zn and 8.33% for $_{32}$Ge). In addition, the comparison of two sets of theoretical and empirical for the three elements $_{29}$Cu, $_{33}$As and $_{48}$Cd are found in excellent agreement, this agreement does not exceed 0.15% except for the $_{29}$Cu where the empirical value is found to be higher by 2.22% than the theoretical result.

7. Conclusion

The average L-shell fluorescence yield measurements reported in the literature covering the period from 1954 to 2015 have been reviewed and presented in a table form (about 316 measurements). A new set of L-shell fluorescence yields has been determined using simple methods for elements in the atomic region 23 ≤ Z ≤ 96. The deduced empirical fluorescence yields were in a relatively good agreement with those of other groups for the whole range of atomic number. Comparing the empirical fluorescence with the mcdfgme calcultaions for a few cases, we can see that the largest discrepancies are for Ni (~12%) and Ge (~8%), although the latter are in agreement with other works (see Table 2). Descrepancies between calculated and measured L-shell atomic parameters for Ge and Ni have been discussed in M. Guerra et al. (2015, 2018). These have been attributed to solid-state effects in the experiments that are not present in the mcdfgme calculations of isolated atoms. In addition to the available experimental and theoretical average L-shell fluorescence yields, the present values can be added to the databases and made available for workers in the field of atomic inner-shell ionization processes.

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