PHYSICAL REVIEW A VOLUME 22, NUMBER 5 NOVEMBER 1980

Average L-shell fluorescence, Auger, and electron yields

M. O. Krause
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 16 June 1980)

The dependence of the average L-shell fluorescence and Auger yields on the initial vacancy distribution is shown to be small. By contrast, the average electron yield pertaining to both Auger and Coster-Kronig transitions is shown to display a strong dependence. Numerical examples are given on the basis of Krause's evaluation of subshell radiative and radiationless yields. Average yields are calculated for widely differing vacancy distributions and are intercompared graphically for $40 \leq Z \leq 100$ in the case of the fluorescence and Auger yields, and $12 \leq Z \leq 100$ in the case of the electron yield. Average fluorescence and Auger yields are found to differ by less than 7% from the respective L_3 subshell yields in most cases of inner-shell ionization.

INTRODUCTION

When ionization occurs in an inner shell other than the K shell, vacancies are created in the various subshells in proportion to the relevant partial ionization cross sections. The resulting vacancy distribution then decays by radiative and radiationless transitions to less tightly bound shells and produces an average yield of photons and electrons. These average yields are important in many uses of inner-shell ionization phenomena, and hence their dependence on the initial vacancy distribution is a question of primary concern.

It has been noted before[1] that on the basis of theoretical calculations, the average L-shell fluorescence yield showed only a weak dependence on the initial vacancy distribution. However, this result has not been generally accepted, presumably because different calculations predicted different values of the average yield, and because experimental determinations were not accurate enough to establish a clear trend.[1,2]

In this paper, it is shown that the average fluorescence yield shows, indeed, a very weak dependence on the initial vacancy distribution. Using a recent evaluation[3] of the L-subshell fluorescence, Coster-Kronig, and Auger yields, the average fluorescence yield is calculated for the case of photoionization, and the limits are established within which the average yield can vary. Corresponding results are given for the average Auger yield and for the average electron yield.

THE AVERAGE FLUORESCENCE YIELD

In the usual definition the average L-shell fluorescence yield is given by

$$\bar{\omega} = N_1 \nu_1 + N_2 \nu_2 + N_3 \nu_3 , \tag{1}$$

where $N_1 + N_2 + N_3 = 1$, and N_1, N_2, and N_3 are the fractional numbers of initial vacancies in the L_1, L_2, and L_3 subshells. The ν_i, $i = 1, 2, 3$, are the effective subshell fluorescence yields

$$\nu_1 = \omega_1 + \omega_2 f_{1,2} + \omega_3 (f_{1,3} + f'_{1,3} + f_{1,2} f_{2,3}) , \tag{2}$$

$$\nu_2 = \omega_2 + \omega_3 f_{2,3} , \tag{3}$$

$$\nu_3 = \omega_3 , \tag{4}$$

in terms of the fluorescence yields ω_i, the Coster-Kronig yields $f_{i,k}$, and the intrashell radiative yield $f'_{1,3}$.[4] The limits of the $\bar{\omega}$ values can be given immediately for the extreme distributions $N_1/N_2/N_3 = 1/0/0$; $0/1/0$; and $0/0/1$. Then $\bar{\omega}$ becomes identical with ν_1, ν_2, and ν_3, respectively; and $\bar{\omega}$ for any arbitrary distribution must lie within the boundaries given by ν_i. Numerical $\bar{\omega}$ values are presented in Table I for the extreme distributions and for photoionization.[5] It can be seen that only small variations in $\bar{\omega}$ are possible because $\nu_1 \approx \nu_2 \approx \nu_3 = \omega_3$ numerically. For example, $\bar{\omega}$ varies by less than 2% for the distributions $X/Y/Z \approx 0.16/0.33/0.51$ and $0.50/0.24/0.26$ that are created[6] by photoionization just above the L_1 edge and just below the K edge, respectively. Numerical values of ν_i for all elements can be found in Ref. 3, and values of $\bar{\omega}$ calculated for the case of photoionization are presented in Ref. 5 for every fourth element of the periodic table.

In Fig. 1, the values of ν_1, ν_2, and $\bar{\omega}$ are plotted relative to ω_3 for the elements in the range $40 \leq Z \leq 100$. Throughout the range the yield $\bar{\omega}$ is seen to deviate from ν_1 by only a few percent and from ω_3 by no more than 7%. Noting that most modes of inner-shell ionization lead to vacancies in each subshell, the average fluorescence yield can gen-

TABLE I. Average L-shell fluorescence yield $\bar{\omega}$ for the initial vacancy distributions $N_1/N_2/N_3=1/0/0$; $0/1/0$; $0/0/1$; and $X/Y/Z$ which is created in photoionization ($E_{L1} < h\nu < E_K$). Note the identity of $\bar{\omega}$ with ν_1, ν_2, and ω_3 for the extreme cases given.

Z	ν_1 1/0/0	ν_2 0/1/0	ω_3 0/0/1	$\bar{\omega}$ $X/Y/Z$
^{32}Ge	0.0142	0.0137	0.0150	0.0144
^{48}Cd	0.0575	0.0647	0.0560	0.0586
^{64}Gd	0.160	0.181	0.155	0.163
^{80}Hg	0.345	0.387	0.333	0.352
^{92}U	0.503	0.549	0.489	0.513

erally be given by $\bar{\omega}=1.02\ \nu_1$ or $\bar{\omega}=1.05\ \omega_3$ to a very good approximation for all $Z \gtrsim 45$.

No values are given for the low Z elements, $Z<40$, because of the greater uncertainties in the individual fluorescence and Coster-Kronig yields, ω_i and $f_{i,k}$, and their sensitivity to chemical effects.[3] However, it should be noted that ν_1 is much greater than ω_3 near $Z=19$ due to the *relative* importance of the intrashell radiative yield $f'_{1,3}$.

The uncertainties in the relative ν_i and $\bar{\omega}$ values can be estimated from the uncertainties given in Ref. 3 for the individual yields. If the uncertainties in ω_i and $f_{i,k}$ were assumed to be uncorrelated, the uncertainties in the relative ν_i and $\bar{\omega}$ values would range from 15% at $Z=40$ to 5% at $Z=100$. However, since a strong correlation exists between the different ω_i and $f_{i,k}$,[3] a more realistic estimate leads to uncertainties ranging from 5% at $Z=40$ to less than 2% toward $Z=100$.

Since in most modes of innershell ionization an initial vacancy distribution is created that is not drastically different from the distributions produced by photoionization, it is of interest to compare the present $\bar{\omega}$ values with available experimental data,[1,2] obtained under widely differing conditions. The comparison displayed in Fig. 2 shows a satisfactory agreement between the calculated curve and the measurements of $\bar{\omega}$. On the basis of the results summarized in Fig. 1, the scatter in the measurements of the average fluorescence yields must be attributed by and large to experimental inaccuracies rather than to the influence of the initial vacancy distribution.

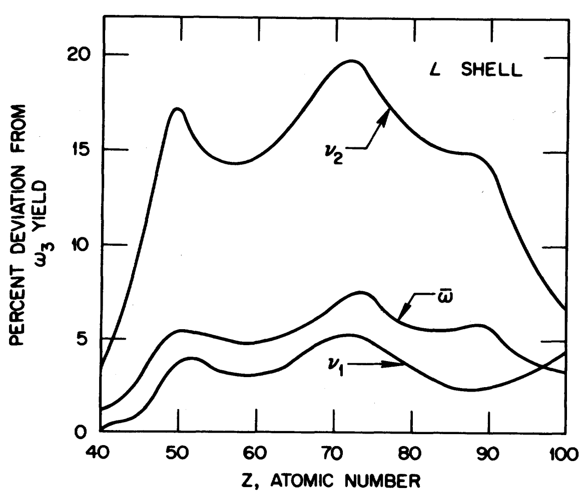

FIG. 1. The percent deviation of ν_1, ν_2, and $\bar{\omega}$ from the L_3-subshell fluorescence yield ω_3. The average yield $\bar{\omega}$ is calculated for the case of photoionization ($E_{L1} < h\nu < E_K$); ν_1 corresponds to an initial vacancy distribution $N_1/N_2/N_3=1/0/0$, ν_2 to $0/1/0$, and ω_3 to $0/0/1$.

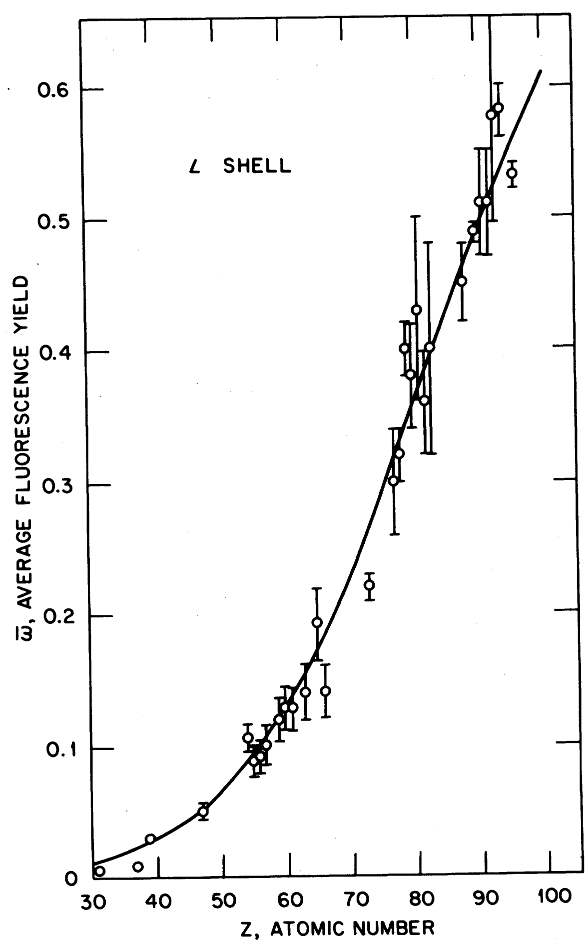

FIG. 2. Comparison of the average fluorescence yield $\bar{\omega}$ calculated in this work with experimental data taken from Refs. 1 and 2.

TABLE II. Average L-shell Auger yield $\bar{a}_A$ for different vacancy distributions; $\alpha_{1,A}$, $\alpha_{2,A}$, and a_3 are identical with $\bar{a}_A$ for $N_1/N_2/N_3 = 1/0/0$; $0/1/0$; and $0/0/1$.

Z	$\alpha_{1,A}$ 1/0/0	$\alpha_{2,A}$ 0/1/0	a_3 0/0/1	$\bar{a}_A$ [a] $X/Y/Z$
^{30}Zn	0.988	0.989	0.988	0.988
^{45}Rh	0.954	0.950	0.954	0.953
^{60}Nd	0.872	0.857	0.875	0.870
^{80}Hg	0.658	0.613	0.667	0.648
^{95}Am	0.470	0.422	0.474	0.456

[a] For vacancy distributions created by photoionization ($E_{L1} < h\nu < E_K$).

TABLE III. Average L-shell electron yield $\bar{\alpha}$ for extreme initial vacancy distributions and for photoionization at two energies. The α_1, α_2, and α_3 values are identical with the $\bar{\alpha}$ values for the initial vacancy distributions $N_1/N_2/N_3 = 1/0/0$; $0/1/0$; and $0/0/1$, respectively.

Z	α_1 1/0/0	α_2 0/1/0	α_3 0/0/1	$\bar{\alpha}$ [a] $X/Y/Z$	$\bar{\alpha}$ [b] $X'/Y'/Z'$
^{30}Zn	1.825	1.015	0.989	1.16	1.46
^{45}Rh	1.665	1.100	0.950	1.11	1.37
^{60}Nd	1.392	1.009	0.857	1.01	1.18
^{80}Hg	1.361	0.733	0.613	0.81	1.02
^{95}Am	1.072	0.625	0.422	0.64	0.79

[a] Distribution for $h\nu \approx E_{L1}$; $X/Y/Z \approx 0.16/0.33/0.51$.
[b] Distribution for $h\nu \approx E_K$; $X'/Y'/Z' \approx 0.50/0.24/0.26$.

THE AVERAGE AUGER YIELD

In complete analogy to the average fluorescence yield, the average Auger yield (see Table II) is given by

$$\bar{a}_A = N_1\alpha_{1,A} + N_2\alpha_{2,A} + N_3\alpha_{3,A}, \qquad (5)$$

where the effective L-subshell Auger yields are given by

$$\alpha_{1,A} = a_1 + a_2 f_{1,2} + a_3(f_{1,3} + f'_{1,3} + f_{1,2}f_{2,3}), \qquad (6)$$

$$\alpha_{2,A} = a_2 + a_3 f_{2,3}, \qquad (7)$$

$$\alpha_{3,A} = a_3, \qquad (8)$$

in terms of the subshell Auger yields a_i and the Coster-Kronig yields $f_{i,k}$.

The values of $\alpha_{1,A}$ and $\alpha_{3,A}$ are plotted in Fig. 3 relative to the L_3 subshell yield a_3. Also plotted is the average yield $\bar{a}_A$ which was calculated for the representative case of photoionization. The uncertainties in the relative values of $\alpha_{1,A}$, $\alpha_{2,A}$, and $\bar{a}_A$ are estimated to range from less than 1% at $Z \lesssim 50$ to about 2% at $Z = 100$.

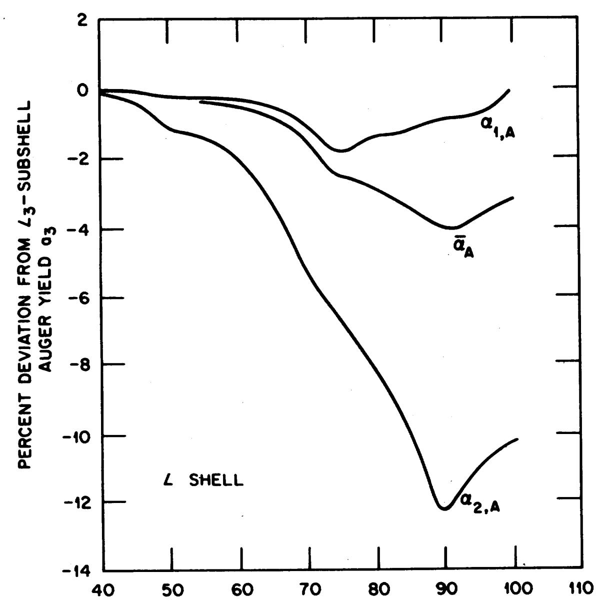

FIG. 3. The percent deviation of $\alpha_{1,A}$, $\alpha_{2,A}$, and $\bar{a}_A$ from the L_3-subshell Auger yield a_3. The average yield $\bar{a}_A$ is calculated for the case of photoionization ($E_{L1} < h\nu < E_K$); $\alpha_{1,A}$ pertains to an initial vacancy distribution $N_1/N_2/N_3 = 1/0/0$, $\alpha_{2,A}$ to $0/1/0$, and a_3 to $0/0/1$.

THE AVERAGE ELECTRON YIELD

Following the definitions of average fluorescence and Auger yields, the average electron yield for

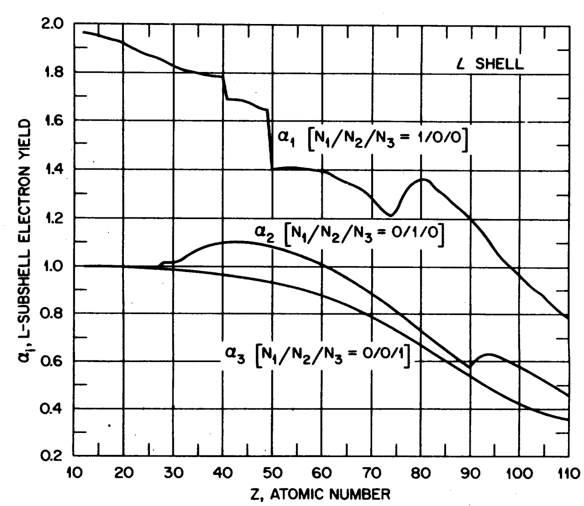

FIG. 4. The average electron yields for the extreme initial vacancy distributions indicated. These yields pertain to Auger and Coster-Kronig electrons; α_1 and α_2 can be interpreted as the effective electron yields of the L_1 and L_2 subshells.

all radiationless transitions can be written as

$$\bar{\alpha} = N_1\alpha_1 + N_2\alpha_2 + N_3\alpha_3 , \tag{9}$$

where the effective electron yields α_i are given by

$$\alpha_1 = \alpha_{1,A} + f_{1,2} + f_{1,3} + f_{1,2}f_{2,3} , \tag{10}$$

$$\alpha_2 = \alpha_{2,A} + f_{2,3} , \tag{11}$$

$$\alpha_3 = \alpha_{3,A} = a_3 , \tag{12}$$

in terms of the *effective* Auger yields $\alpha_{i,A}$ and the Coster-Kronig yields $f_{i,k}$. The average electron yield includes both the Auger electrons and the Coster-Kronig electrons. As a rule, the Coster-Kronig electrons form a group of slow electrons and the Auger electrons form a group of faster electrons. Because Coster-Kronig yields $f_{i,k}$ contribute heavily, α_1 is much greater than either α_2 or α_3, up to almost twice α_3 at low Z. As a consequence the average electron yield $\bar{\alpha}$ depends markedly on the initial vacancy distribution. In contrast to the average fluorescence and Auger yields, the average electron yield is much greater for photoionization at high energies than for photoionization at low energies. Numerical values of $\bar{\alpha}$ for photoionization at $h\nu \gtrsim E_{L1}$ and $h\nu \approx E_K$ are given in Table III; values of α_1, α_2, and α_3 which correspond to extreme vacancy distributions are plotted in Fig. 4 for all elements.

CONCLUSIONS

Using reliable values for the radiative and radiationless yields of the individual L subshells, the average fluorescence yield and the average Auger yield were shown to be insensitive to the initial vacancy distribution. These average yields can be equated with the L_3 subshell yields ω_3 and a_3 in most practical applications without incurring a large error. By contrast, the average electron yield shows a strong dependence on the vacancy distribution and requires a detailed evaluation for each case.

Because the general trends of the various yields of the M subshells are similar to those of the L subshells, the conclusions of this work may reasonably be transferred to the M shell. Specifically, we might expect that in the high-Z range the average fluorescence and Auger yields can be replaced by the M_5 subshell yields ω_5 and a_5 to a good approximation regardless of the initial vacancy distribution. However, the average electron yield is expected to display an even stronger dependence on the initial vacancy distribution because of the profusion of Coster-Kronig transitions in the M shell.

This research was sponsored by the Division of Chemical Sciences/Office of Basic Energy Sciences, U. S. Department of Energy, under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

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[4]Here as in Ref. 3, the yields $f'_{1,3}$ and $f'_{1,2}$ are included in ω_1; since $f'_{1,2} \ll f'_{1,3}$, $f'_{1,2}$ is neglected.

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