

I have introduced a hypothesis of parametric coupling of λ_e , the deBroglie wavelength of electrons moving along the polished surface layer of the target, with the corresponding photon wavelength λ_ν , the bremsstrahlung short-wavelength limit, by the relation

$$n\lambda_e = \lambda_\nu, \quad (1)$$

where n is any integer greater than one. The electron in the initial state carries a momentum p as it moves along the surface, given by

$$E^2 = c^2 p^2 + m_0^2 c^4. \quad (2)$$

After the emission of photon λ_ν at the short-wavelength limit in a typical photon-emission event, the electron loses almost all of its energy and belongs to the Brillouin-zone boundary at the surface layer of the solid. From the equations

$$\lambda_e = h/p \quad (3)$$

and

$$mc^2 - m_0 c^2 = T = h\nu_{\text{limit}} = hc/\lambda_\nu \quad (4)$$

and Eqs. (1) and (2), we deduce

$$T = 2m_0 c^2 / (n^2 - 1). \quad (5)$$

From Eq. (5), we should observe discrete peaks

at 340.7, 127.8, 68.1, 42.6, 29.2, and 21.3 keV for $n=2, 3, 4, 5$, and 6 , respectively. This holds true if the amplitude for the electromagnetic process has characteristically large values because of the condition of parametric coupling imposed through the hypothesis $n\lambda_e = \lambda_\nu$ for electrons moving along the thin surface layer of the target. The experimental results presented here support my predicted values. Considering the conservation of momentum and energy, I have introduced a collective-emission process which is somewhat analogous to the superdirected radiation from a linear array of antennas. This will be reported separately at a later date.

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Charge-State Dependence of the Ne *K* Fluorescence Yield Deduced from High-Resolution Emission Spectra*

N. Stolterfoht and D. Schneider

Hahn-Meitner-Institut für Kernforschung Berlin GmbH, D-1 Berlin 39, Germany

and

P. Richard and R. L. Kauffman

Department of Physics, Kansas State University, Manhattan, Kansas 66506

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Semiempirical Ne *K* fluorescence yields for the vacancy configurations KL^i were deduced for $i=1$ to 7 by comparing satellite intensities in 30-MeV $O^{5+} + \text{Ne}$ and 35-MeV $O^{8+} + \text{Ne}$ x-ray and Auger spectra measured recently with high resolution. For some cases the semiempirical fluorescence yields are found to be significantly larger than theoretical values and to differ with previous semiempirical values for the higher degrees of multiple ionization.

In this paper a method is described to determine semiempirical *K* fluorescence yields of Ne in ionization states KL^i for $i=1$ to 7 . The method requires high-resolution *K* x-ray intensity ratios,^{1,2} the *K* Auger-electron intensity ratio for the KL^0 configuration,^{3,4} and the average fluorescence

yield⁵ determined from x-ray and Auger-electron production cross sections. The analysis assumes that the ionization probability is described by a binomial distribution in the probabilities for single *K*-shell and single *L*-shell ionization.^{6,7} Theoretical *K* fluorescence yields of Ne have been

TABLE I. Measured relative intensities of Ne K x rays, R_i , and Ne KLL Auger electrons, Q_i , from 30-MeV O^{+5} and 35-MeV O^{+8} bombardment.

Initial-state configuration KL^i i	X-ray ratios R_i		Auger-electron ratios Q_i		
	30-MeV O^{+5} ^a	30-MeV O^{+5} ^b	35-MeV O^{+8} ^b	30-MeV O^{+5} ^c	35-MeV O^{+8} ^c
0	...	0.013	...	0.03	0.005
1	0.061	0.060	0.008	0.13	0.04
2	0.138	0.134	0.031	...	...
3	0.159	0.214	0.074	...	...
4	0.229	0.253	0.172	...	...
5	0.224	0.205	0.331	...	...
6	0.132	0.089	0.249	0.02	0.09
7	0.058	0.031	0.142	...	...

^aSee Ref. 1. As discussed in the text, the data were reanalyzed to include KL^0 , KL^1 , and KL^2 contributions.

^bSee Ref. 2.

^cSee Ref. 3.

given by Bhalla and co-workers⁸ and are found to increase with increasing L -shell ionization. In addition, Matthews *et al.*³ have calculated semi-empirical fluorescence yields of Ne which differ from the values of Bhalla and co-workers and which are not independent of the projectile producing the ionization. In the present paper we analyze the cases of 30-MeV $O^{5+} + Ne$ and 35-MeV $O^{8+} + Ne$ and obtain a set of fluorescence yields for ionization states KL^i which are consistent within the experimental errors. These are the only two cases for which enough data are available to obtain fluorescence yields by the present technique.

In the following, we consider the initial configurations KL^i which denote one K -shell and i L -shell vacancies. Let $q_i = \sigma(i) / \sum_i \sigma(i)$ be the normalized cross section for producing the configuration KL^i . Let R_i and Q_i be, respectively, the relative intensities of all x-ray and Auger satellite lines attributed to a certain configuration KL^i . It can easily be shown that the fluorescence yield $\omega(i)$ for the state KL^i is given by

$$\omega(i) = \bar{\omega} R_i / q_i, \quad (1)$$

where $\bar{\omega} = \sum_i q_i \omega(i)$ is the mean fluorescence yield. It should be noted that this simple formula is identical to the expression $\omega^{-1}(i) = 1 + Q_i(1 - \bar{\omega}) / R_i(\bar{\omega})$ given by Matthews *et al.*³ In the present analysis the R_i were deduced from the high-resolution x-ray spectra reported by Kauffman *et al.*¹ and Matthews, Johnson, and Moore,² and the values of q_i for $i=0, 1$, and 6 were determined from the high-resolution Auger spectra.^{3,4} The remaining q_i were calculated in an extrapolation procedure assuming a binomial distribution for the production probabilities of the KL^i states.

The highly resolved x-ray spectra from 30-MeV $O^{5+} + Ne$ and 35-MeV $O^{8+} + Ne$ show a number of distinct peaks, each of which can primarily be attributed to a certain state KL^i as discussed by Kauffman *et al.*⁹ The numbers R_i were obtained by integrating the KL^i x-ray peaks and normalizing to the total spectral intensity.¹⁰ This total intensity was determined by integrating the x-ray spectrum for energies up to 925 eV; i.e., x-ray intensities due to double K -shell ionization or bound-state excitation are neglected. The measured x-ray intensities, R_i , and Auger intensities, Q_i , are given in Table I. Oxygen x-ray intensities, underlying the KL^i peaks with $i=0, 1$, and 2, were estimated and subtracted from the Ne spectrum. Furthermore, x-ray lines due to initial quartet states of the KL^6 configuration (three-electron system) are found in the region of the KL^5 peak.⁹ Therefore, a correction is made for R_5 and R_6 because of an estimation that 81% of the KL^6 intensity is present in the KL^5 peak. This estimate is based on high-resolution Ne K x-ray spectra from high-energy Ar-Ne and Cl-Ne collisions (see Mowat *et al.*¹¹ and Ref. 9, respectively). An analogous situation exists in the two-electron system in which the $1s2p^3P_1$ and $1s2p^1P_1$ states mix and are observed to decay with approximately equal intensity.^{3,12} The corrected x-ray intensities are given in Table II.

Values of q_i^{ex} for the $i=0, 1$, and 6 are deduced by using the relation

$$q_i^{ex} = \bar{a} Q_i + \bar{\omega} R_i, \quad (2)$$

where $\bar{a} = 1 - \bar{\omega}$ is the mean Auger yield. Values of $\bar{\omega}$ for 30-MeV O^{5+} and 35-MeV O^{8+} are given in Table II. At present, the complete analysis

TABLE II. Measured x-ray ratios, R_i , corrected for multiplet splitting; experimental ionization probabilities q_i^{ex} ; semiempirical ionization probabilities q_i^{em} ; and fluorescence yields ω_i .

Initial ionization state KL^i		30-MeV O^{5+} ($\bar{\omega} = 0.038$)				35-MeV O^{8+} ($\bar{\omega} = 0.076$)				$\omega(i)^a$
i	R_i	q_i^{ex}	q_i^{em}	$\omega(i)$	$\omega(i)^a$	R_i	q_i^{ex}	q_i^{em}	$\omega(i)$	
0	...	0.028	0.028	...	0.018	...	0.0046	0.0046	...	...
1	0.061	0.127	0.127	0.018	0.019	0.008	0.037	0.035	0.017	0.018
2	0.138	...	0.250	0.021	0.022	0.031	...	0.118	0.020	0.021
3	0.159	...	0.280	0.022	0.031	0.074	...	0.227	0.025	0.027
4	0.229	...	0.195	0.045	0.054	0.172	...	0.273	0.048	0.053
5	0.117	...	0.088	0.051	0.099	0.129	...	0.210	0.047	0.125
6	0.239	0.02	0.024	0.378 (0.450) ^b	0.161	0.451	0.117	0.101	0.339 (0.293) ^b	0.201
7	0.058	...	0.004	0.551	1.000	0.142	...	0.028	0.385	1.000

^aSee Ref. 3.^bThe $\omega(i)$ values in parentheses are obtained by using q_i^{ex} as opposed to q_i^{em} .

of the Ne Auger spectrum^{4,13} is not possible because of its complexity and the lack of accurate calculations of Auger transition energies. However, for $i=0$ and 1 the complete set of Auger lines is known from electron-excited Auger spectra.¹⁴ The Q_i values for $i=0$ and 1 are derived by integrating all Auger satellite lines of a certain KL^i state and normalizing the sum to the total Auger spectrum. The total intensity is obtained by integrating the Auger spectrum for energies up to 806 eV; i.e., lines due to double K -shell ionization and bound-state excitation are neglected in accordance with the treatment of the x-ray spectrum. Auger transition energies and branching ratios required in the analysis are taken from Ref. 14. The q_i^{ex} determined from the Auger spectra are shown in Table II.

The mean fluorescence yield for 30-MeV O^{5+} is obtained from the ratio $\bar{\omega}(30\text{-MeV } O^{5+})/\bar{\omega}(5\text{-MeV } H^+) = 2.4$, and the absolute value of $\bar{\omega}(H^+) = 0.016$ given by Burch and co-workers.⁵ The value of $\bar{\omega}(35\text{-MeV } O^{8+})$ has not been measured directly. Its value can be estimated by using the R_i values for O^{8+} and the $\omega(i)$ values obtained below from the O^{5+} analysis in the formula

$$1/\bar{\omega} = \sum_i R_i / \omega(i). \quad (3)$$

A value of $\bar{\omega}(O^{8+}) = 0.076$ was obtained. It should be noted that (3) is identical to the expression $\bar{\omega}^{-1} = 1 + \sum_i R_i [1 - \omega(i)] / \omega(i)$ given by Matthews *et al.*³

Values of q_i^{em} with $i=0$ to 7 were calculated from a relation describing a binomial distribu-

tion,

$$q_i^{\text{em}} = \binom{8}{i} p^i (1-p)^{8-i}, \quad (4)$$

where p is the one-electron probability for the removal of an L -shell electron by the projectile passing through the K -shell radius. Equation (4) assumes that the probabilities for $2p$ - and $2s$ -subshell ionization are equal. The use of a binomial distribution in the description of multiple-ionization effects has been formulated previously and its validity has been verified experimentally.⁷ Here, the quantity p is treated as an unknown parameter which was derived by solving Eq. (4) for $i=0$ and 1. The values obtained for p are 0.36 for O^{5+} and 0.49 for O^{8+} . The calculated values of q_i^{em} are given in Table II. The value q_6^{ex} does not enter into the fluorescence-yield analysis. It is seen that the semiempirical q_6^{em} is in good agreement with the corresponding experimental value q_6^{ex} . This agreement gives some confidence for the use of the binomial distribution in the present case.

The semiempirical fluorescence yields, $\omega(i)$, are obtained by using Eq. (1) and the values of R_i , q_i^{em} , and $\bar{\omega}$ given in Table II. The $\omega(i)$ are also given in Table II. The values in parentheses are obtained by using q_i^{ex} instead of q_i^{em} . The $\omega(i)$ values for $i=1, \dots, 6$ are consistent within experimental errors for the O^{5+} and O^{8+} cases. For $i=7$ the competing Auger transitions are absent; however x rays from the metastable states $1s2s(^1S_0, ^3S_1)$ and $1s2p\ ^3P_{0,2}$ are partly not observed because of higher-order photon decay modes and

because of metastable states recoiling out of the viewing region before decay. This loss in x-ray intensity probably accounts for the derived value of $\omega(7)$ being less than 1. For the O^{8+} analysis the value of $\bar{\omega}$ used is derived and not measured. From Eq. (1) we see that a change in $\bar{\omega}$ modifies all the values of $\omega(i)$ by a multiplicative constant and does not change the i dependence.

In Fig. 1 the present semiempirical fluorescence yields are compared with the theoretical calculations of Bhalla and co-workers.⁸ As can be seen from the figure more than one fluorescence yield is possible for some states of L -shell ionization. The maximum and minimum possible theoretical fluorescence yields are plotted on the curve. The minimum values in all cases correspond to no vacancies in the $2s$ subshell. For KL^i , $i=4, 5, 6$, we obtain values of $\omega(i)$ that exceed the maximum possible fluorescence yield given in Ref. 8. In particular $\omega(6)$ is approximately 4 times the value of Ref. 8. In the original cal-

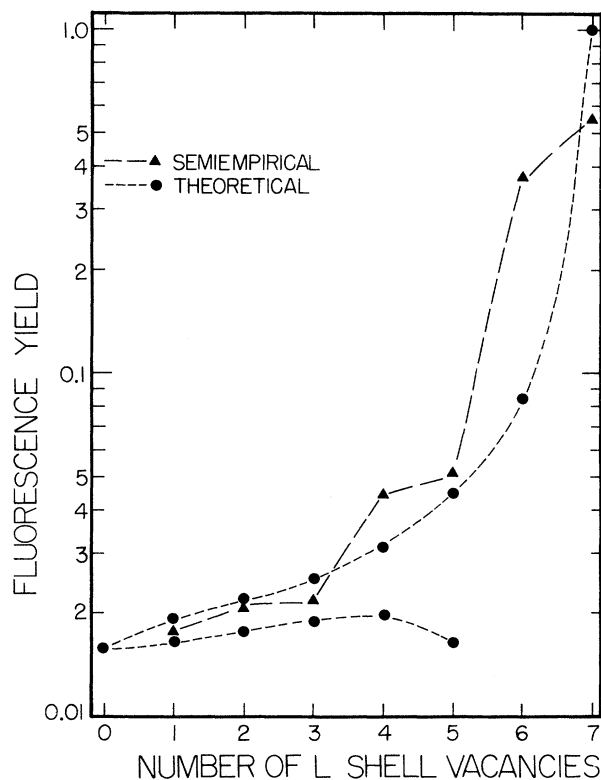


FIG. 1. Semiempirical fluorescence yield for KL^i configurations of Ne produced by 30-MeV O^{5+} as a function of the number i of L -shell vacancies. Theoretical fluorescence yields derived by Bhalla and co-workers (Ref. 8) are given for comparison. The minimum theoretical values correspond to states with no vacancies in the $2s$ subshell (see text).

culations of Bhalla and co-workers⁸ the fluorescence yields for defect configurations were calculated by using average Auger and x-ray rates. Recently Chen and Crasemann¹⁵ and Bhalla¹⁶ have calculated the fluorescence yields for Ar L for specific multiplet states. By taking a statistically weighted average of the fluorescence yields over multiplet states they obtained considerably different values from those obtained by the original method. A similar improved analysis is needed for the K shell of Ne.

Included in Table II for comparison are the values derived by Matthews *et al.*³ for the two cases studied. One difference in the two analyses is that in the present paper, the normalized ionization cross sections q_i are fitted with a binomial distribution. Matthews *et al.* fitted the Auger cross sections Q_i with a binomial distribution. This assumes that the x-ray contribution is negligible. Another difference between the two procedures is that Matthews *et al.* made no correction in the R_5 and R_6 values. This gives Matthews *et al.* values for $\omega(5)$ and $\omega(6)$ which depend upon the bombarding projectile. Also, Matthews *et al.* assume that KL^7 has a fluorescence yield of 1.

In conclusion consistent values of Ne K fluorescence yields are found for 30-MeV O^{5+} -Ne and 35-MeV O^{8+} -Ne collisions. It would be of interest to see whether consistent values can be obtained over a large range of energies for different projectile species.

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Influence of Sample Rotation on the NMR Spin-Lattice Relaxation of CH_3 Groups in Solids

R. A. Wind and S. Emid

Laboratorium voor Technische Fysika, Technische Hogeschool Delft, Delft, The Netherlands

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When nuclear spin-lattice relaxation in solids is due to rapid random rotation of methyl groups, the Zeeman relaxation can be nonexponential. This is because the magnetization is dynamically coupled to the so-called rotational polarization. It is shown that rotating the sample perpendicular to the magnetic field with angular velocity large compared with the relaxation rate decouples these parameters, resulting in an almost exponential Zeeman relaxation close to that predicted by the spin-temperature theory.

When the random reorientation of CH_3 groups is the dominant relaxation mechanism in a solid, the NMR spin-lattice relaxation is often nonexponential, not only in single crystals¹ or diluted samples,²⁻⁴ but also in polycrystalline nondiluted materials.⁵⁻⁷ This has been explained by Emid and Wind⁸ by modifying the Hilt and Hubbard theory⁹ where the relaxation of isolated methyl groups is considered, taking into account the cross correlations in the motion of the methyl protons. This modification consists of the inclusion of the spin-diffusion process. It is found that under motional-narrowing conditions the spin diffusion cannot restore a Boltzmann distribution between all adjacent energy levels of the CH_3 groups, but only between energy levels within one of the A , E^a , and E^b symmetry species characterizing the CH_3 group (this has been called symmetry-restricted spin diffusion). This has been further evaluated by Emid and co-workers¹⁰⁻¹² and it is found that firstly, the dipolar energy is dynamically coupled to the population difference between the A and E species, and secondly, the Zeeman magnetization is dynamically coupled to the population difference between the E^a and E^b species, which has been called rotational polarization. As

a result the observed nonexponentiality could be explained satisfactorily. It is the purpose of this paper to demonstrate that a specific rotation of the sample decouples the Zeeman magnetization and the rotational polarization, and that this can cause a considerable change in the observed spin-lattice relaxation, not only for single crystals, but also for a powder.

To this end we first consider a nonrotating single crystal consisting of methyl groups with an angle β_j between their symmetry axes and the static magnetic field. With restriction to the case of extreme narrowing, $\omega_0\tau_c \ll 1$ (ω_0 is the Larmor frequency, τ_c is the correlation time for the random rotation of the groups), the Zeeman relaxation due to the intramethyl dipolar interaction is given by the following rate equations¹²:

$$\begin{pmatrix} \dot{\Psi}_1 \\ \dot{\Psi}_4 \end{pmatrix} = C \begin{pmatrix} -2(1+3\cos^2\beta_j) & 6\cos\beta_j \\ 4\cos\beta_j & -3 \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_4 \end{pmatrix} \quad (1)$$

where $\Psi_1 = M_z - M_0$, $\Psi_4 = P_{E^a} - P_{E^b}$, M_z is the Zeeman magnetization and M_0 its equilibrium value, and P_{E^a} and P_{E^b} are the total populations of the E^a and E^b species, respectively. $C = \frac{9}{16}\tau_c\gamma^4\hbar^2/r_0^6$; r_0 is the proton-proton distance. The result is a