Evaluation of soft x-ray yield of Al from 27.557-MeV neutral particles

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Extreme ultraviolet (XUV) emission from Al bombarded by 50-MeV H^0 particles has been reported by James, Sauers, and Arakawa. However, the contribution to the observed signal from scattered electrons has not been evaluated, and the origin of XUV light was not determined since only broadband filters were used. We have therefore measured the XUV emission for 15 keV electrons incident on an Al target using a grazing incidence spectrometer. We find the emission is composed primarily of Al L_{23} soft x rays and determine a yield of 0.021 photons/electron. This value is large compared with previous work with high-Z materials, and our yield values are 100 times higher than standard theories which do not consider secondary electrons. We show that L-shell emission in low-Z materials is due primarily to ionizations from secondary electrons created near the surface. Since the number of secondary electrons created by an energetic particle is roughly proportional to the energy deposited by the particle, relative x-ray yields from energetic protons and electrons can be determined from a knowledge of stopping powers. Using stopping power calculations, we estimate that the Al L_{23} soft x-ray yield from 27.542-MeV proton bombardment is 0.027 photons/proton. A 27.557-MeV H^0 particle is essentially equivalent to a 27.542-MeV proton and a 15-keV electron; thus, the yield of Al L_{23} soft x rays from 27.557-MeV H^0 particle bombardment is 0.048 photons/particle.

INTRODUCTION

Experimental yields of characteristic high-energy x-ray radiation emitted from high-Z materials when bombarded with electrons, protons, or ions are well documented in the literature, and their values agree well with theoretical calculations.[1–9] However, yields for extreme ultraviolet (XUV) radiation produced in low-Z elements from electron, proton, or neutral particle bombardment are more difficult to obtain. For K-shell emission from Li and Be and L-shell emission from Mg, Al, and Si, uncertainties in the fluorescent yield make theoretical yield calculations inaccurate, and the low efficiency and large background of energy-dispersive solid-state analyzers in the XUV range make experimental yield measurements difficult. The lack of comparative results for experiments involving XUV emission makes yield values for these light elements questionable. One such experiment involves XUV emission from Al bombarded with neutral particles. Previous experimental work for the Lethality Assessment Program of the Strategic Defense Initiative (SDI) by James, Sauers, and Arakawa gave a yield of 0.04–0.08 XUV photons/H^0 particle for XUV radiation emitted by Al when bombarded with 50-MeV H^0 particles.[10] The origin of the emission was not determined since only broadband filters were used for wavelength discrimination. Additionally, the experiment did not assure that scattered electrons, which might have falsely increased yield, were completely eliminated.

In this paper, we determine the yield of Al L_{23} soft x rays bombarded by 27.557-MeV H^0 particles to further specify the magnitude and constituents of the yield reported by James, Sauers, and Arakawa.[10] We determine the XUV yield for H^0 by experimentally measuring the yield from electron bombardment and calculating the yield from proton bombardment. Our calculations of the proton-induced yield from the electron-induced yield are based on the role that secondary electrons play in the L-shell vacancy production of low-Z elements.

We have measured the emission spectrum in the XUV region of Al bombarded by 15-keV electrons using a grazing incidence spectrometer. Special care was taken to exclude scattered electrons. With the elimination of scattered electrons and the dispersive analysis provided by the spectrometer, we have determined the specific nature of the XUV emission. We find that the emission in the XUV region is composed primarily of Al L_{23} soft x rays.

Gryzinski[11] has provided theoretical cross sections for ionization by electrons. With values for the stopping power, range, fluorescent yield, and the absorption coefficient of Al, the theoretical yield of Al L_{23} soft x rays from 15-keV electron bombardment can be calculated. However, despite good agreement between theoretical and experimental values in previous experiments involving K-shell x rays of high-Z materials, our experimental values for L-shell x rays of Al, a low-Z element, do not agree with standard theories.[1–4] We attribute this discrepancy to the additional ionizations produced by secondary electrons in the sample. By modifying standard theories with the inclusion of soft x-ray production by secondary electrons, we show that secondary electrons can considerably increase the L-shell x-ray yield in low-Z elements. For 15-keV electron bombardment, the Al L_{23} soft x-ray emission is due primarily to secondary electron interactions near the surface of the solid. We use these observations and stopping power data for electrons and protons in Al to calculate the Al L_{23} soft x-ray yield from 27.542-MeV protons. This leads to the yield of Al L_{23} soft x rays bombarded by 27.557-MeV H^0 particles.

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EXPERIMENT

A scanning electron microscope[12] (SEM) provided the 15-keV electron beam for excitation. The electrons were incident on an Al sample 45° from the normal to the sample surface. Soft x rays emitted perpendicular to the incident electrons (−45° from the sample normal) entered a grazing incidence spectrometer (Fig. 1). The electron beam illuminated 0.01 mm^2 of Al, and the beam current hitting the sample was monitored. Typical beam currents were 1.0–25.0 μA.

Soft x rays passed through a slit and baffle arrangement and illuminated a Au-coated 600 grooves/mm spherical grating at an incident angle of 84.4°. The grating efficiency was measured to be 0.17. Once the soft x rays strike the grating, a certain fraction will be focused and diffracted into a spectrum. The spectrum of soft x rays was detected by a channeltron electron multiplier[13] (CEM) with a 0.72-mm slit. The CEM was operated in the analog mode with a −2.5-kV potential on the photocathode, and the gain of the channeltron was measured to be 3×10^4. The quantum efficiency of the CEM photocathode was measured at the National Synchrotron Light Source at Brookhaven National Laboratory. A CEM quantum efficiency of 0.24 was measured just below the Al L_{23} edge by comparing the photocurrent emitted by the CEM photocathode with the photocurrent generated by a calibrated Au photodiode with a known efficiency.

By scanning the exit slit and CEM across the spectrum, the entire soft x-ray region could be examined. A typical scan of the XUV spectrum is shown in Fig. 2. Peaks of interest were integrated to determine the total number of x rays detected from that wavelength region. The combination of slits and baffles, a negative 2.5-kV bias on the CEM, and bending magnets eliminated spurious signals by preventing scattered electrons from reaching the CEM.

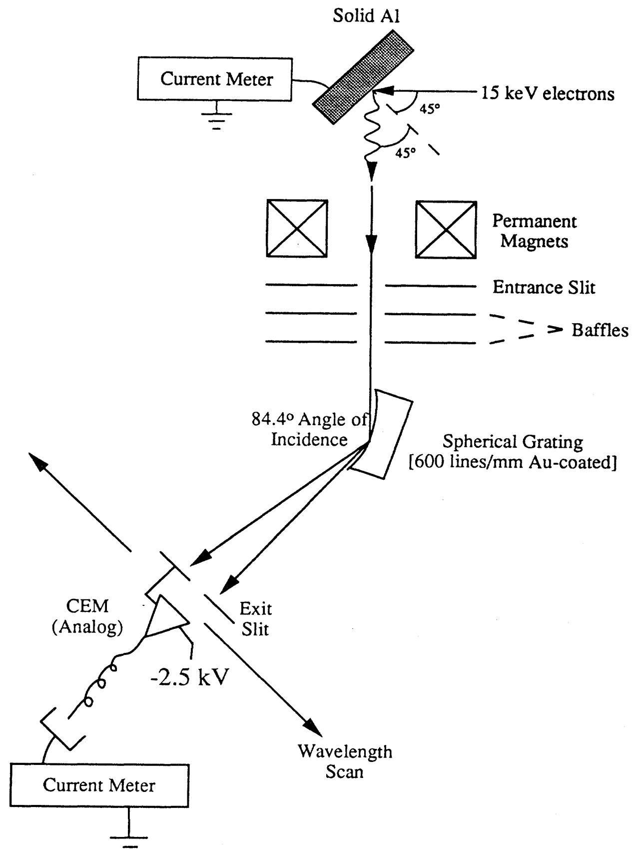


FIG. 1. Experimental apparatus for determining the Al L_{23}-shell soft x-ray yield from 15-keV electron excitation.

RESULTS AND CALCULATIONS FOR 15-keV ELECTRONS

The experimental yield of Al L_{23}-shell soft x rays produced per 15-keV electron can be determined by the equation

$$Y=\frac{N_\gamma \Omega}{N_e \Delta\Omega \varepsilon}\ , \tag{1}$$

where N_γ is the number of photons detected by the CEM, N_e is the number of incident electrons, $\Delta\Omega$ is the solid angle subtended by the spectrometer, Ω is the relative total angle photon emission assuming a $\cos^2$ distribution of photons, and ε is the grating efficiency. We obtained a yield of 0.021 Al L_{23} soft x rays per incident 15-keV electron. This yield represents the number of Al L_{23} soft x rays emitted into the vacuum region from solid Al when bombarded with 15-keV electrons at an angle of 45° from the normal of the Al-vacuum interface.

Standard theories can be used to calculate the Al L_{23} soft x-ray yield; however, several factors make the theory inaccurate. Specifically, uncertainties in the fluorescent yield, uncertainties in the range of electrons in Al, and contributions to the yield from secondary electrons make reliable theoretical calculations difficult. Nevertheless, theoretical calculations can be used to help describe the physical processes that lead to soft x-ray emission. The yield of soft x rays induced by the primary electron will be calculated using standard theories; then, the yield induced by secondary electrons will be calculated.

The yield from the primary electron can be calculated by the formula

$$Y_{\text{primary}}=\int_U^{E_0} 6N\omega_L\sigma(E)\left[\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi/2} e^{-\mu x\cos\alpha/\cos\phi}\sin\phi\, d\phi\, d\theta\right]\left[\frac{dx}{dE}\right]dE\ , \tag{2}$$

where N is the density of atoms and $\sigma(E)$ is the cross section for ionization per L-shell electron. The limits of integration the binding energy of the L_{23}-shell electrons (U) and the energy of the incident electron (E_0); the factor of 6 corresponds to the six electrons in the L_{23} shell. The fluorescent yield[14] ω_L is given by

$$\omega_L=\frac{Z^4}{1.02\times10^8+Z^4}\ . \tag{3}$$

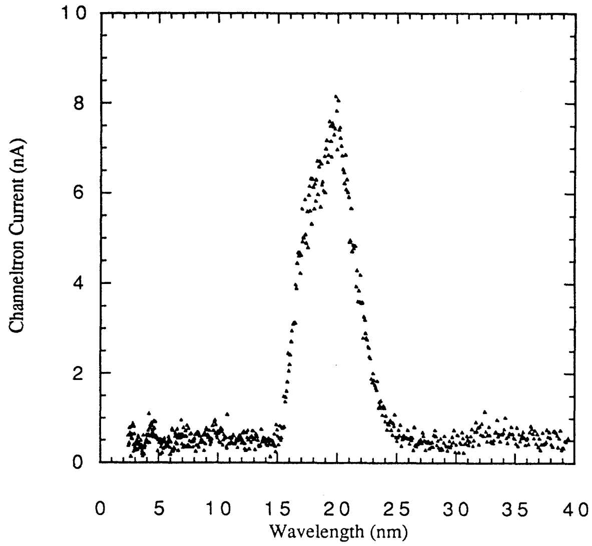


FIG. 2. Extreme ultraviolet spectrum of Al L_{23}-shell soft x rays produced by 15-keV electron bombardment. The detailed structure of the emission spectrum is not apparent since large slits were used to increase light collection for more accurate results.

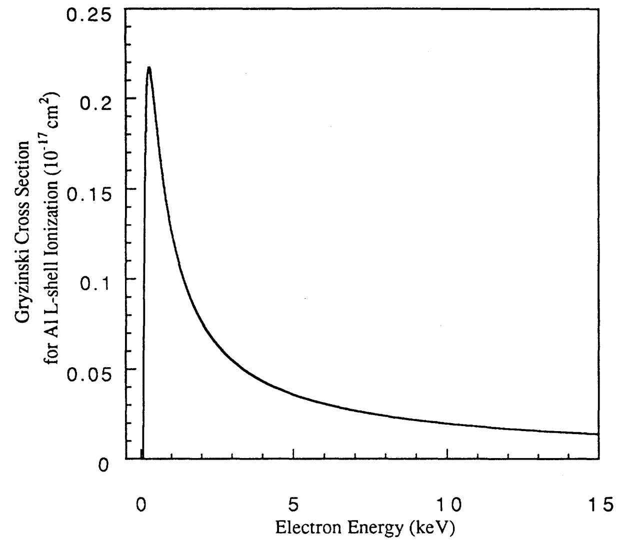


FIG. 3. Theoretical cross section for Al L-shell ionization given by Gryzinski (Ref. 11).

The double integration of the exponential term in Eq. (2) accounts for the average x-ray absorption in the sample, with the normalization factor $1/(4\pi)$. The inverse of the stopping power (dX/dE) is an empirical fitting to the stopping power calculated by Ritchie, McConnell *et al.*[15]

The ionization cross section per L-shell electron as a function of the excitation electron energy (E) and the binding energy of the emitted electron (U) is given by Gryzinski[11] as

$$\sigma(E)=\frac{\sigma_0}{U^2} g\left[\frac{E}{U}\right] . \tag{4}$$

If the bombarding particle is an electron, σ_0 is 6.56×10^{-14} $\text{eV}^2\,\text{cm}^2$. The function $g(E/U)$ is a maximum at $\sim 4U$ as shown in Fig. 3.

The limits of integration for the inner double integral limit the solid angle of emission to 2π since x rays emitted into the sample will be completely absorbed. μ is the mass absorption coefficient for Al L_{23} soft x rays in Al, α is the incidence angle for the electrons (45°), and ϕ is the angle of exit for the x rays relative to the sample normal. μ is $4\pi k/\lambda$, where k is the extinction coefficient of Al.[16] The distance x traversed by the electrons in the sample as a function of energy is given by

$$x(E)=R(E_0)-R(E) , \tag{5}$$

where R is the range of an electron in Al.

There are discrepancies in the range of electrons in Al in the literature for electron energies of interest here. Three different range-energy expressions were used. Feldman gives

$$R(E)=257E^{1.77} , \tag{6}$$

where R is in 10^{-8} cm and E is the electron energy in keV.[17] Thomas and Pattison give

$$R(E)=256.5\times10^{-5}E^{1.3} , \tag{7}$$

where R is in $\mu\text{g}\,\text{cm}^{-2}$ and E is the electron energy in eV.[18] Finally, Fitting gives

$$R(E)=900\rho^{-0.8}E^{1.3} , \tag{8}$$

where R is in 10^{-8} cm, ρ is the density in $\text{g}\,\text{cm}^{-3}$, and E is the electron energy in keV.[19] The formulas of Feldman, Thomas and Pattison, and Fitting give a range of 3.10, 2.64, and 1.37 μm for a 15-keV electron in Al, respectively. These range expressions represent the maximum range of an electron in the solid. The average range of a number of electrons should be smaller. The discrepancy in the ranges causes a significant variation in the yield calculations as a result of the short penetration depths of the soft x rays. Evaluation of Eq. (2) with the above parameters gives yields of 0.000 23, 0.000 37, and 0.000 70 photons/electron for the primary 15-keV electron (Table I).

TABLE I. Theoretical yield of Al L_{23}-shell soft x rays from 15-keV electron bombardment due to the primary electron, secondary electrons, and primary plus secondary electrons. Yields are given in photons per primary electron for different range-energy expressions.

Range-energy expression	Y_{primary}	Y_{2nd}	$Y=Y_{\text{primary}}+Y_{\text{2nd}}$
Feldman	0.000 23	0.0013	0.0015
Thomas and Pattison	0.000 37	0.0020	0.0024
Fitting	0.000 70	0.0034	0.0041

The yield from the secondary electrons created in the solid by the primary electron can be calculated in a similar fashion. If $S(e,E)$ is a function that describes the secondary electron distribution created in Al by an electron with energy E, the yield from secondary electrons with energy e can be written as

$$Y_{2\mathrm{nd}}=\int_U^{E_0} 6N\omega_L \frac{\int_U^E S(e,E)\sigma(e)de}{\int_{E_{\min}}^E S(e,E)de}\left[\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi/2} e^{-\mu x\cos\alpha/\cos\phi}\sin\phi\, d\phi\, d\theta\right]\left[\frac{dx}{dE}\right]dE \; . \tag{9}$$

Here the cross section for ionization by the primary electron in Eq. (2) is replaced by the integral of the secondary electron distribution multiplied by the cross section for ionization by the secondary electron; the integral of the secondary electron distribution alone in the denominator serves to normalize the integral in the numerator. The limits of integration for the numerator are the binding energy of the L_{23}-shell electrons (U) and the degraded energy of the primary electron (E). The limits of integration for the denominator are $E_{\min}$ and E, where $E_{\min}$ represents the minimum energy of the secondary electrons.

$S(e,E)$ was chosen to be $1/e$ for all primary energies (E) based on the measurements by McConnell *et al.*[15] Since $1/e$ goes to infinity at $e=0$, 10 eV was used as $E_{\min}$. This includes the Al volume plasmon energy of 15 eV. Evaluation of Eq. (7) with the above parameters gives yields of 0.0013, 0.0020, and 0.0034 photons/primary electron from the secondary electrons produced by the primary electron (Table I). The total yield is the sum of the yield from the primary electron and the yield from the secondary electrons produced in the solid. The total calculated yield Y becomes $Y_{\mathrm{primary}}+Y_{2\mathrm{nd}}$ or 0.0015, 0.0024, and 0.0041 photons/primary electron (Table I). Approximately 85% of this yield is due to the soft x rays created by the secondary electrons in the solid. Figures 4, 5, and 6 show the relative contribution to the yield by primary and secondary electrons for calculations using the Feldman, Thomas and Pattison, and Fitting range-energy expressions.

The theoretically determined yields differ from the experimental value by factors between 5 and 10. The primary uncertainties in the theory are the fluorescent yield, the approximate secondary electron distribution, and the range of the electrons in the solid. The theory does not include soft x-ray emission from secondary fluorescence or soft x-ray emission from electrons that enter the solid, create L-shell ioniozations, and then exit the solid. Any of these processes or combinations of these processes could account for the difference between experimental and theoretical results. These uncertainties indicate the difficulty of theoretically calculating the soft x-ray yield for light elements. However, the theory clearly shows that the yield of soft x rays in solid Al is primarily due to secondary electrons created near the surface of the solid.

CALCULATION OF YIELD FOR 27.557-MeV H^0 PARTICLES

We can calculate the yield of Al L_{23} soft x rays from H^0 bombardment using the yield from electrons obtained in our experiment. A H^0 particle consists of a proton and electron. Since the electron and proton are bound by a small energy (13.6 eV), an energetic H^0 particle striking a solid will immediately split into an energetic proton and electron. Thus a beam of H^0 particles is essentially equivalent to a beam of protons and a beam of electrons. Although the incident proton and electron are traveling with the same velocity upon impact, their energies are different because of their masses; therefore, a 27.557-MeV H^0 particle will be equivalent to a 27.542-MeV proton and a 15-keV electron. We have measured an Al L_{23} soft x-ray yield of 0.021 photons/electron for 15-keV electron excitation. The yield from 27.542-MeV proton excitation can be calculated by examining the processes involved in emission from electron excitation.

When a 15-keV primary electron enters solid Al, it gradually loses energy by scattering or by collision processes until it comes to rest at a depth $>1.0\ \mu$m. L_{23} soft x rays can be produced when a primary electron or a secondary electron produces a vacancy in an Al L_{23} shell. The cross section for the production of an Al L_{23}-shell vacancy is greatest for electrons with an energy of $\sim 4U$ (~ 300 eV), where U is the ionization energy for the Al

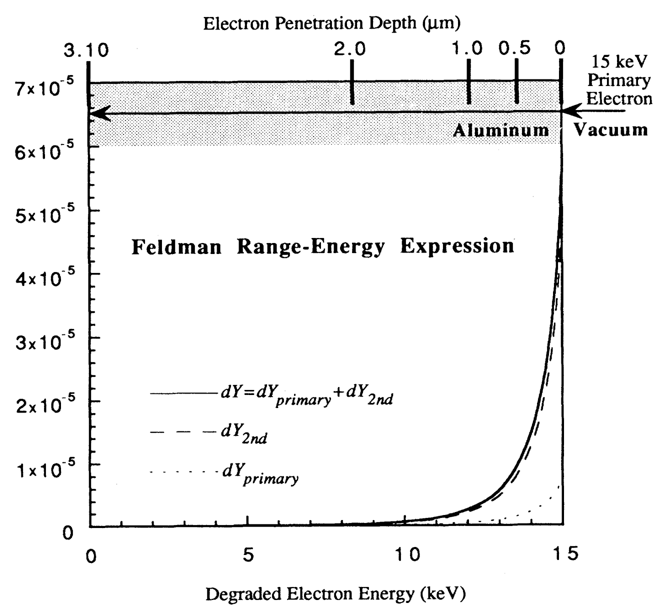
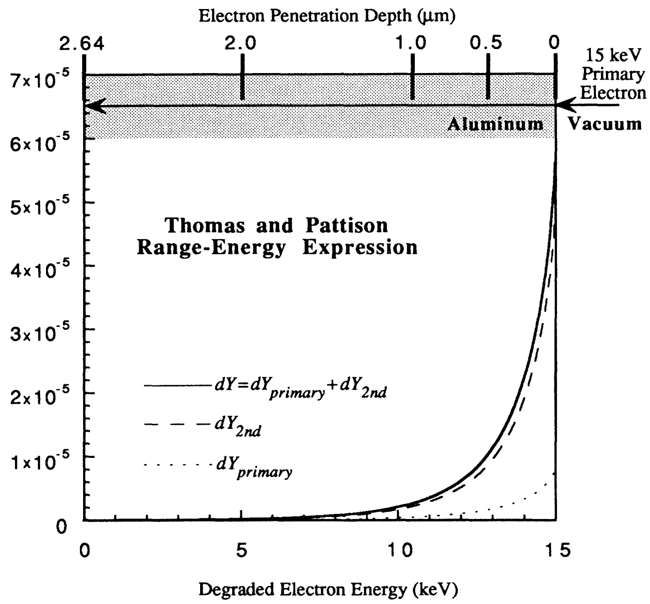


FIG. 4. Contribution to the Al L_{23}-shell soft x-ray yield by the primary 15-keV electron and the secondary electrons in terms of the degraded energy of the primary electron and the penetration depth of the primary electron according to Feldman.



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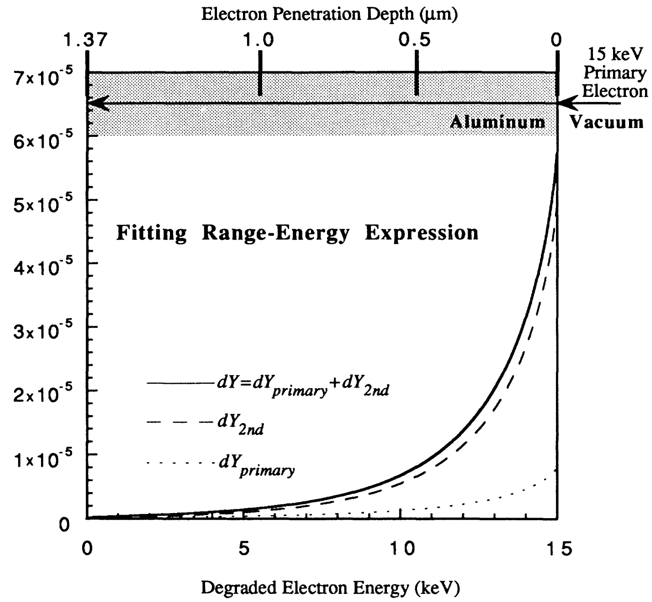

FIG. 6. Contribution to the Al L_{23}-shell soft x-ray yield by the primary 15-keV electron and the secondary electrons in terms of the degraded energy of the primary electron and the penetration depth of the primary electron according to Fitting.

L_{23} shell (72.5 eV). Thus primary electrons will have the greatest probability of producing an L_{23}-shell vacancy at a depth of >1.0 μm when they have slowed to energies close to 300 eV. However, secondary electrons with energies ranging from 100 to 1000 eV will have relatively high probabilities of producing L_{23}-shell vacancies all along the track of the primary electron. The majority of L_{23} soft x rays contributing to the yield are created within 1 μm of the surface since the absorption coefficient for Al L_{23} soft x rays in Al is 2.5 μm^{-1}.[15] Therefore, secondary electrons produced within 1.0 μm of the surface are mainly responsible for L_{23} soft x-ray emission. Since 27.542-MeV protons penetrate into the sample much deeper than 15-keV electrons, the soft x-ray emission process for 27.542-MeV protons will also be primarily due to secondary electrons.

For keV electrons and MeV protons, the energy lost in the first 1.0 μm of an Al sample is virtually all transferred to secondary electrons, and the energy distribution of those electrons is the same. Thus the relative number of secondary electrons produced by electrons and protons in the first 1.0 μm of an Al sample can be obtained from the relative amount of energy deposited in that region by the incident electron and proton. The stopping powers for a 15-keV electron and a 27.542-MeV proton in Al are 3.3 keV/μm (Ref. 15) and 4.2 keV/μm, respectively.[20] Therefore, the ratio of secondary electrons produced by a 15-keV electron and a 27.542-MeV proton in the first 1.0-μm layer of Al is 3.3/4.2, and the yield of Al L_{23} soft x rays from 27.542-MeV proton bombardment is (4.2/3.3) 0.021 or 0.027 photons/proton. Finally, the yield of Al L_{23} soft x rays from 27.557-MeV H^0 particle bombardment determined by our experiment is 0.021 photons/electron $+0.027$ photons/proton or 0.048 photons/(H^0 particle).

The yield from 50-MeV H^0 particles should not be more than the yield from 27.557-MeV H^0 particles. A 50-MeV H^0 particle is essentially composed of a 27.217-keV electron and a 49.973-MeV proton. The stopping powers for a 27.217-keV electron and a 49.973-MeV proton are 1.9 keV/μm (Ref. 15) and 2.4 keV/μm (Ref. 20), respectively; these values are 0.57 of the values corresponding to the 27.557-MeV H^0 particle. The yield from 50-MeV H^0 particles should be related to the yield from 27.557-MeV H^0 particles by roughly the same factor; thus, our results give a yield of (0.57) 0.048 or 0.027 photons/(H^0 particle) for 50-MeV H^0 particle bombardment. Our result is within a factor of 2 of the yield reported by James, Sauers, and Arakawa of 0.04–0.08 photons/particle from 50-MeV H^0 particle bombardment.

CONCLUSION

We have measured the absolute intensity of L_{23} soft x rays from an Al target bombarded with 15-keV electrons. Our experimental yield of 0.021 Al L_{23} soft x rays per incident 15-keV electron is 100 times higher than predicted by standard theories which neglect ionizations produced by secondary electrons. Including secondary-electron-induced ionizations shows that the majority of ionizations capable of producing L_{23} soft x rays that can exit the solid are produced by secondary electrons near the surface. By the use of stopping power data and by including secondary electrons in L-shell vacancy production, we calculate a yield of 0.027 Al L_{23} soft x rays per incident 27.542-MeV proton. Using our measured yield from electron bombardment and calculated yield from proton bombardment, we have determined a yield of 0.048 photons/particle for Al L_{23}-shell soft x rays from 27.557-MeV H^0 particles.

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[1]V. Metchnik and S. G. Tomlin, Proc. Phys. Soc. London **81**, 956 (1963).

[2]A. J. Campbell, Proc. R. Soc. London **274**, 319 (1963).

[3]M. Green and V. E. Cosslett, Proc. Phys. Soc. London **78**, 1206 (1961).

[4]M. Green and V. E. Cosslett, J. Phys. D **1**, 425 (1968).

[5]J. D. Garcia, Phys. Rev. A **1**, 280 (1970).

[6]G. A. Bissinger, J. M. Joyce, E. J. Ludwig, W. S. McEver, and S. M. Shafroth, Phys. Rev. A **1**, 841 (1970).

[7]G. A. Bissinger, S. M. Shafroth, and A. W. Waltner, Phys. Rev. A **5**, 2046 (1972).

[8]S. M. Shafroth, G. A. Bissinger, and A. W. Waltner, Phys. Rev. A **7**, 566 (1973).

[9]C. E. Busch, A. B. Baskin, P. H. Nettles, S. M. Shafroth, and A. W. Waltner, Phys. Rev. A **7**, 1601 (1973).

[10]D. R. James, I. Sauers, and E. T. Arakawa, Phys. Rev. B **36**, 4458 (1987).

[11]M. Gryzinski, Phys. Rev. **138**, A336 (1964).

[12]Novascan 30, SEMCO Instruments Co. Ltd., Ottawa, Canada, K2C OA7.

[13]Model 4028, Galileo Electro-Optics Corp., Galileo Park, Sturbridge, MA 01518.

[14]N. A. Dyson, *X-rays in Atomic and Nuclear Physics* (Cambridge University Press, Cambridge, England, 1990), pp. 76–77.

[15]W. J. McConnell, R. D. Birkhoff, R. N. Hamm, and R. H. Ritchie, Radiat. Res. **33**, 216 (1968).

[16]*Handbook of Optical Constants,* edited by E. D. Palik (Academic Press, New York, 1985), p. 395.

[17]C. Feldman, Phys. Rev. **117**, 455 (1960).

[18]S. Thomas and E. P. Pattison, J. Phys. D **3**, 349 (1970).

[19]H. J. Fitting, Phys. Status Solidi A **26**, 525 (1974).

[20]H. H. Anderson and J. F. Ziegler, *Hydrogen Stopping Powers and Ranges in All Elements* (Pergamon Press, New York, 1977).

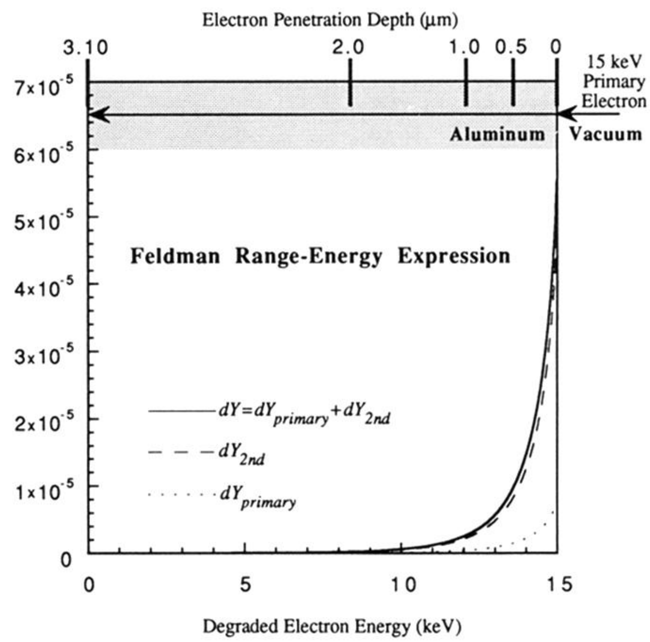
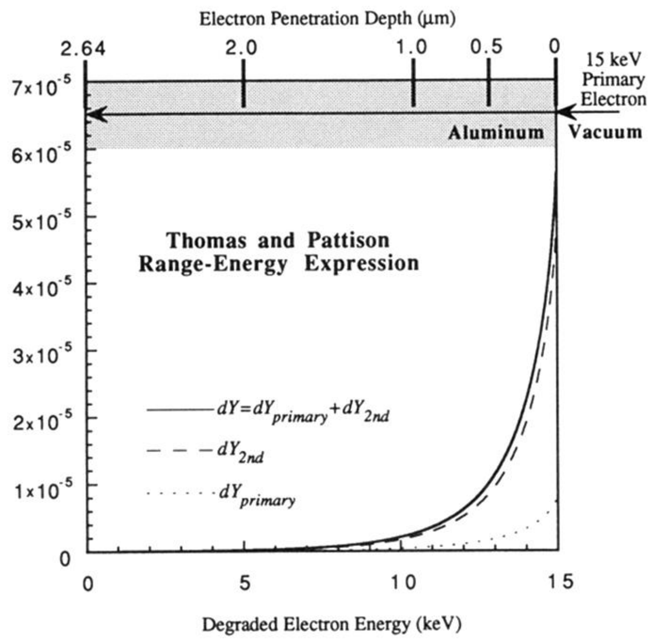


FIG. 4. Contribution to the Al L_{23}-shell soft x-ray yield by the primary 15-keV electron and the secondary electrons in terms of the degraded energy of the primary electron and the penetration depth of the primary electron according to Feldman.



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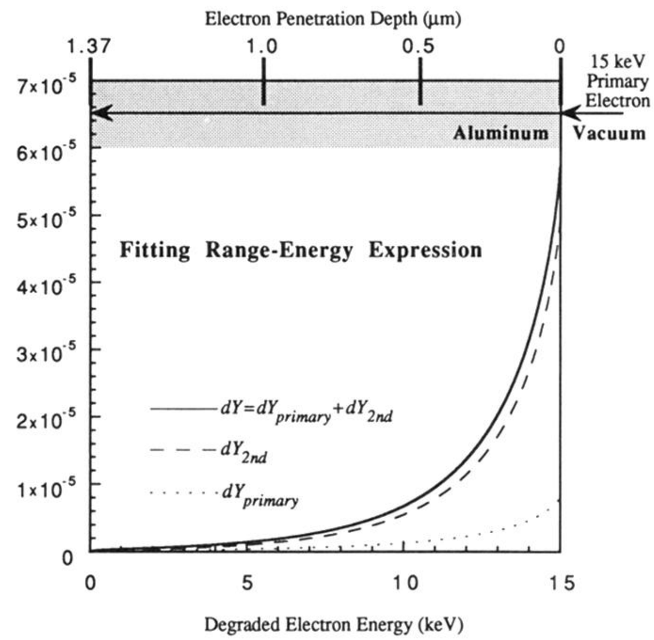

FIG. 6. Contribution to the Al L_{23}-shell soft x-ray yield by the primary 15-keV electron and the secondary electrons in terms of the degraded energy of the primary electron and the penetration depth of the primary electron according to Fitting.