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X-Ray Production in Low Energy Proton Stopping

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Abstract

The X-ray yields of stopping protons in an iron-nickel-cobalt alloy are calculated for use in predicting radiation damage in encased electronic devices.

INTRODUCTION

It is observed in some electronic devices that radiation effects result from low energy protons stopping in the external casing materials without crossing the device sensitive region (refs. 1 and 2). In order to explain this phenomenon, secondary radiations produced in the casing material are suspect. The most likely radiations to penetrate the casing material are the X-rays produced by proton impact. In the present note, the X-ray yields from stopping protons in an iron-nickel-cobalt alloy are calculated. The methods are easily extended to other materials.

X-RAY PRODUCTION CROSS SECTIONS

The K-shell and L-shell ionization cross sections for iron, cobalt, and nickel have been evaluated with the results given in Tables 1 and 2, using the work of Khandelwal, Choi, and Merzbacher (ref. 3). The X-ray fluorescence yield is in competition with Auger and Coster-Kronig transitions, and the fractional fluorescence yield is given in refs. 4, 5, and 6. The K-shell and L-shell fractional yields are shown in Table 3.

LOW ENERGY PROTON TRANSPORT

If nuclear processes and straggling are neglected, the proton transport equation is given as

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S(E)\right] \psi\ (x,E) = 0 \tag{1}$$

where $\psi(x,E)$ is proton flux at x of energy E. The solution is given as

$$\psi(x,E) = \frac{S[\varepsilon(x + R(E))]}{S(E)} \psi\ [0,\varepsilon\ (x + R(E))] \tag{2}$$

where $r(E) = \int_0^E dE'/S(E')$ and $\varepsilon(x)$ is inverse of R(E). The result (equation 2) can now be used to calculate the X-ray yields $Y_X(x)$as

$$Y_X(x) = \overline{w}_X \int_0^\infty \sigma_X(E)\ \psi(x,E)\ dE \tag{3}$$

where $\sigma_X(E)$ is the macroscopic ionization cross section and $\overline{w}_X$ is the shield's fractional fluorescence yield. The yield for a monoenergetic beam of protons is

$$Y_X\ (x) = \overline{w}_X \int_0^\infty \sigma_X(E)\ \phi_P\ \frac{S[\varepsilon(x + R(E))]}{S(E)}\ \delta(\varepsilon[x + R(E)] - E_0)\ dE$$

$$= \overline{w}_X \int_0^\infty \sigma_X\ [\varepsilon(r)]\ \phi_P\ \delta(x + r - r_0)\ dr \qquad (4)$$

where $r_0 = R(E_0)$ and $r = R(E)$. The result is

$$Y_X\ (x) = \overline{w}_X\ \sigma_X[\varepsilon(r_0 - x)]\ \phi_P \qquad (5)$$

as one would presume. The total yield $\overline{Y}_X$ in stopping is then

$$\overline{Y}_X = \overline{w}_X\ \phi_P \int_0^{r_0} \sigma_X\ [\varepsilon(r_0 - x)]\ dx \qquad (6)$$

The required functions will now be approximated to evaluate the integral (equation 6).

STOPPING POWER AND CROSS SECTION PARAMETERS

The low energy portion of the stopping power curve was shown by Fermi to be

$$S(E) \approx a\sqrt{E} \qquad (7)$$

The stopping power to several MeV is adequately approximated by

$$S(E) = \frac{a\sqrt{E}}{(1 + bE)} \qquad (8)$$

and is known to have a maximum at approximately $E_m \approx 100$ keV so that

$$\left.\frac{dS}{dE}\right|_{E_m} = 0 \tag{9}$$

and

$$S_m = S(E_m) \tag{10}$$

are sufficient to determine the coefficients a and b to find

$$S(E) = Z\, S_m \sqrt{\frac{E}{E_m}} \Big/ \left(1 + \frac{E}{E_m}\right) \tag{11}$$

The range is then found to be

$$R(E) = \frac{\sqrt{E_m E}}{S_m} \left(1 + \frac{E}{3\, E_m}\right) \tag{12}$$

Assuming the density to be 8.4 g/cm^3 and taking $S_m \simeq 246$ keV/μ, we find the ionization cross sections can be reasonably approximated by

$$\sigma_X\,[E(r)] \simeq \sigma_X\,(E_0)\,\left(\frac{r}{r_0}\right)^{2.2} \tag{13}$$

which holds below 1 MeV. This gives a total yield of

$$Y_X = \frac{\overline{w}_X}{3.2}\, r_0 \sigma_X(E_0)\, \phi_P \tag{14}$$

We have taken the composition of the alloy to be 54 percent Fe, 29 percent Ni, and 17 percent Co to find the K shell fluorescence yield for 1 MeV protons to be

$$\overline{Y}_K = 9 \times 10^{-4} \text{ X-rays/proton} \tag{15}$$

To assess the effects of these X-rays on device performance requires additional transport calculations of the X-rays through the device itself.

CONCLUDING REMARKS

The present formalism provides a means of estimating the X-ray production in proton exposures. The fluorescence yield may be used as source terms in a photon/electron transport code to further evaluate their effects on device performance.

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Table 1 - K-shell Ionization Cross Sections (b) as a Function of Proton Energy (MeV)

E	Fe	Co	Ni
0.1	0.054	.035	.021
0.5	11.0	8.49	5.86
1.0	70.8	50.3	35.5

Table 2 - L-shell Ionization Cross Sections (b)
as a Function of Proton Energy (MeV)

E	Fe	Co	Ni
0.1	4.27E4	2.71E4	1.62E4
0.5	3.68E5	2.80E5	2.06E5
1.0	5.28E5	4.14E5	3.25E5

Table 3 - Fractional Fluorescence Yield

Element	$\bar{w}_K$	$\bar{w}_L$
Fe	0.34	6.4E - 3
Co	~0.37	7.7E - 3
Ni	0.41	9.1E - 3

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