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# Silicon Detector Dead Layer Thickness Estimates using Proton Bremsstrahlung from Low Atomic Number Targets

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**Abstract.** Proton induced bremsstrahlung radiation in the 1-5 keV energy range has been used to estimate the silicon dead layer thickness in a Si(Li) detector. This novel technique does not require accurate bremsstrahlung cross sections with X-ray energy, it just assumes these cross sections and hence the efficiency corrected yield is both smooth and continuous across the Si K edge at 1.838 keV.

**Keywords:** Bremsstrahlung, detector efficiency, dead layer estimates

## INTRODUCTION

Heavy ions, with MeV energies, impinging on both thin and thick low atomic number targets produce bremsstrahlung X-ray radiation in the energy range 1-10 keV. This radiation is both continuous and smoothly varying and typically has production cross sections which vary from $10^{-8}$ barns/ (keV.sr) at 10 keV to a few barns/ (keV.sr) at 1 keV [1,2]. These characteristics of being smooth, continuous and having higher production yields in the lower 1-5 keV X-ray energy region make them ideal to accurately determine X-ray detection efficiencies. In particular, for silicon type X-ray detectors which have the Si K edge energy at 1.838 keV, this bremsstrahlung radiation can be used to estimate the dead layer thickness at the front of these detector crystals.

Here we describe a novel method for the estimation of silicon detector dead layer thicknesses in the range 0-1 µm in the presence of all other non-silicon absorbers which can be several orders of magnitude thicker. The method uses the measured bremsstrahlung from 3 MeV protons on thin beryllium and 2 MeV protons on thick carbon targets. It does not require an accurate knowledge of the bremsstrahlung production cross sections only that they are smooth and continuous with X-ray energy around the silicon K edge energy at 1.838 keV. Data for a Si(Li) detector with a nominal dead layer of order of 0.1µm is presented in the presence of 75µm thick beryllium window absorbers used to absorb the scattered MeV incident proton beam.

## BREMSSTRAHLUNG MEASUREMENTS

Recent, work shows that the detected heavy ion induced bremsstrahlung radiation has at least three key components covering the X-ray energy range 1-10 keV namely, quasifree (QFEB), secondary electron (SEB) and atomic bremsstrahlung (AB) [1]. For MeV ion bombardment of materials lighter than aluminium ($Z_T$<13) and for copper the characteristic X-rays peaks (for K and L shell excitation) do not generally interfere with the bulk of the background bremsstrahlung radiation in the 1-5 keV X-ray region. For 1-4 MeV proton bombardment the measured bremsstrahlung radiation generally peaks in this region, depending on detection efficiencies, and is ideally suited to determine absolute semiconductor detector efficiencies in this traditionally difficult but important X-ray energy region.

The parameters for characteristic X-ray production by ion beam bombardment are sufficiently well known to predict the X-ray peak yields from both thin and thick targets from a given matrix to within a few percent [3]. For a relatively thin target Cohen and Clayton [3] gave the following expression for the yield Y for an element bombarded by an ion of energy E MeV entering the target at angle $\theta_i$ as,

$$Y = 4.968.10^{-17}\, N.\sigma^{Brem}\, .Q.\Omega.\varepsilon.\ \rho x.\exp[-(\mu/\rho)_T.\ \rho x.\sec(\theta_o)]/\sin(\theta_i) \qquad (1)$$

where N was the number of target matrix atoms/ $cm^3$, $\rho x$ was the target thickness in $\mu g/cm^2$, Q was the total ion charge hitting the target in µC, Ω was the detection solid angle in steradians, ε was the total detection efficiency for the emergent X-rays, $(\mu/\rho)_T$ was the target mass attenuation coefficient ($cm^2/g$) for this X-ray emerging at angle $\theta_o$ to the target surface normal, ρ was the target density in $g/cm^3$. The bremsstrahlung production cross sections $\sigma^{Brem}$ (in barns/ (kev.sr)), have been theoretically calculated by Murozono et al [2] for 3 MeV protons on a range of targets.

For targets up to a few $mg/cm^2$ thick Equ. (1) is quite accurate as a thin target approximation as the exponential term relates to self absorption corrections in the target. Generally this equation is good to 10% or better for targets thinner than one quarter of the ion range in most light matrix materials. Indeed it works reasonable well for X-rays for thick targets too if you assume that the thick target is a thin target with a thickness of between one quarter and one third of the ion range in the target [3].

Equ. (1) shows that the measured yield is proportional to the cross section and the detection efficiency. Hence if the cross is smooth and continuous we would expect the detection efficiency corrected yield to also be smooth and continuous over the same X-ray energy region. We will use this fact in discussions below.

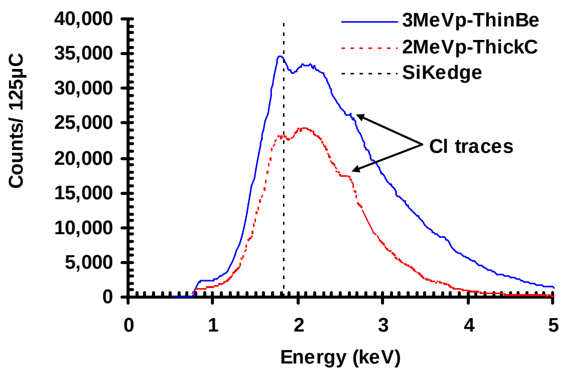


**Fig. 1.** Typical experimental bremsstrahlung yield for 125 µC of 3 MeV protons on thin beryllium and 2 MeV protons thick carbon. The Si K-edge energy is shown as a vertical dotted line.

Fig. 1 shows the measured yield for 125 µC of 3 MeV protons on a relatively thin, 3.4 $mg/cm^2$, beryllium target and for 2 MeV protons on an infinitely thick carbon target. The range of 3 MeV protons in beryllium was 18 $mg/cm^2$ and 2 MeV protons in carbon was 8.4 $mg/cm^2$.

The detector was a Si(Li) detector with a 25 µm Be window and a nominal dead layer thickness of 0.1 µm. The detector solid angle was 1.3 msr. The bremsstrahlung radiation peaked at around 2 keV and rolled off at lower X-ray energies due to the rapidly decreasing detection efficiency with X-ray energy. There was also a discontinuity at 1.838 keV for both spectra corresponding to the Si K edge (see the vertical dotted line in Fig. 1). This K edge jump is discussed further below but was due entirely to the thickness of the dead layer in the Si(Li) detector used. The small peaks to the right of the main bremsstrahlung peaks were due to traces of chlorine in both the beryllium and carbon targets.

## DETECTOR EFFICIENCY

Silicon detector efficiencies and the detection efficiencies of associated absorbing layers and filters between the target and the detector for 1-60 keV X-rays have been study for many years and have been the subject of many successful model simulations, see, for example, reference [3, 4] and the references therein.

The form of the total detection efficiency (ε) is the product of all transmissions ($f_k$) through each absorbing layer (k) and the intrinsic crystal efficiency ($\varepsilon_I$), namely,

$$\varepsilon = f_{Be} * f_{ice} * f_{Au} * f_d * \varepsilon_I \qquad (2)$$

where,

$$f_k = \exp[-(\mu_k/\rho_k)\rho_k x_k] \qquad (3)$$

$(\mu_k/\rho_k)$ is the mass attention coefficient and $\rho_k x_k$ is the thickness of layer with k =Be, ice, Au, and d, for the beryllium window, the ice layer, the gold contact layer and the dead layer respectively and,

$$\varepsilon_I = 1 - \exp[-(\mu_{Si}/\rho_{Si})\ \rho_{Si} D_{Si}] \qquad (4)$$

where $D_{Si}$ is the intrinsic crystal thickness. All these terms and explicit expressions for them have been given elsewhere [3, 4] and will not repeated here.

Fig. 2 is the calculated detection efficiency (for 1-5 keV X-rays) modeled for the current Si(Li) detector with a 25 µm Be window, 0.02 µm gold front contact layer for a 0.1 µm and 0.5 µm dead layer thicknesses. The existence of Si K edge jump at 1.838 keV was clearly a strong function of the dead layer thickness and did not depend on any other non-silicon absorbers between the target and the detector crystal. This demonstrates that the Si Kedge jump in the data of Fig. 1 was due entirely to the thickness of the Si(Li) dead layer in the detector used to obtain these data. Other smaller discontinuities, associated with the gold front contact of the detector are also visible in Fig. 2 but well above 2 keV.

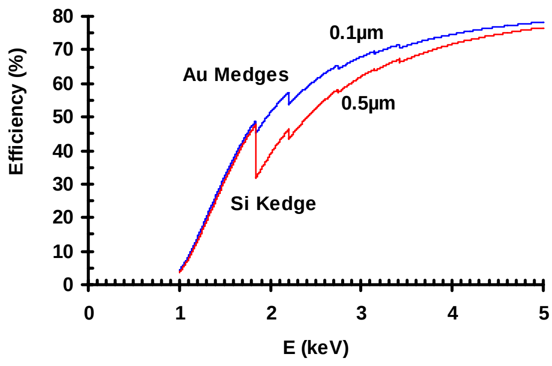


**Fig. 2.** Calculated Si(Li) detector efficiency with X-ray energy, using the techniques of Cohen [4], for 0.1µm (upper curve) and 0.5µm (lower curve) silicon dead layer thicknesses.

Note also that detection efficiencies below 1 keV were much less than 1%, had a higher error associated with them, and hence were not used in this work.

## DEAD LAYER ESTIMATES

Taking the yields of Fig.1 and dividing them by the modeled detector efficiency and replotting as the Yield/ µC/ sr/ 100% efficiency we obtained the data of Fig. 3 for X-ray energies between 1 keV and 5 keV. This log plot covers 5 decades in yield and the Si K edge jump is not clearly visible so has been shown as an expanded section around 1.838 keV.

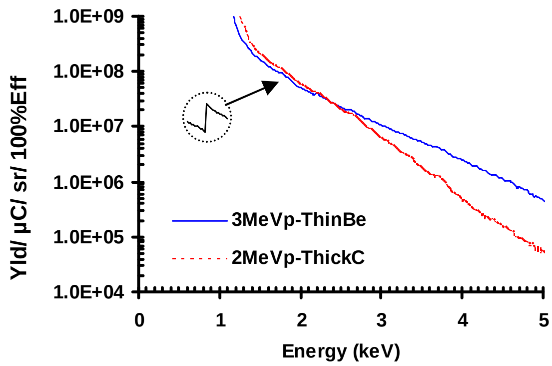


**Fig. 3.** Yields/ µC/ sr/ 100% detector efficiency for 3 MeV protons on thin beryllium and 2 MeV protons thick carbon. The yield across the Si K edge jump at 1.838 keV is shown as the expanded section in the plot.

The height of this jump in the yield curve was a strong function of the dead layer thickness and the idea was to adjust this thickness so that this jump was continuous and smooth across the Si K edge energy. This was done by plotting the yield jump height just above the edge to just below the edge as a function of the dead layer thickness. Fig. 4 is such a plot for thin Be and the thick C targets. The intercept of this line with the dead layer thickness axis was used as an estimate of the detector dead layer. Note also corrections have been made for self absorption of the bremsstrahlung radiation emerging from the target (see Equ. (1) above).

Fig. 4 shows that for dead layers too thin negative Si K edge jump ratios could be obtained and for very thick dead layers the yield curve would not be smooth and continuous as expected. The best dead layer estimates were obtained for the zero Si K edge jump heights. For 3 MeV protons on beryllium a dead layer estimate of (0.083±0.018) µm was obtained and for 2 MeV protons on thick carbon layer the estimate was (0.107±0.025) µm. Both estimates were consistent with the manufacturer's nominal estimate of 0.1 µm.

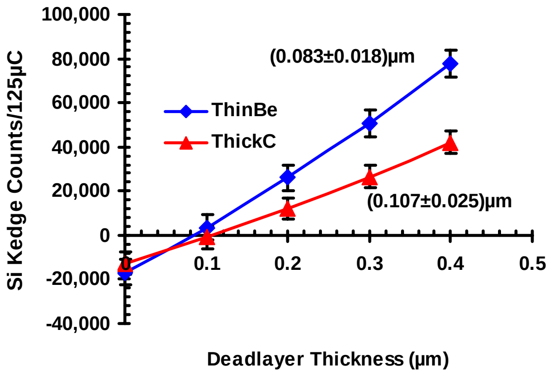


**Fig. 4.** Plots of the Si Kedge jump height yields for thin beryllium and thick carbon bombarded with 3MeV and 2 MeV protons respectively. The zero K edge intercept was an estimate of the detector dead layer thickness.

The thin Be target was preferred because the slope of line of Fig. 4 was steeper and the self absorption corrections were better determined for a thin sample.

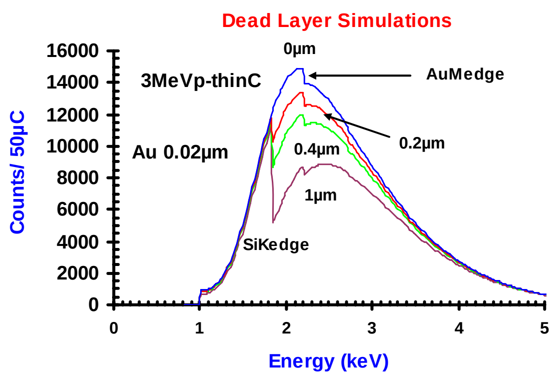


**Fig. 5.** Dead layer bremsstrahlung yield simulations for 3 MeV protons on 2.7 $mgcm^{-2}$ thin carbon.

The shape and position of the bremsstrahlung curve between 1.5 keV and 2.5 keV depended critically on the ion energy, the target atomic number, the dead layer thickness and the gold contact layer thickness of the Si(Li) detector. For heavier targets bombarded with higher ion energies the peak of the bremsstrahlung radiation increases moving towards higher X-ray energies.

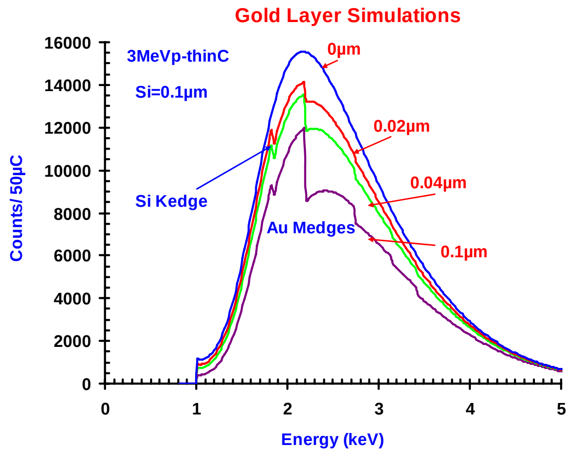


**Fig. 6.** Gold contact layer bremsstrahlung yield simulations for 3 MeV protons on 2.7 mgcm$^{-2}$ thin carbon.

Figs. 5 and 6 are simulations, using Equ. (1) of the bremsstrahlung yield for 50 µC of 3 MeV protons on thin carbon (2.7 mgcm$^{-2}$). Compared with Fig. 1 the bremsstrahlung peak has shifted to higher energies and the Si K edge is now smaller and on the low energy side of the peak and the gold M edges lie closer to the peak maximum.

In Fig. 5 the gold contact layer was kept constant at 0.02 µm and the dead layer varied between 0 µm and 1 µm. While in Fig. 6 the silicon dead layer was kept constant at 0.1 µm and the gold contact layer varied between 0 µm and 0.1µm. The manufacturer's specifications were 0.1 µm for the dead layer and 0.02 µm for the gold contact layer.

Clearly the height and shape of the bremsstrahlung yield curve in the 1 keV to 3 keV X-ray region was a strong function of the dead layer and gold contact layer thicknesses and can be optimized by judicial selection of the ion energy and the target atomic number to estimate either the dead layer thickness or the gold contact thickness of the detector.

## SUMMARY

The smooth and continuous nature of bremsstrahlung radiation production cross sections in the 1-5 keV X-ray region produced by proton bombardment of thin beryllium and thick carbon targets has been used to determine the dead layer thickness of a Si(Li) detector. Provided no other absorbers between the target and the detector are silicon this method can be used to estimate dead layer thicknesses of the order of 0.1 µm or less even in the presence of other absorbers or filters whose thickness can be several orders of magnitude thicker than this.

It is also clear that this method could be used to estimate gold contact layer thicknesses for similar detectors and this work is proceeding.

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