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**THE VARIABLES CONTROLLING THE INTENSITY AND
PURITY OF FLUORESCENCE X RAYS**

by

Edward R. Lawrence, B.Sc., B.Ed.

**A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfilment of the requirements for the degree of**

Master of Science

Department of Physics

Carleton University

Ottawa, Ontario

July 7, 1993

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**THE VARIABLES CONTROLLING THE INTENSITY AND
PURITY OF FLUORESCENCE X RAYS**

submitted by Edward R. Lawrence, B.Sc., B.Ed.

in partial fulfilment of the requirements
for the degree of Master of Science

Thesis Supervisor

Chair, Department of Physics

Carleton University

Date: 11 / 13

Abstract

There are several potential applications and benefits associated with using monoenergetic x-ray beams. These beams can be approximated by fluorescence x-ray beams.

A conventional W-anode x-ray tube was used to irradiate seven pure elemental foils: Zr, Ag, Sn, La, Ho, W, and Pb. The purity and intensity of the resulting fluorescence radiation produced from the Sn and Pb foils was studied as a function of: kVp, primary beam filter thickness, fluorescence beam filter thickness, fluorescence foil thickness, detector angle, and foil angle, using a high purity Ge spectrometer.

In order of decreasing importance, the variables controlling the intensity of the fluorescence x-rays produced are: fluorescence beam filter thickness, kVp, fluorescence foil thickness, primary beam filter thickness, foil angle, and detector angle. Purity is most sensitive to: fluorescence beam filter thickness, and kVp (if close to the K-edge of the foil). The other variables had a much smaller effect on purity.

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Table of Contents

Acceptance sheet	ii
Abstract	iii
Acknowledgements	iv
Table of Contents	v
List of Tables	viii
List of Figures	ix
List of Symbols	xi
 Chapter 1 Introduction	
1.1 Current x-ray spectra	1
1.2 Difficulties with polyenergetic x rays	2
1.3 Methods of producing monoenergetic beams	4
1.3.1 Methods of creating K-shell vacancies	5
1.4 Purity and intensity considerations	8
1.5 Previous investigations of fluorescence x rays	11
1.5.1 Summary of the previous investigations	11
1.5.2 The missing information in the previous studies	19
1.6 Objective of this thesis	20
 Chapter 2 Theoretical considerations	
2.1 Photon interactions and detection	22
2.1.1 Photoelectric interactions and K-shell vacancies	22
2.1.2 Incoherent scatter	24
2.1.3 Coherent scatter	27
2.1.4 Theoretical prediction of Sn K α intensity	28
2.2 Theoretical effect of the variables being studied	29

2.2.1	X-ray tube potential	29
2.2.2	Primary beam filter thickness	31
2.2.3	Fluorescence foil thickness	33
2.2.4	Fluorescence foil orientation	33
2.2.5	Detector orientation	34
2.2.6	Fluorescence beam filter thickness	35
2.3	Detector response	37
 Chapter 3 Apparatus		
3.1	Diagram of the experimental apparatus	40
3.2	Equipment used	41
3.2.1	System assembly	42
3.2.2	System operation	43
3.3	Fluorescence foils studied	44
 Chapter 4 Experimental procedure		
4.1	Detector response correction	46
4.1.1	Energy calibration	47
4.1.2	Isolating the monoenergetic lines	47
4.2	Acquisition of the fluorescence spectra	51
4.3	Measurement of error	52
 Chapter 5 Results		
5.1	Spectra from each of the seven fluorescence foils	54
5.2	Visual effect of fluorescence beam filtration	63
5.3	Intensity and purity vs the controlling variables for Sn	65
5.3.1	X-ray tube potential	65
5.3.2	Primary beam filter thickness	67
5.3.3	Fluorescence foil thickness	69
5.3.4	Fluorescence foil orientation	71

5.3.5	Detector orientation	73
5.3.6	Fluorescence beam filter thickness	75
5.4	Intensity and purity vs the controlling variables for Pb	77
5.4.1	X-ray tube potential	77
5.4.2	Primary beam filter thickness	79
5.4.3	Fluorescence foil thickness	81
5.4.4	Fluorescence foil orientation	83
5.4.5	Detector orientation	85
5.4.6	Fluorescence beam filter thickness	87
 Chapter 6 Conclusions		
6.1	Effect of the variables on intensity	89
6.2	Effect of the variables on purity	91
6.3	Intensity output factor	92
6.4	General remarks	93
6.5	Future work	93
 Appendix 1 Glossary		95

List of Tables

Table	Caption	Page
1.1	Summary of the variables studied in the previous...	19
2.1	Interaction cross sections (10^{-24} cm ² /atom)	25
2.2	Minimum Compton scatter angle	27
3.1	Foils studied	45
4.1	Radioisotopes used for detector response...	46
5.1	Parameters used for each spectrum	55

List of Figures

Figure	Caption	Page
1.1	Typical polyenergetic x-ray spectrum	1
1.2	Radioisotope irradiation of a fluorescence foil	6
1.3	Tin fluorescence spectrum	8
1.4	Schematic diagram of the experimental apparatus	21
2.1	Linear attenuation coefficient vs energy for Gd	32
2.2	Detector response to 59.5 keV photons	37
3.1	Schematic diagram of the experimental apparatus	40
4.1	Probability of detector response events vs energy	50
5.1	Zirconium spectrum	56
5.2	Silver spectrum	57
5.3	Tin spectrum	58
5.4	Lanthanum spectrum	59
5.5	Holmium spectrum	60
5.6	Tungsten spectrum	61
5.7	Lead spectrum	62
5.8	Tin spectrum (no filtration of fluorescence beam)	63
5.9	Tin spectrum (0.125 mm Ag used as filtration)	64
5.10	Effect of x-ray tube potential (Sn)	66
5.11	Effect of primary beam filter thickness (Sn)	68
5.12	Effect of fluorescence foil thickness (Sn)	70
5.13	Effect of fluorescence foil angle (Sn)	72
5.14	Effect of detector angle (Sn)	74
5.15	Effect of fluorescence beam filter thickness (Sn)	76
5.16	Effect of x-ray tube potential (Pb)	78

5.17	Effect of primary beam filter thickness (Pb)	80
5.18	Effect of fluorescence foil thickness (Pb)	82
5.19	Effect of fluorescence foil angle (Pb)	84
5.20	Effect of detector angle (Pb)	86
5.21	Effect of fluorescence beam filter thickness (Pb)	88

List of Symbols

Symbol	Meaning
A	Isotope activity
A_b	Beam area irradiating the fluorescence foil
A_t	Isotope activity needed to irradiate a fluorescence foil to yield the same output as obtained using a W-anode x-ray tube
A_2	Detector area exposed
α	$h\nu/m_0c^2$
c	Speed of light
D	Beam diameter irradiating the fluorescence foil
d	Diameter of the radioactive source of activity A
d_1	Distance from the anode or isotope to the fluorescence foil
d_2	Distance from the fluorescence foil to the detector
E_s	Low energy cutoff for deposition of energy due to the escape of incoherently scattered photons from the Ge crystal
E_b	Minimum energy deposition due to incoherently scattered photons entering the Ge crystal
E_B	Binding energy
E_c	Maximum energy deposition due to the escape of incoherently scattered photons from the Ge crystal
E_K	Binding energy of the K-shell
E_L	Binding energy of the L-shell
E_M	Binding energy of the M-shell
F	Ge fluorescence escape peak
F_K	Fraction of primary beam photons with energy greater than E_K

F_{KN}	Klein-Nishina factor
$F(x_s, Z)$	Atomic form factor
$h\nu$	Photon energy
$h\nu'$	Energy of an incoherently scattered photon
I	Tube current
λ	Photon wavelength
M	Molar mass
m_0	Electron rest mass
μ	Linear attenuation coefficient
$\mu_{K\alpha}$	Linear attenuation coefficient of the fluorescence beam filter at the $K\alpha$ energy of the fluorescence foil
$\mu_{K\beta}$	Linear attenuation coefficient of the fluorescence beam filter at the $K\beta$ energy of the fluorescence foil
μ_p	Linear attenuation coefficient of primary beam filter at energy $h\nu$
μ_s	Linear attenuation coefficient of the fluorescence beam filter at the average scattered photon energy from the fluorescence foil
N	Number of photons of energy $h\nu$ transmitted by the primary beam filter
N_A	Avogadro's number
N_s	Number of atoms/cm ² in the fluorescence foil
N_i	Number of photons of energy $h\nu$ interacting with the foil
$N_{K\alpha}$	Number of $K\alpha$ fluorescence photons
$N_{K\beta}$	Number of $K\beta$ fluorescence photons
N_o	Number of photons of energy $h\nu$ incident on the primary beam filter
N_s	Number of scattered photons
$O_{1,1}$	Output function
Ω	Solid angle
ω_K	K-shell fluorescence yield
P	Fluorescence beam purity

P_{coh}	Probability of a photon scattering coherently from the fluorescence foil such that it is detected
P_{inc}	Probability of a photon scattering incoherently from the fluorescence foil such that it is detected
P_p	Photopeak
Φ	Photon fluence
ϕ	Fluorescence foil angle
R	Distance from the anode focal spot to where Φ is measured
ρ	Density
r_e	Classical radius of an electron
S	Scaling factor
$S(x, Z)$	Incoherent scattering function
σ	Standard deviation
σ_{coh}	Atomic coherent cross section
σ_{inc}	Atomic incoherent cross section
t	Time
T_K	K-shell transition probability
$t_{1/2}$	Half-life
τ	Photoelectric attenuation coefficient
θ	Detector angle / photon scattering angle
V_K	K-shell vacancy probability
x	Fluorescence foil thickness
x_{opt}	Optimum fluorescence beam filter thickness for maximizing purity
x_p	Thickness of the primary beam filter
x_s	Momentum transfer argument
X_{d_1, d_2}	Exposure measured at d_1, d_2
Z	Atomic number

Chapter 1

Introduction

1.1 Current x-ray spectra

X-ray spectra currently used in medical diagnostic imaging are polyenergetic in nature (Figure 1.1). In an x-ray tube, bremsstrahlung radiation is created when the electrons moving from the cathode to the anode slow down rapidly upon impacting the anode. Such radiation is a continuum. If, for example, an x-ray machine was run with a peak voltage of 100 kV, the resulting x-ray photons produced would range in energy from 0 to 100 keV.

Figure 1.1 Typical polyenergetic x-ray spectrum [Ref. 1, p. 23].

As can be seen from Figure 1.1, the resulting bremsstrahlung x-ray spectrum emanating from the x-ray tube does not actually contain photons near 0 keV even though photons very near 0 keV are produced inside the anode. It is also evident that the spectrum is non-uniform in photon fluence rate over the resulting energy range. These two characteristics of bremsstrahlung x-ray tube spectra are due to the fact that the energy fluence rate of bremsstrahlung production falls off linearly as bremsstrahlung photon energy increases (the Kramer's spectrum shape [Ref. 2, p. 212]), and that the lower energy bremsstrahlung photons produced are attenuated within the anode itself, and in the glass envelope, oil, and window of the x-ray tube. The resulting spectrum will have the characteristic shape as seen in Figure 1.1, with few low energy photons and few high energy photons.

Superimposed upon the bremsstrahlung continuum are the fluorescence lines from the anode material. A fluorescence line is created when an electron impinging on the anode causes a K-shell vacancy in an atom of the anode material. The resulting vacancy in the K-shell is quickly filled when an electron from one of the higher atomic shells drops to the K-shell. When this occurs, a photon which has an energy equal to the difference in the binding energies of the shells involved is released. Since the binding energies of the atomic shells are characteristic of the chemical element, the resulting fluorescence x rays produced are sometimes called characteristic x rays.

The two closely spaced lower energy fluorescence lines in Figure 1.1 result from electrons in the L-shell filling K-shell vacancies, while the higher energy fluorescence lines result from electrons in the N- and M-shells filling K-shell vacancies.

1.2 Difficulties with polyenergetic x rays

For certain tasks, it would be advantageous if instead of using a polyenergetic x-ray beam, a monoenergetic x-ray beam could be used

As shown by Motz and Danos [3], all imaging tasks have an optimal energy which will minimize the dose/SNR ratio. If, instead of using a polyenergetic x-ray beam, a monoenergetic x-ray beam at this particular optimal energy was used, the radiation dose to the patient could be reduced while maintaining the same image quality.

Dual energy radiography could be used more efficiently to eliminate the problem of patient motion during subtraction angiography. Currently when imaging the blood vessels in a given region of the body, it is necessary to make an exposure prior to the injection of a radiopaque contrast agent and then to re-expose after the contrast agent has moved into the vessels of interest. If the patient has moved between the two exposures, subtraction of the images will not yield an image which contains only the blood vessels. If, however, two monoenergetic x-ray beams of energies just below and above the K-edge of the contrast agent were used in rapid succession to make a pair of images with the contrast agent filling the vessels, the resulting subtracted image would theoretically show only the vessels of interest. Rutt, Cunningham, and Fenster [4], demonstrated this concept by using lanthanum K-fluorescence to selectively image iodine contrast agent.

With the use of a monoenergetic x-ray beam, it could also be possible to eliminate CT beam hardening artifacts which result when a polyenergetic beam is used. Current CT image reconstruction algorithms assume that a monoenergetic x-ray beam is being used. When a polyenergetic beam is used, the preferential attenuation of the lower energy photons leads to image artifacts such as cupping and streaking [Ref. 5, p. 644].

There are also several general uses for monoenergetic x-ray beams outside of imaging. Device testing and energy calibrations are typical physics laboratory uses. The determination of bone mineral content by examining the ratios of coherent to incoherently scattered photons from bone has been discussed by Olkkonen, Puumalainen, Karjalainen, and Alhava [6], as a method of determining the degree of osteoporosis in bone.

1.3 Methods of producing monoenergetic beams

There are several methods of producing monoenergetic beams.

A radioactive source which decays involving the release of a γ ray of appropriate energy could be used. However, the following calculation shows that a very high activity is necessary in order to approximate the output of a typical x-ray machine. The calculation assumes that one decay gives rise to one γ ray. Data has been taken from page 17 of the Catalogue of Spectral Data For Diagnostic X-rays [1]. The reference x-ray spectrum chosen has a peak tube kilovoltage of 70 kV and a photon fluence, Φ , of $3.0 \times 10^8 \text{ cm}^{-2}$ at a distance of 75 cm from the x-ray tube anode per mAs supplied to the tube. In order to match this output, the activity, A , of the isotope must be

$$A = \Phi I 4\pi R^2 \quad , \quad (1)$$

where I is the tube current in milliamperes, and $R=75 \text{ cm}$ is the distance in cm from the anode focal spot to where Φ is measured. Using a tube current of 200 mA, the activity necessary to match the x-ray tube's output is approximately $4.2 \times 10^{15} \text{ Bq}$.

The diameter, d , of the radioactive source which has activity, A , is given by

$$d = \left(\frac{6 M t_{1/2} A}{\ln 2 \rho \pi N_A} \right)^{1/3} \quad , \quad (2)$$

where the factor M is the molar mass of the isotope, $t_{1/2}$ is its half-life, ρ is its density, and N_A is Avogadro's number.

Consider the use of ^{125}I which emits a 35 keV photon, has a half-life of 5.2×10^6

seconds (60.2 d), and a density of 4.94 g/cm^3 . Assuming that one decay gives rise to one γ ray, it would have a diameter of approximately 1.4 cm if it is to yield an output of $4.2 \times 10^{15} \text{ Bq}$.

Since the linear attenuation coefficient of iodine at 35 keV is 155 cm^{-1} , only photons generated very near the surface of the isotope will actually escape. If we assume that only photons generated within one mean free path (0.0065 cm) of the outer surface of the sphere escape, we could then take the volume of the sphere of diameter 1.4 cm and calculate the diameter a circular disc of depth 0.0065 cm would have to have in order to produce the same activity as the sphere. The diameter turns out to be approximately 16.8 cm. This is a problem since an imaging source must be small enough to approximate a point source in order to produce a sharp image. The focal spot of an x-ray tube typically has a focal spot area of approximately 1 mm^2 .

Synchrotron radiation could be monochromatized via Bragg reflection and used as a monoenergetic beam. This would yield a much higher fluence than that attainable using a radioisotope. However, it is not very practical to replace all existing x-ray tubes with synchrotron sources due to the cost, size, and portability considerations involved.

The most practical method of creating a monoenergetic beam appears to be through the production of fluorescence radiation by creating K-shell vacancies in some material.

1.3.1 Methods of creating K-shell vacancies

There are several methods of creating K-shell vacancies in a particular material which will subsequently cause the release of the desired fluorescence x rays.

Let us consider bombarding a pure elemental foil with photons. In order to determine how efficient this will be, we must consider the geometry of the system, and

the characteristics of the foil.

The geometrical factors are calculated in terms of the fluorescence foil to radiation source distance, d_1 , and the diameter, D , of the beam irradiating the foil. The foil characteristics are calculated in terms of fluorescence foil thickness, x , photoelectric attenuation coefficient, τ , linear attenuation coefficient, μ , and the factors V_K , T_K , and ω_K , which are respectively: the vacancy probability, transition probability, and the fluorescence yield, for the K-shell of the fluorescence foil. This allows us to develop a general scaling factor given by:

$$S = [(1 - e^{-\mu x}) \left(\frac{\tau}{\mu} \right) V_K T_K \omega_K] \left(\frac{D^2}{16 d_1^2} \right) \quad (3)$$

A radioisotope could be used as the photon source to create K-shell vacancies in the material via photoelectric interactions between the γ rays emitted from the isotope and the atoms of the foil undergoing isotope irradiation (see Figure 1.2).

Figure 1.2 Radioisotope irradiation of a fluorescence foil.

We can calculate the isotope activity, A_f , needed to irradiate a foil to yield the fluorescence output of a typical W-anode x-ray imaging system. This simply involves using our scaling factor, S , for the previously calculated activity, A . The isotope activity, A_f , becomes:

$$A_f = \frac{A}{S} \quad (4)$$

Using ^{125}I placed 3 cm from a Sn fluorescence foil of thickness 0.05 cm with a collimating aperture creating a beam 0.5 cm in diameter, we obtain $S = 9.77 \times 10^{-4}$ and so the isotope activity needed to produce the same output as the referenced x-ray imaging system is approximately 4.3×10^{18} Bq. This required activity is not practical.

A different approach using charged particle bombardment with high energy protons and α particles to create K-shell vacancies in materials has been investigated by Merzbacher and Lewis [7]. This option is not particularly practical since linear accelerators or Van de Graaf generators would be necessary. Electron bombardment of a foil will also produce K-shell vacancies, however, as with typical x-ray tube spectra, much of the radiation given off will be bremsstrahlung.

Since higher photon fluences are available from x-ray tubes more conveniently than from isotopes, excitation of target materials using a spectrum similar to that of Figure 1.1, generated using a typical W-anode x-ray tube, seems to be the most practical way of creating K-shell vacancies. The vacancies in the material are created via photoelectric interactions of the x-ray photons generated by the x-ray tube with the atoms of the material. This method of creating a monoenergetic x-ray beam is the basis of this thesis.

1.4 Purity and Intensity considerations

The fluorescence spectrum (shown in Figure 1.3) produced as a result of creating K-shell vacancies via x-ray excitation of a target will not be truly monoenergetic, that is, it will not be 100 percent pure.

Define spectral purity , P , to be the ratio of the number of counts in the $K\alpha$ fluorescence peaks to the total number of counts in the spectrum:

$$P = \frac{\text{Number of } K\alpha \text{ counts}}{\text{Total number of counts}} \quad (5)$$

Figure 1.3 Sn fluorescence spectrum.

The purity of a given spectrum, or beam, is degraded by four components:

- 1) Incoherent scatter of the primary x-ray beam off the foil being irradiated,
- 2) Coherent scatter,
- 3) The presence of $K\beta$ fluorescence radiation,
- 4) The presence of low energy L and M fluorescence radiation.

Incoherent scatter occurs when a primary photon of energy $h\nu$ scatters off of one of the atomic electrons in the foil. In doing so, it imparts some of its energy to the electron, freeing it from the atom it was bound to. This creates a vacancy in the atomic shell from which the electron was ejected. However, the scattered photon might scatter at an angle such that it is coincident with the fluorescent x-ray beam, and so degrade the purity of the beam. The scattered photon energy $h\nu'$ is dependent upon the scattering angle θ , and is given by

$$h\nu' = \frac{h\nu}{1 + \alpha (1 - \cos\theta)} \quad , \quad (6)$$

where $\alpha = h\nu/m_0c^2$, and m_0c^2 is the rest energy of an electron (511 keV).

Coherent scatter occurs when a primary photon of energy $h\nu$ scatters off one of the atoms in the foil. However, the photon does not impart any of its energy to the atom, and thus the scattered photon will have the same energy $h\nu$ as the incident primary photon. Since no energy is transferred, coherent scatter does not lead to the creation of a vacancy in the foil.

The probability of an incoherent or a coherent interaction taking place is dependent upon the incident photon energy $h\nu$, the scattering angle θ , and on the number of electrons in the atom available for scattering the photon. These dependences will be discussed in detail in Chapter 2.

$K\beta$ fluorescence radiation occurs as a result of M and N to K transitions to fill K-shell vacancies. The L to K transitions result in the desired $K\alpha$ fluorescence x rays being emitted.

The fourth and final unwanted component, L and M fluorescence radiation, is due

to transitions from higher levels to fill L- and M-shell vacancies. These vacancies are created when electrons from the L and M shells fill K-shell vacancies created due to photoelectric or Compton interactions. Photoelectric and Compton interactions can also create L- and M-shell vacancies leading to L and M fluorescence emissions.

The relative probability of $K\alpha$ versus $K\beta$ emission is dependent on the particular atom in which the K-shell vacancy has been created. In general, the probability of $K\alpha$ emission is several times that of $K\beta$ emission. It is possible to selectively filter out the $K\beta$ fluorescence radiation along with the lower energy L and M fluorescence radiation, thereby increasing the spectral purity. These filtering techniques will be discussed in Chapter 2.

It should be noted that the fluorescence radiation is given off isotropically. The only angular dependence occurs due to self filtration of the photons within the fluorescence foil.

In the interest of convenience, from this point on, we will be referring to the number of photons detected as intensity. This distinction is necessary since intensity is normally defined as the rate of energy transfer per unit area.

It is evident that the intensity of a fluorescent x-ray beam generated by creating $K\alpha$ x rays from a fluorescence foil must be much less than that of the primary x-ray beam. There are several factors which control the conversion efficiency of primary to fluorescence radiation generated. They include the fraction of primary photons with an energy greater than the K-edge energy of the foil, and the factors associated with S (Equation 3).

1.5 Previous investigations of fluorescence x rays

This section will deal with previous investigations of fluorescence x rays. The investigations and their findings will be summarized in Section 1.5.1. Section 1.5.2 will indicate what was omitted in terms of the exploration of the effect of the variables controlling the intensity and purity of fluorescence x rays in the previous studies.

1.5.1 Summary of the previous investigations

In 1952, Rogers [8] investigated the use of fluorescence x rays for microradiography which consisted of microchemical analysis by x-ray absorption spectrometry. The aim was to establish the variables governing the intensity and degree of monochromaticity of fluorescence x rays.

The study was carried out using low Z irradiators ($Z=22$ to $Z=42$) yielding low energy fluorescence x rays. The fluorescence target was in the form of a disc 1.9 cm in diameter and 0.254 cm thick. It was placed 5 cm from the x-ray tube anode at an angle of 45° to the primary beam. The detector, consisting of an ionization chamber, was placed 5 cm from the fluorescence target at 90° to the primary beam. A primary beam of diameter 3.0 mm was allowed to impinge on the fluorescence target.

The intensity of fluorescence radiation from a Cu fluorescence target was measured as a function of x-ray tube potential. Intensity was found to increase with increasing kVp. Using 60 kVp and a tube current of 30 mA, the maximum exposure rate was on the order of 12000 R/h. The relative intensity was also measured as a function of the atomic number of the fluorescence target and the atomic number of the x-ray anode material.

Purity measurements were made using aluminum absorption curves plotted on

semilog paper. For monochromatic radiation, such a plot will yield a straight line. The purity of titanium fluorescence ($K\alpha_1=4.51$ keV) was studied in greatest detail. The purity was found to decrease as kVp was increased beyond approximately 12 kV. Purity was also found to decrease as the fluorescence target thickness was increased.

Larson, Myers, and Roesch [9] published a paper in 1955 reporting their investigation of fluorescence x rays. Their aim was to produce monoenergetic sources for energy-sensitivity studies of γ ray instruments. An industrial x-ray machine run at 15 mA was used to irradiate secondary targets of: Cu, Cd, La, W, Pb, and U. The fluorescence x rays generated were studied using absorption measurements made with aluminum and tin. A free air chamber was used as the detector. The distances from anode to foil, and foil to detector were not given. The foil area irradiated was not given.

Maximum exposure rates ranged from 1375 mR/h for Cd using 60 kVp and no filtration of the fluorescence beam, to 55 mR/h for U using 130 kVp and 0.97 mm Sn as fluorescence beam filtration. The purities of the resulting beams were not given; instead estimates of the scattered radiation component in the beam were given. The amount of scattered radiation ranged from 1 % for the low Z irradiators Cd and La run at 60 kVp with no fluorescence beam filtration, to 15 % for U run at 130 kVp with 0.97 mm Sn as fluorescence beam filtration.

The general relevant conclusions reached were: the detector system should be placed at right angles to the primary beam to minimize scattered radiation, the x-ray machine voltage should be as low as possible consistent with the desired yield of fluorescence x rays, and light filtration of the fluorescence beam should be used to remove low energy scatter, and L and M etc. x rays.

In 1971, Kathren, Rising, and Larson [10] published a paper examining K x-ray fluorescence as a multi-use tool for health physics. Their objective was to determine the factors controlling the intensity and purity of the resulting fluorescence beam. An x-ray

tube was used to irradiate secondary targets set at 45° to the primary beam. The fluorescence x rays generated were detected using ionization chambers and a Ge(Li) detector positioned at 90° to the primary beam.

Their findings indicate that intensity is dependent on: target thickness (for which there appeared to be an optimum thickness), tube current (mA), and kVp. These parameters along with the geometry of the setup allowed variation of exposure rates from a few mR/h to several R/h. Purity was regulated by four parameters: kVp, target thickness, target impurities, and the presence of L-fluorescence radiation. The presence of $K\beta$ radiation was omitted from the list since all K x-ray radiation was considered to be essentially monoenergetic.

In 1974, Hoffman and Phelps [11] used a W-anode x-ray tube and fluorescence targets of Cu, Ge, Mo, Ag, Cd, Te, Sm, Gd, W, and Pb to investigate the role of kVp in optimizing fluorescence x-ray beam purity. Purity was defined as the ratio of the number of $K\alpha$ and $K\beta$ photons to the total number of photons in the fluorescence beam. The conversion efficiency defined as the ratio of the number of $K\alpha$ and $K\beta$ photons emitted from the front face of the foil to the number of primary photons incident on the foil was also studied as a function of kVp. The x-ray generator used produced a tube current ranging from 0 to 8.5 mA, and allowed a variation in kVp from 63 to 145. The secondary targets were mounted at 45° to the primary beam at a distance of approximately 40 cm from the anode. The detector was mounted at 90° to the primary beam and the target to detector distance was 45.7 cm.

As kVp was increased, the conversion efficiency decreased for the low Z targets but increased for the high Z targets. The maximum conversion efficiency achieved was 0.41 using a Mo target at 63 kVp. The minimum was 0.002 using a Pb target at 95 kVp. Spectral purities of 0.85 to 0.90 were obtained for the targets irradiated at optimal kilovoltages. The optimal kilovoltages for the low Z targets (estimated at 20 to 30 kVp) were below the lowest available 63 kVp of the generator, and as a result purity decreased

as available kVp was increased in the case of the low Z targets. The optimal kilovoltages for the high Z targets (estimated at 160 to 200 kVp) were above the available 145 kVp, and as a result spectral purities increased as the available kVp was increased towards the 145 kVp upper limit.

In 1975, Drexler, Gossrau, Pranzner, and Schöfer [12] used an x-ray tube with a well-type anode to irradiate fluorescence targets. The objective of this work was to increase the primary photon intensity striking the fluorescence target. This generates a greater fluorescence beam intensity, or allows the same intensity to be produced given a smaller target area irradiated.

A tube of this type operating at 100 kVp produced average (over different elements) fluorescence exposure rates of 100 R/h measured 35 cm from the fluorescence target using tube currents of 50 mA (which was the upper limit due to thermal restrictions of the x-ray tube). Purity was defined as the ratio of the number of $K\alpha$ plus $K\beta$ photons to the total number of photons in the fluorescence spectrum. Purities between 0.85 and 0.95 were achieved. It was found that it was not possible to meet all the requirements of simultaneously maximizing intensity and purity since increasing the kVp to yield maximum intensities increased the amount of scatter in the fluorescence beam. It was concluded that the best compromise was to set the kVp to approximately three times the value of the K-fluorescence energy characteristic of the target.

Fluorescent x rays were investigated by Vyborny, Doi, Metz, and Haus [13] in 1977 for the purpose of testing the speed of x-ray film-screen systems as a function of energy. The investigation examined the purity of the resulting fluorescence beam as a function of fluorescence target material, kVp, and filters used. The source consisted of a diagnostic x-ray tube, fluorescence targets, and various filters. The fluorescence target was located 11 cm from the focal spot of the tube at an angle of 45° to the primary beam. A Ge detector was used to monitor the purity and intensity of the fluorescence beam. Purity was defined as the ratio of the number of $K\alpha$ photons to the total number of

photons in the beam.

Spectral purities up to 0.95 were observed for low Z materials, while high Z materials produced maximum purities just under 0.90. Spectral purity was found to decrease as tube potential increased in the case of low Z targets, while it increased as tube potential increased for high Z targets.

In 1982, Doi, Vyborny, and Holje [14] investigated the production of fluorescence radiation for the purpose of determining the basic properties of radiographic recording systems.

Fluorescence targets were placed at a 45° angle to the primary x-ray beam emanating from a diagnostic x-ray tube. Filters placed between the fluorescence target and a Ge detector were chosen such that they preferentially filtered out the $K\beta$ radiation leaving a fluorescence beam dominated by $K\alpha$ radiation. Target energies ranged from 9.9 keV for Ge to 96.5 keV for U. Purities above 90% were generated for all targets except for the very high and low Z targets. Due to incomplete information, the exposure rates reported are ambiguous (10 mR/100 mA).

In 1983, Rutt, Cunningham, and Fenster [4] investigated the possibility of using lanthanum K fluorescence to selectively image iodine contrast agent. This was accomplished by using pre-patient iodine and barium filters to alter the ratio of $K\alpha_1$ and $K\alpha_2$ radiation emanating from the fluorescence foil. By subtracting images made with different $K\alpha$ ratios, iodinated structures can be isolated.

The lanthanum target was mounted at an angle of 17.5° to the secondary axis at a distance of 10 cm from the x-ray tube's focal spot. A foil approximately 30 mm wide by 3 mm high was irradiated with 60 kVp primary x rays using 0.25 mm Cu as added filtration to the primary beam. The geometry therefore created an effective imaging focal spot on the La foil of 10 mm x 3 mm. Detection of the fluorescence beam using a high

purity Ge spectrometer determined that approximately 95% of the fluorescence beam was composed of K fluorescence radiation. The fluorescence output of an unfiltered 300 mAs pulse at 50 cm from the fluorescence target was measured to be 3 mR (10 μ R/mAs). This was approximately 0.1% of the primary output. The addition of the necessary iodine filtration would further decrease this exposure by a factor of five. By optimizing the geometry, it was concluded that with a high power x-ray tube operating at 500 mAs per pulse at 60 kV, each pulse would yield approximately 10 mR. This would allow detection of a 10 mg/cm² iodine region of 1 mm² with an SNR greater than five.

In 1991, Harding, Jordan, and Kosanetzky [15] published a paper describing a fluorescent x-ray source consisting of a conical fluorescence target enclosed in a conical anode x-ray tube. The objective of this work was to examine the variation in fluorescence photon flux and spectral purity as a function of applied tube voltage.

Since the fluorescence target (chosen to be Ta) was placed so close to the anode, the resulting fluorescence intensities were greater than those obtained using fluorescence targets placed outside the x-ray tube. The effective size of the Ta source viewed by the detector was a circle of radius 1 mm. The photon counting rate per unit solid angle at 160 kV and 1 mA was calculated to be 3.5×10^9 photons s⁻¹ sr⁻¹. This value was compared to a 518 MBq ²⁴¹Am source with a 2 mm active diameter which yielded 6.6×10^6 photons s⁻¹ sr⁻¹. Spectral purities were indicated by examining the ratio of the number of counts in the K α peak to the number of counts in the background about the K α peak; this was typically between 4.5 and 5.0. Total spectral purities including the K β contribution were not given.

One paper was found reporting a study which resembles the experiment carried out in this thesis. In 1972, Chartier, Portal, Roman, and Dugay [16] investigated the influence of various parameters on the purity and intensity of fluorescence radiation produced by irradiating fluorescence targets using a diagnostic x-ray tube.

The experimental arrangement consisted of low and high energy x-ray tubes, primary beam filters, secondary beam filters, fluorescence targets, various collimating diaphragms, and a Ge(Li) detector which was placed at 90° to the primary beam. The effect of the following variables was investigated: thickness, orientation, and position of the fluorescence target, area of the primary beam, fluorescence filter thickness, and kVp. The variables not studied were: effect of detector angle, and effect of primary beam filter thickness. Purity was defined as the ratio of the number of $K\alpha$ photons to the total number of photons in the fluorescence beam.

From the results of the experiment, the fluorescence target should be placed at approximately 45° to the primary beam to maximize intensity. It is generally thought that the target should neither be too thin nor too thick. If the target is too thin, the output will be low. If too thick, there will be an increase in high energy scatter which will degrade purity. The actual results indicate that when the foil is thin intensity increases quickly with changing foil thickness. Purity did not show a large variation over the range of thicknesses used. The target should be placed as close to the x-ray tube anode as possible. This will aid in maximizing fluorescence intensities. Due to the experimental setup, the minimum distance possible was approximately 25 cm.

The area of the primary beam affects the number of atoms in the target that are irradiated and therefore affects the intensity of the fluorescence beam. Fluorescence intensity was found to increase as the square of the diameter of the collimating aperture in front of the target so long as the total target area was larger than the target area irradiated. Purity tended to increase slightly with the increasing diameter of the primary beam collimators. This was thought to be due to a lessening in the percentage of scatter of the primary beam off the collimating aperture.

An increase in tube potential was found to increase fluorescence intensity in all cases. The effect on purity depended on the K-edge energy of the target irradiated. When the kVp was increased from just above the K-edge to a value of only two to three

times that of the K-edge energy of the target, purity rose with increasing tube potential. When the tube potential was increased still further, a decline in purity resulted due to the increasing proportion of scatter of the primary beam off the target.

A copper primary filter was used to harden the primary beam. Purity and intensity were not studied as a function of primary beam filter thickness.

Fluorescence beam filters were used to eliminate $K\beta$ and L-fluorescence radiation. Fluorescence intensity decreased with increasing filter thickness, while purity increased. For example, the irradiation of a uranium target at 225 kV produced an exposure rate of approximately 6 R/h when 0.37 g/cm^2 of Th was used. This dropped to 2 R/h when 1.5 g/cm^2 of Th was used. Purity increased from approximately 0.90 to 0.98 for the same increase in filter thickness.

In an effort to facilitate comparisons between the various studies and this thesis, Table 1.1 summarizes the variables studied in four of the previous studies and in this thesis.

Table 1.1 Summary of the variables studied in the investigations.

<u>Variables Studied</u>	Rogers [8] 1952	Kathren et al. [10] 1971	Chartier et al. [16] 1972	Hoffman et al. [11] 1974	This study 1993
kVp	yes	yes	yes	yes	yes
Primary beam filter thickness	no	no	no	no	yes
Secondary beam filter thickness	no	yes	yes	no	yes
Fluorescence foil thickness	yes	yes	yes	no	yes
Foil angle (ϕ)	no	no	yes	no	yes
Detector angle (θ)	no	no	no	no	yes

1.5.2 The missing information in the previous studies

Most of the previous studies examined the effect of tube potential on the intensity and purity of fluorescence x rays. Studies such as those of Kathren, Rising, and Larson [10] examined several variables such as: fluorescence foil thickness, tube current, and tube potential. The study carried out by Chartier, Portal, Roman, and Dugay [16] was the most comprehensive study. However, they did not examine the effect of detector angle, or primary beam filter thickness on fluorescence beam intensity and purity.

One of the main difficulties encountered when examining the previous investigations is the lack of a standard method for reporting results. Many results are often given without specifying all the parameters used.

1.6 Objective of this thesis

In this study, the following six variables which control the intensity and purity of fluorescence x ray production were examined:

- 1) X-ray tube potential
- 2) Primary beam filter thickness
- 3) Fluorescence foil thickness
- 4) Foil angle (ϕ)
- 5) Detector angle (θ)
- 6) Fluorescence beam filter thickness

Clearly there are other more obvious variables such as the tube current applied, the distance of the foil from the anode, d_1 , and the distance of the detector from the foil, d_2 , which also control the intensity of the fluorescence radiation measured. These variables were not investigated since their effect on intensity is predictable.

Figure 1.4 defines the foil angle, detector angle, filter placements, and fluorescence foil placement. The aim of this thesis is to determine the effect of each of the variables being studied.

Figure 1.4 Schematic diagram of the experimental apparatus (overhead view).

Chapter 2

Theoretical considerations

2.1 Photon interactions and detection

Given the primary beam photon energy range that we are dealing with (0 - 130 keV), there are three types of interactions that can occur between a primary x-ray photon and the fluorescence foil. They are:

- 1) Photoelectric effect
- 2) Incoherent scattering
- 3) Coherent scattering

As mentioned in Section 1.3.1, photoelectric interactions can lead to the creation of K-shell vacancies, while coherent interactions cannot. Incoherent interactions can lead to the creation of K-shell vacancies, however, this will only occur when high energy photons scatter at large angles in low Z materials. It is only under these conditions that enough energy is transferred from the photon to the atom to cause a K-shell vacancy. For example, the minimum photon energy necessary to create a K-shell vacancy due to incoherent scatter in Sn (K-edge = 29.2 keV) is 102.2 keV.

2.1.1 Photoelectric interactions and K-shell vacancies

A photoelectric interaction occurs when a photon of energy $h\nu$ is absorbed by an atom leading to the ejection of one of the bound electrons. The electron emerges from

the atom with energy $h\nu - E_B$, where E_B is the binding energy of the shell from which it was ejected. The atom is left with a vacancy in the shell and is therefore in an excited state. If the interaction took place between the primary photon and a K-shell electron, a K-shell vacancy is the result.

As the K-shell vacancy is filled, three different processes may occur. The atom may emit the desired $K\alpha$ fluorescence photon, a $K\beta$ fluorescence photon, or an Auger electron.

Auger electrons are emitted when energy liberated by an electron transition from a higher shell to the vacancy is transferred to one of the electrons in a higher shell. If for example, an M-shell Auger electron was emitted after an electron moved from the L-shell to the K-shell to fill a vacancy, it would have kinetic energy $E_K - E_L - E_M$.

The probability of the emission of fluorescence radiation (instead of an Auger electron) is called the fluorescence yield. It is usually denoted by ω . The fluorescence yield can be calculated for each atomic shell. In terms of the K-shell:

$$\omega_K = \frac{\text{Number of K x-ray photons emitted}}{\text{Number of K-shell vacancies}} \quad (7)$$

For low atomic number materials, Auger electron emission is favoured, while for high atomic number materials fluorescence is favoured. For example, the value of ω_K for $_{13}\text{Al}$ is 0.036, while for $_{82}\text{Pb}$ it is 0.968 [17].

Note that along with the emission of $K\alpha$, $K\beta$, and Auger electrons, which occur as a result of K-shell vacancies being filled, there will be vacancies created in the L-shell or M-shell as electrons move from these higher shells to fill the K-shell vacancies. These vacancies will lead to the subsequent emission of L and M x-ray fluorescence photons.

These fluorescence photons will be of much lower energy than the K x-ray photons emitted. Low energy Auger electrons can also be emitted due to these L- and M-shell vacancies.

The probability of a photoelectric interaction occurring is very high at low photon energies and decreases as $(h\nu)^{-3}$ as photon energy is increased [Ref. 5, p. 146]. It is, however, still the predominant type of interaction for the fluorescence foil materials and for the energy range used in this study.

Since in a photoelectric interaction the photon is totally absorbed by the atom, and the fluorescence radiation generated is emitted isotropically, the only variation with angle will be as a result of self filtration of the fluorescence photons before they leave the fluorescence foil. This is analogous to the anode heel effect as seen with normal x-ray tubes.

2.1.2 Incoherent scatter

Incoherent interactions occur as described on page 9. In general, for the fluorescence foils used in this study, the incoherent cross section is almost independent of photon energy above 30 keV. The relative probability of an incoherent versus a photoelectric interaction increases as primary photon energy increases since the photoelectric cross section decreases rapidly as photon energy increases. It must be pointed out however, that photoelectric interactions are still the most likely type of interaction over the entire energy range for the Z values used in our experiments. Table 2.1 contains interaction cross sections (10^{-24} cm²/atom) for the three processes for different values of Z at different energies [17].

Table 2.1 Interaction cross sections (10^{-24} cm²/atom) [17].

Energy (keV)	Z=29 Cu (Coh,Inc,Pho)			Z=50 Sn (Coh,Inc,Pho)			Z=82 Pb (Coh,Inc,Pho)		
10.0	152	8.20	23000	517	12.1	27400	1690	15.8	44000
30.0	35.1	13.1	1090	133	20.1	7940	456	28.7	9750
50.0	15.3	13.9	241	61.3	22.2	2040	231	33.0	2440
70.0	8.70	13.8	87.8	34.9	22.5	795	123	34.2	967
100.0	4.60	13.4	30.0	18.7	22.1	288	67.6	34.4	1780
125.0	3.10	12.8	15.4	12.6	21.4	151	45.4	33.6	996

We will now discuss the factors affecting the probability of an incoherent interaction occurring and the scattered photon being detected.

The probability, P_{inc} , of a photon of energy $h\nu$ interacting incoherently with a fluorescence foil of atomic number Z , and scattering at an angle θ such that it is detected in the fluorescence beam is

$$P_{inc} = \frac{d\sigma_{inc}(h\nu)}{d\Omega} d\Omega N_a \quad , \quad (8)$$

where the first factor on the right hand side of Equation 8 is the differential incoherent atomic cross section per unit solid angle, $d\Omega$ is the solid angle subtended by the detector crystal, and N_a is the number of atoms/cm² in the fluorescence foil.

This differential cross section can be written as:

$$\frac{d\sigma_{inc}(h\nu)}{d\Omega} = \frac{r_e^2}{2} (1 + \cos^2\theta) F_{KN}(h\nu) S(x_s, Z) \quad (9)$$

The quantity r_e is the classical radius of an electron and has a value of 2.8179×10^{-15} m. $S(x_s, Z)$ is known as the incoherent scattering function which accounts for electron binding in the atoms. $S(x_s, Z)$ is dependent upon the atomic number Z of the atom the photon is scattering from, and on x_s which is the momentum transfer argument,

$$x_s = \frac{\sin(\frac{\theta}{2})}{\lambda} \quad (10)$$

where λ is the wavelength of the photon of energy $h\nu$. Tables of $S(x_s, Z)$ for each element have been created by Hubbell et al. [18], which allows the incoherent scattering function to be interpolated for any photon energy $h\nu$.

The factor F_{KN} is known as the Klein-Nishina factor and is given by

$$F_{KN} = \left[\frac{1}{1 + \alpha(1 - \cos\theta)} \right]^2 \left\{ 1 + \frac{\alpha^2(1 - \cos\theta)^2}{[1 + \alpha(1 - \cos\theta)](1 + \cos^2\theta)} \right\} \quad (11)$$

where $\alpha = h\nu/m_e c^2$.

F_{KN} has a value which lies between 0 and 1, depending on photon energy $h\nu$ and scattering angle θ . For low photon energies and/or small scatter angles, F_{KN} tends towards 1. For high energies and large scattering angles, F_{KN} tends towards 0.

Table 2.2 shows that the probability of Compton scatter (incoherent scatter off a free electron) is a minimum for a scattering angle of 90° in the low-energy limit, and increases to 99.4° at 150 keV.

Table 2.2 Minimum Compton scatter angle.

h ν (keV)	$\theta_{\min}$
0	90.0°
20	92.1°
40	93.8°
60	95.3°
80	96.5°
100	97.6°
150	99.4°

To find the angle at which the probability of incoherent scatter from the bound electron in an atom is a minimum, the value of the incoherent scattering function, $S(x, Z)$, must be taken into account. Since $S(x, Z)$ increases as scatter angle increases, the angle at which the probability of incoherent scatter is minimized is shifted towards smaller scattering angles. For example, the minimum is shifted from 93.8° to 89.8° for Sn at 40 keV.

2.1.3 Coherent scatter

Coherent interactions occur as described on page 9. In general, the coherent cross section varies approximately as $(h\nu)^2$ [Ref. 2, p. 153]. It may be noted that at low energies coherent interactions are, in general, much more likely than incoherent interactions, but are much less likely than photoelectric interactions (see Table 2.1).

The probability, P_{coh} , of a photon of energy $h\nu$ interacting coherently with a

fluorescence foil of atomic number Z , and scattering at an angle θ such that it is detected is given by

$$P_{coh} = \frac{d_a \sigma_{coh}(h\nu)}{d\Omega} d\Omega N_a \quad , \quad (12)$$

where the first factor on the right hand side of Equation 12 is the differential coherent atomic cross section per unit solid angle.

The differential coherent atomic cross section can be written as:

$$\frac{d_a \sigma_{coh}(h\nu)}{d\Omega} = \frac{r_o^2}{2} (1 + \cos^2\theta) [F(x_s, Z)]^2 \quad (13)$$

The factor $F(x_s, Z)$ is known as the atomic form factor and accounts for inter-electron interference. Values of $F(x_s, Z)$ have been tabulated for each element so that the atomic form factor can be found for a particular value of $h\nu$ for any element [18].

For small values of x_s (low energy or small angle θ), $F(x_s, Z)$ approaches Z , while for large values of x_s , it tends towards zero. This implies that coherent scatter is strongly forward peaked.

2.1.4 Theoretical prediction of $K\alpha$ intensity from a Sn foil

It is possible to theoretically predict the number of expected $K\alpha$ events, $N_{K\alpha}$, seen by the detector given a set of initial parameters. A typical 80 kV x-ray spectrum [Ref. 1, p. 21] was used to simulate the spectrum impinging on a 0.0075 cm thick Sn fluorescence foil. We can use the scaling factor, S , from Equation 3 to account for the anode to foil geometry and for the characteristics of the Sn foil. The equation yielding

$N_{K\alpha}$ can be written as:

$$N_{K\alpha} = \Phi_{d_1} F_K S A_2 \frac{d_1^2}{d_2^2} \quad , \quad (14)$$

where Φ_{d_1} represents the photon fluence at d_1 ($1.6 \times 10^{12} \text{ cm}^{-2}$), F_K is the fraction of primary photons with energies greater than the K-edge of Sn (0.79), and A_2 is the detector area exposed (0.196 cm^2). The values of d_1 , d_2 , and S , are 18.3 cm, 66.7 cm, and 1.24×10^{-5} respectively. Given these parameters, we expect $N_{K\alpha} = 2.3 \times 10^5$ counts.

A spectrum obtained experimentally under similar conditions produced 1.7×10^5 counts. The results agree reasonably well given that we cannot expect a perfect match between the experimental primary spectrum and the theoretical primary spectrum.

2.2 Theoretical effect of the variables being studied

The six variables being studied control the intensity and purity of the fluorescent x-ray beam produced. We will now examine the theoretical effect of each of the variables.

2.2.1 X-ray tube potential

From Figure 1.1 it is evident that to maximize the intensity of the fluorescence beam, the x-ray tube potential should be as high as possible. This will extend the spectrum to the right and provide the maximum number of primary photons with energies greater than the K-edge energy of the material. It is difficult to predict the exact dependence of fluorescence intensity on tube potential. This is due to the fact that the very high energy photons will not interact photoelectrically as efficiently as the photons

which have an energy just above the K-edge of the foil. Those that do interact photoelectrically will tend to do so deeper within the foil and thus the fluorescence radiation generated will not be able to reach the detector as easily. As a result when very high tube potentials are used, there may only be gains due to the increase in the number of photons just above the K-edge as opposed to a gain from the photons produced at higher energies as well. Therefore, when the kVp is initially set such that it is not too far above the K-edge of the fluorescence foil, we expect a superlinear increase in fluorescence intensity as kVp is increased. Once the kVp is much greater than the K-edge of the fluorescence foil, we expect the increase in fluorescence intensity to be approximately linear. This is because inspection of typical spectra [1] shows that there is an approximately linear increase in the number of primary photons at a given energy just above the K-edge of the foil with increasing kV.

When a tube potential is chosen which lies far above the K-edge energy of the fluorescence foil, the purity of the resulting fluorescence beam will be degraded. As alluded to in the previous paragraph, the maximum probability of creating K-shell vacancies occurs when the primary photon energy lies just above the K-edge energy of the fluorescence foil. As primary photon energy increases beyond this point, the ratio of the photoelectric to scattering cross sections decreases (see Table 2.1). As a result, high intensity, lower purity fluorescence beams will be created when very high x-ray tube potentials are used to irradiate foils with low K-edge energies.

When x-ray tube potentials are not far enough above the K-edge energy of the fluorescence foil, both the intensity and purity of the fluorescence beam will be low. This is due to the large number of primary photons whose energies are less than the K-edge energy of the material. These primary photons cannot augment intensity by creating K-shell vacancies, but can however scatter off the foil thereby degrading spectral purity.

Clearly a compromise is necessary such that a reasonable intensity can be maintained without compromising purity. To accomplish this, it has been proposed by

Kathren et al. [10], that tube potential be maintained at no more than twice the Z value of the foil being irradiated.

Ideally to maximize purity, one would like to reshape the primary x-ray beam such that primary x rays with either too high or too low an energy are eliminated. This would leave a narrowed primary spectrum consisting of photons with energies just above the K-edge energy of the foil. This may be attempted by placing a filter of appropriate material and thickness between the x-ray tube and the fluorescence foil. We call this filter a primary beam filter.

2.2.2 Primary beam filter thickness

The number of photons, N , of a given energy $h\nu$, transmitted by the primary beam filter is given by

$$N = N_0 e^{-\mu_p x_p} \quad , \quad (15)$$

where N_0 is the number of photons of energy $h\nu$ impinging on the primary beam filter, x_p is the primary beam filter thickness, and μ_p is its linear attenuation coefficient at energy $h\nu$.

In order to properly shape the primary x-ray beam, the primary beam filter must be chosen in accord with the K-edge energy of the fluorescence foil. If we are irradiating a foil which has a high K-edge energy, we would use a low Z primary beam filter such as Al or Cu. These would preferentially filter out the low energy primary photons, thereby decreasing their contribution to purity degradation due to scatter.

When irradiating a fluorescence foil with a lower K-edge energy, it may be possible to preferentially filter out both primary photons whose energies lie below and too far above the K-edge energy of the foil using the same primary beam filter. This is

possible because we can choose a filter whose own K-edge energy lies some distance above the K-edge energy of the foil. The linear attenuation coefficient of the filter will be high at low photon energies, and will decrease as we approach and go past the K-edge energy of the foil. It will then increase sharply when the K-edge energy of the filter is reached (see Figure 2.1). This will cause the preferential attenuation of primary photons of low energy and with energies above the K-edge of the filter leaving the primary photons whose energies are near the K-edge of the foil relatively unfiltered.

Figure 2.1 Linear attenuation coefficient μ_p vs energy for Gd [17].

Theoretically, if the correct primary beam filter is chosen, the greater the filter thickness the greater the increase in fluorescence beam purity. This however, would be at the expense of intensity since according to Equation 15, there would be fewer photons transmitted by the primary beam filter to create K-shell vacancies in the foil.

2.2.3 Fluorescence foil thickness

The number, N_i , of primary photons of energy $h\nu$ interacting with the fluorescence foil of thickness, x , and linear attenuation coefficient, μ , is

$$N_i = N (1 - e^{-\mu x}) \quad , \quad (16)$$

where N is the number of primary x-ray photons of energy $h\nu$ transmitted through the primary beam filter to impinge on the fluorescence foil.

From Equation 16 we see that when x is small (such that μx is small) the number of interactions increases linearly with increasing foil thickness. When x becomes larger, the number of photons interacting saturates at N .

As fluorescence foil thickness increases a slight decrease in purity is expected since the higher energy primary photons become more likely to interact with the foil. These high energy photons are more likely to scatter than the lower energy photons that interact with the foil (see Table 2.1).

Fluorescence foil thickness will have a direct influence on self filtration of the fluorescence photons as they leave the foil. A thin foil will give rise to little self filtration, while a thicker foil will give rise to more substantial self-filtration since some of the fluorescence photons will be generated deeper within the foil.

2.2.4 Fluorescence foil orientation

Referring to the schematic diagram of the experimental apparatus on page 21, we see that as the foil angle ϕ tends towards 0 fluorescence intensity should increase. This is due to the fact that when ϕ is small, the primary x-ray beam will be nearly parallel to

the face of the foil. When this occurs there is an effective increase in foil thickness since the path length through the foil for the incident primary photons is greater. As discussed in Section 2.2.3, increased thickness results in increased intensity but slightly decreased purity.

If ϕ is small and the detector angle θ is much greater than ϕ , the fluorescence area will appear to be spread out horizontally over the fluorescence foil. This is undesirable for actual imaging situations since a small fluorescence area is necessary to produce a sharp image. If θ is not much greater than ϕ , the fluorescence area will appear smaller horizontally, which will allow sharper images to be produced. However, in this case, the gain in intensity as a result of effectively increasing fluorescence foil thickness cannot be fully realized since the increased heel effect, which depends on the difference $\theta - \phi$, will decrease the number of fluorescence photons reaching the detector.

It is possible to use foil angles greater than 90° . Under these circumstances one would generally use the "transmitted" as opposed to the "reflected" fluorescence beam. Results reported by Chartier et al. [16] suggest that this is not advantageous since transmitted fluorescence intensities are lower than reflected fluorescence intensities.

2.2.5 Detector orientation

Detector angle θ affects the detected spectrum mainly in two ways.

The angular dependences of both incoherent and coherent scatter were discussed in Sections 2.1.2 and 2.1.3 respectively. Recall that coherent scatter is strongly forward peaked. Therefore small detector angles should not be used, and slight decreases in coherent scatter detected should be observed as detector angle is increased. On the other hand, we have seen from Section 2.1.2 that the probability of incoherent scatter is a minimum for detector angles of approximately 90° depending on the energy of the primary photon being scattered, and on the material scattering the photon. Therefore, by

placing the detector at approximately 90° , it should be possible to minimize the presence of incoherent scatter. The combination of these two effects suggests that there is an angle θ which minimizes overall scatter. This angle should lie somewhere between 90° and 180° depending on the amount of each type of scatter.

The second way in which the detector angle affects the fluorescence beam detected is its influence on the heel effect due to self filtration of the fluorescence photons within the foil. When the geometry is such that the path of the photons from the fluorescence area on the foil to the detector lies nearly parallel to the face of the foil, the heel effect will be most pronounced. This occurs when the detector angle θ and foil angle ϕ , as shown in Figure 3.1, are nearly the same. In order for the fluorescence photons generated in the fluorescence foil to be detected, they must pass through a greater thickness of fluorescence foil. Therefore, as $\theta - \phi$ tends towards 90° we expect an increase in intensity due to the decreasing heel effect. The deeper the fluorescence photons are generated in the fluorescence foil, the greater the magnitude of the effect on intensity.

2.2.6 Fluorescence beam filter thickness

The fluorescence beam filter has two purposes. Its primary purpose is to selectively filter out the $K\beta$ fluorescence radiation leaving the $K\alpha$ fluorescence radiation relatively unfiltered. This is accomplished by choosing a fluorescence beam filter whose K-edge energy lies between the $K\alpha$ and $K\beta$ energies of the fluorescence foil. For example, consider Ag acting as the K-edge filter for Sn fluorescence. The K-edge energy of Ag is 25.5 keV, while for Sn its $K\alpha_1$ energy is 25.3 keV and its $K\beta_1$ energy is 28.5 keV. The linear attenuation coefficient for Ag at the $K\alpha_1$ energy of Sn is approximately 100 cm^{-1} while at the $K\beta_1$ energy of Sn it is approximately 400 cm^{-1} . Given these linear attenuation coefficients, a reasonable K-edge filter thickness would be on the order of 0.01 cm. We see that under these conditions approximately 2% of the $K\beta_1$ fluorescence radiation and 37% of the $K\alpha_1$ fluorescence radiation would be transmitted. The unfiltered ratio of $K\beta$ to $K\alpha$ radiation from Sn fluorescence is approximately 0.25. By using the

Ag filter we change this ratio to approximately 0.01. Assuming that this was the only source of purity degradation, this K-edge filtering would increase the purity from 0.75 to 0.99.

The second purpose of the fluorescence beam filter is to filter out low energy scatter, and the low energy L and M fluorescence radiation discussed in Section 1.4. For example the strongest L-fluorescence line of Sn has an energy of 3.4 keV. Since the linear attenuation coefficient of Ag at these low energies is approximately 12000 cm^{-1} , the transmission through 0.01 cm is negligible.

If the thickness of the fluorescence beam filter is increased beyond a certain point, when there is not much $K\beta$ fluorescence radiation getting through the filter, the increased thickness will only serve to decrease the purity of the beam. This occurs because when this point is reached, increasing the filter thickness will begin to decrease the absolute numbers of $K\alpha$ photons faster than the $K\beta$ photons. This will eventually decrease purity since the K-edge filter will not remove the high energy scatter very effectively and thus the ratio of scatter to $K\alpha$ intensity will increase. Therefore, there is an optimal fluorescence beam filter thickness, x_{opt} , for a given beam which maximizes purity. Assume the scattered radiation has an average energy E_s , and that there are $N_{K\alpha}$ photons, $N_{K\beta}$ photons, and N_s scattered photons emanating from the fluorescence foil. The optimal thickness is given by the expression

$$x_{opt} = \frac{\ln [(\mu_{K\beta} - \mu_{K\alpha}) N_{K\beta}] - \ln [(\mu_{K\alpha} - \mu_s) N_s]}{(\mu_{K\beta} - \mu_s)}, \quad (17)$$

where $\mu_{K\alpha}$, $\mu_{K\beta}$, and μ_s are the linear attenuation coefficients of the fluorescence beam filter at the $K\alpha$, $K\beta$, and scatter energies.

We see from Equation 17 that when $\mu_{K\beta} = \mu_s$, or $\mu_{K\alpha} = \mu_s$, then x_{opt} becomes

infinite. This is reasonable since it implies that there is only $K\alpha$ and $K\beta$ radiation. Under these circumstances as much K-edge filtration as possible should be used if the sole concern is to maximize purity.

It is evident that increases in spectral purity by K-edge filtering are at the expense of intensity. Therefore, fluorescence beam filters should be chosen with minimum thicknesses for the desired purity.

2.3 Detector response

When a detector system is exposed to a monoenergetic source of radiation, the resulting spectrum contains not only the monoenergetic photopeak, but also several continua due to detector response. For example, Figure 2.2 is a spectrum obtained by exposing our detector system to 59.5 keV photons from ^{241}Am . The continua are due to escape of energy from the detector crystal, or incoherently scattered radiation being absorbed by the crystal.

Figure 2.2 Detector response to 59.5 keV photons.

The continuum from E_s to E_c is due to the escape of incoherently scattered photons from the detector crystal. When this occurs, only the energy of the recoil electrons will be left behind to be registered by the detector. Maximum energy is left behind at E_c , which occurs when a photon scatters back out of the crystal at 180° . The value of E_c is given by

$$E_c = hv - \frac{hv}{1 + \alpha [1 - \cos(180^\circ)]} \quad (18)$$

For $hv = 59.5$ keV, E_c is 11.2 keV.

The continuum from E_s to the full energy photopeak, P_p , is a result of photons being absorbed fully in the crystal after having scattered incoherently off the detector collimation or backscattering into the crystal after having passed through it. The scatter angle determines the amount of energy the scattered photon will possess when it enters the crystal. This can range from just below 59.5 keV for a very small scattering angle, down to E_s which occurs when the photon scatters at 180° before entering the crystal. E_s can be calculated from Equation 6 to be 48.3 keV.

The continuum from E_c to E_s is due to energy left behind when a 59.5 keV photon scatters more than once before leaving the detector, depositing energy in the form of two or more recoil electrons, or, when the photon scatters more than once in the collimation prior to detection. Actually, any energy from 0 to P_p could be left behind under these circumstances. The continuum from E_c to E_s indicates the relative amount of multiple scatter taking place, and the two other continua in fact also have a multiple scatter component.

The peak labelled F, which is known as an escape peak, is due to the escape of fluorescence photons generated within the detector crystal itself. The detector crystal is

pure Ge which has a $K\alpha_1$ fluorescence energy of 9.9 keV. The total energy deposited will be $59.5 - 9.9 = 49.6$ keV.

A photon will be registered in the full energy peak, P_f , when its energy is fully absorbed in the detector crystal. This occurs when the Ge fluorescence photons and scattered photons generated within the crystal are fully absorbed before they can escape.

One method for correcting for detector response is that of Yaffe et al. [19]. The detector is exposed one at a time to isotopes which emit different energies. The resulting spectra are then analyzed to yield probabilities for detector events contributing to each of the continua and the escape peak for the different photon energies. The energy dependent probabilities for each type of detector response event are then plotted and lines of best fit are applied. The equations of the lines of best fit are then put into an iterative detector response correction algorithm. This allows detector response artifacts to be removed from each subsequently measured spectrum.

Chapter 3

Apparatus

3.1 Diagram of the apparatus

Figure 3.1 Schematic diagram of the experimental apparatus (overhead view).

3.2 Equipment used

The following is a list of the major components of the experimental apparatus:

X-ray Generator : Picker GX550 (1- ϕ)

X-ray Tube : Machlett Dynamax rotating W-anode (model 62R)

- Focal spot size = 1.2 x 1.2 mm

Varian Dynalyzer IIIA : Tube current and tube voltage monitoring, via connection to a digital multimeter

Detector : Ortec high purity Ge (LEPS) (model GLP 16195/10-P)

- beryllium entrance window, thickness = 0.127 mm
- active diameter = 16 mm
- sensitive depth = 10 mm
- energy range = 3 keV - 1 MeV
- FWHM at 122 keV = 0.495 keV

Detector power supply : Ortec High Voltage Power Supply (model 456)

- Bias potential = 1500 V (negative)

Amplifier : Canberra (model 2024)

- input polarity : (-)
- output : unipolar
- shaping time constant : 4 μ s
- baseline restorer : threshold - auto / mode - asymmetric
- total gain : 21X
- pileup rejector : unipolar

Analogue to Digital Converter (ADC) : Canberra (model 8077)

- Wilkinson type (450 MHz clock rate)
- range/gain : 4K
- offsets : off
- peak detect : auto
- pulse height analysis selected
- coincidence selected
- ADC in selected
- LLD : 0.21 V

Multichannel Analyzer (MCA) : Aptec series 2000 (PCMCA/WIN)

3.2.1 System assembly

The x-ray tube was mounted vertically onto an aluminum stand. The stand was then bolted to the bench top. An optical bench was positioned so that it was parallel to the primary x-ray beam emerging from the collimation cone in the window of the x-ray tube. The optical bench was then bolted to the bench top. A translator providing transverse and longitudinal adjustments was used to position the fluorescence foil holder at the desired location on the optical bench. The foil holder was constructed of brass and contained a 4 cm x 4 cm window which housed the fluorescence foil. An angular scale mounted to the foil holder served the dual purpose of indicating both ϕ and θ via pointing devices for each.

The fluorescence foil was contained within a Pb shielded enclosure, see Figure 3.1. The enclosure was 0.3 cm thick and contained a slit approximately 1.2 cm in height which ran around the entire curved surface of the Pb enclosure. This provided vertical collimation of the fluorescence beam. Horizontal collimation was provided by placing rectangular pieces of Pb over the slit.

The detector was positioned inside a mobile cabinet so that it could be moved to give the desired detector angle θ , and foil to detector distance d_f . Lead collimation was added around the sides of the detector to minimize ambient scatter from reaching the detector crystal. In front of the detector window a 0.5 cm diameter aperture in 0.3 cm thick Pb was placed to ensure that the radiation entered the detector near the centre of the crystal. This helped to minimize creation of detector response artifacts.

3.2.2 System operation

When an x ray from the fluorescence foil enters the Ge crystal, ionizations occur via photoelectric and Compton interactions creating electron-hole pairs. The number of electron-hole pairs created is proportional to the incoming x-ray energy; it takes approximately 2.96 eV to create one electron-hole pair at 77 K [Ref. 20, p. 340].

To ensure that the only free charge that exists in the crystal is due to the ionizations caused by the incident x ray, the detector system is chilled to 77 K to reduce thermally induced leakage currents. The presence of free charges not caused by the interactions of the x ray would seriously reduce system resolution. Liquid nitrogen is used to chill the detector. It is contained in an insulated dewar and the detector is kept in contact with the liquid nitrogen via a thermally conductive rod (cryostat).

High voltage is applied across the detector crystal which creates an electric field in the crystal. This field causes the electrons and holes to move to the opposite sides of the crystal where they are collected by the charge sensitive stage of the preamplifier. The preamplifier then puts out a voltage pulse which is proportional to the amount of charge collected. This voltage pulse is sent to the main amplifier where it is shaped and amplified.

Shaping is necessary because in order to ensure that complete charge collection occurs, preamplifiers usually provide long decay times (50 μ s) for the pulse [Ref. 20,

p.564]. This minimizes charge loss while collection is taking place at the charge sensitive stage of the preamplifier. If significant losses were to occur, the voltage pulses from the preamplifier would indicate photon energies below those actually incident on the detector. Due to the long decay time, when count rates are high, pulses will tend to overlap one another. This overlap creates a problem as it gives rise to larger voltage pulses than it should given the amount of charge generated due to a single x-ray interaction. Thus the energy registered by the system for a given photon interaction will be too high. The overlap can also cause voltage saturation to occur as the pulses from the preamplifier continually build on each other. To combat these effects, the signal from the preamplifier is usually differentiated (shaped) when received by the amplifier. This eliminates the long tail of the pulse, which decreases the amount of overlap and the possibility of voltage saturation occurring.

The amplifier output is a shaped pulse within the amplitude range of 0-10 V. This pulse is sent to the Analogue to Digital Converter (ADC) which digitizes the pulse amplitude. The signal is then sent to the Multichannel Analyzer (MCA), which sorts the pulse into a memory location (channel) based on its digitized value. Each input pulse to the MCA increments the appropriate memory location by one count. Our experimental configuration used 4096 channels over a 0 - 140 keV energy range. Each channel is therefore 0.034 keV wide.

The spectrum collected is displayed on a computer screen as a plot of the number of counts in each channel versus either channel number or energy.

3.3 Fluorescence foils studied

Table 3.1 contains a list of all fluorescence foils irradiated. The variables controlling purity and intensity were studied in detail using the Sn and Pb fluorescence foils.

Table 3.1 Foils studied.

Z	Element	$K\alpha_1$ Energy (keV)
40	Zr	15.77
47	Ag	22.16
50	Sn	25.27
57	La	33.44
67	Ho	47.54
74	W	59.31
82	Pb	74.96

Chapter 4

Experimental procedure

4.1 Detector response correction

The theory behind detector response has already been discussed in Section 2.3. The last paragraph of that section describes the general idea behind characterizing a detector system. We will now discuss the procedure and resources used to characterize our system.

Table 4.1 lists the radioisotopes used, along with their corresponding γ -ray and fluorescent x-ray energies emitted.

Table 4.1 Radioisotopes used for detector response characterization.

Isotope	Principal energies (keV) and relative number of photons emitted [Ref. 21, App. 4].					
^{57}Co	136.5 (γ)	0.104	122.1 (γ)	0.804	14.4 (γ)	0.092
^{109}Cd	88.0 (γ)	0.037	25.0 ($\text{K}\beta$)	0.169	22.1 ($\text{K}\alpha$)	0.794
^{137}Cs	661.7 (γ)	0.919	36.4 ($\text{K}\beta$)	0.013	32.1 ($\text{K}\alpha$)	0.068
^{241}Am	59.5 (γ) 13.9 ($\text{L}\alpha$)	0.488 0.181	20.8 ($\text{L}\gamma$)	0.067	17.8 ($\text{L}\beta$)	0.264

The low energy lines emitted from ^{109}Cd , ^{241}Am , and ^{137}Cs are self fluorescence x rays from the silver, neptunium, and barium respectively. These elements are created from the decay of the isotopes.

4.1.1 Energy calibration

Prior to characterizing the detector and doing the experiments, an energy calibration was performed. Three of the lines from ^{57}Co (136.5, 122.1, and 14.4 keV) were used along with the 59.5 keV line from ^{241}Am . The ADC and MCA were initialized such that there were 4096 channels over a 0 to 140 keV energy range. Each channel was therefore approximately 0.034 keV wide.

4.1.2 Isolating the monoenergetic lines

The two higher energy lines from ^{57}Co were separated from the 14.4 keV line by placing 0.125 cm Al and 0.123 cm Cu (as filtration) between the isotope and the detector. As a result only the intense 122.1 keV and less intense 136.5 keV photons impinged upon the detector system. The spectrum containing the two lines was collected over a two hour period. Since the collection time was long, a natural background spectrum was also collected and then subtracted from the filtered spectrum. The resulting spectrum contained only the 122.1 keV and 136.5 keV lines, and the associated detector response artifacts. The spectrum was analyzed, allowing the total number of counts for each detector response continuum to be obtained. The probability of a particular response event occurring is just the ratio of the number of counts in that response continuum to the total number of counts in the spectrum. When the 122.1 and 136.5 keV lines are weighted by intensity, they are equivalent to a single line at 123.7 keV, and the detector performance obtained was assigned to this energy.

The 88 keV line of ^{109}Cd was separated from the two lower energy Ag fluorescence lines by using 0.123 cm Cu and 0.83 cm Al as filtration. The spectrum

containing only the 88 keV line was collected over a 20 hour period. A 20 hour natural background spectrum was then subtracted from the filtered spectrum. The resulting response continua were again analyzed to generate probabilities for detector response events at 88 keV.

The 59.5 keV line from ^{241}Am was also separated from the three lower energy Np fluorescence lines by using 0.123 cm Cu and 0.83 cm Al as filtration during a 20 hour counting sequence. The appropriate natural background spectrum was subtracted from the filtered spectrum, and the resulting spectrum was then analyzed to generate detector response probabilities at 59 keV.

Each detector response spectrum generated above was acquired by simply filtering out the low energy photons from each isotope and then implementing the appropriate natural background subtraction. This was a relatively simple process. In order to generate detector response probabilities for exposure to lower energy photons a more sophisticated approach was attempted.

From Table 4.1, we see that ^{241}Am emits three principal low energy fluorescence x rays. The 17.8 keV x ray is the most intense. The goal was therefore to isolate this particular line using some type of filtration. Since zirconium's K-edge lies at 18 keV, it was used to selectively filter out the 20.8 keV x ray. The 13.9 keV photon was also preferentially filtered by the Zr filter due to the fact that the linear attenuation coefficient at these low energies change quickly with energy. For example at 14 keV, μ_{Zr} is 192.1 cm^{-1} , while at 17.8 keV, it is approximately 96 cm^{-1} . Thus the intense 17.8 keV line was the least attenuated low energy line when using Zr as the filter. However, the filtered spectrum contained the K α x rays emitted from the Zr (15.8 and 15.7 keV) filter as well as the 17.8 keV line emitted from ^{241}Am . This was deemed acceptable since the energy difference between the Zr fluorescence x rays and those emitted from ^{241}Am was small. The Zr filtered spectrum also contained the higher energy 59.5 keV ^{241}Am line. In order to isolate the low energy lines from the 59.5 keV line, the spectrum which contained only

the 59.5 keV line as a result of using Al and Cu filtration was subtracted from the spectrum obtained using Zr filtration. The resulting spectrum should theoretically contain only the low energy lines and the detector response artifacts associated with those lines. This sounds very simple, but is very difficult to achieve.

The difficulty is that the different filters scatter the 59.5 keV photons slightly differently. Since the relative amount of scatter is not exactly the same in both spectra, the subtraction will not completely eliminate the effects due to the 59.5 keV line. The detector response to the 59.5 scattered photons can extend down into the low energy range and interfere with the detector response due to the low energy lines. The only detector response artifacts that were deemed reliable were the Ge fluorescence escape peaks.

Since the fluorescence escape peaks are easily found (knowing that the K α fluorescence energy of Ge is approximately 9.9 keV), the probability of fluorescence escape due to exposure to the 17.8 keV line of ^{241}Am was calculated from an unfiltered and unsubtracted ^{241}Am spectrum. The rest of the detector response probabilities due to exposure to the 17.8 keV line of ^{241}Am were not evaluated.

The attempt to isolate the low energy lines from ^{137}Cs was even more difficult. A spectrum was run without any filtration, yielding the low and high energy lines emitted from ^{137}Cs plus Pb fluorescence lines from the Pb collimation around the detector. When filtration was used to eliminate the low energy lines, the resulting spectrum contained the high energy 661 keV line plus the Pb fluorescence lines. Ideally, a subtraction would yield only the low energy lines. However, the filtration changed the ratio of the number of counts in the Pb fluorescence to full energy peak, therefore, it was not possible to normalize the spectra so that both the Pb fluorescence and the 661 keV peak would disappear upon subtraction. The detector response due to the remaining higher energy peaks can again corrupt the detector response continua due to the low energy peaks. Again, only the fluorescence escape peaks from the low energy lines were deemed

reliable. Therefore, the fluorescence escape probability for the 32.1 keV line was again calculated from an unfiltered and unsubtracted spectrum, and the other detector response probabilities were not evaluated.

It should be mentioned that a higher energy calibration was performed in order to accommodate the 661 keV γ rays given off by ^{137}Cs . This calibration was performed using the three lines from ^{57}Co and the 661 keV line from ^{137}Cs . The ADC and MCA were again set at 4096 channels for the entire spectrum. Each channel was therefore 0.194 keV wide. Once the response spectra were run, the detector was recalibrated for use in our normal energy range (0 - 140 keV) as described in Section 4.1.1.

Figure 4.1 shows the plots of the probabilities of the detector response events as a function of incident energy. Lines of best fit were applied to the plotted probabilities, and the equations of these lines were entered into an iterative detector response correction algorithm based on the work of Yaffe et al. [19].

Figure 4.1 Probability of the detector response events as a function of energy.

4.2 Acquisition of the fluorescence spectra

The acquisition of the fluorescence spectra had to be carried out with care since the Pb enclosure and the pieces of Pb which provided horizontal collimation had to be critically positioned for each acquisition.

In order to acquire a spectrum, the foil was mounted on the holder and positioned at the proper angle and distance from the x-ray tube. The detector was then positioned at the desired angle and distance. Without adding any collimation, the foil was fluoresced for two minutes using an x-ray tube current of 1.5 mA. The number of counts in the $K\alpha$ peaks of the resulting spectrum was noted. The Pb enclosure was then put in place along with collimating pieces of Pb which provided both vertical and horizontal collimation. The foil was then fluoresced under the same conditions. The number of counts in the $K\alpha$ peaks of this collimated spectrum was compared to the previously collected spectrum. If the number of $K\alpha$ counts was reduced by more than 2 standard deviations, the collimation was not positioned correctly. The collimation was therefore moved and the foil was fluoresced again. If the number of $K\alpha$ counts remained at the level prior to adding the collimation, then the primary and fluorescence beam filters could be put in place, and the final preparations for acquiring the fluorescence spectrum could begin.

The true tube potential at a given x-ray generator setting was recorded by connecting the Dynalyzer to a digital multimeter. The voltage was measured while a short fluorescence run was made. All values reported here are the actual kilovoltages and not the nominal.

The actual fluorescence runs lasted for 180 seconds (controlled by the MCA software), and a tube current of 1.5 mA was used (controlled by continually adjusting the x-ray generator). Once the spectrum was acquired it was processed. The number of counts in the $K\alpha$ fluorescence peak (intensity), and in the entire spectrum was determined

so that the purity of the spectrum could be calculated as defined by Equation 5.

4.3 Measurement of error

The effect of each variable on intensity and purity was explored while holding the other variables at a standard (default) value. For example, the effect of tube potential was explored while holding: foil thickness, θ , ϕ , fluorescence beam filter thickness, and primary beam filter thickness at standard values. These default values were maintained for each variable explored. Thus there were six spectra run using identical parameters (one for each variable explored). Theoretically, the purity and intensity of the six spectra should be the same. However, there is some variability due to statistical counting fluctuations, slight changes in positioning the components of the apparatus, slight tube current and voltage variations, and so on. The standard deviations of the intensity and purity among these six spectra are used as an indication of error.

The standard deviations of the intensity and purity for a default Sn fluorescence spectrum were approximately 1.1% of the average intensity of a default spectrum, and 0.08% of the average purity of a default spectrum, respectively.

For Pb fluorescence spectra, the standard deviation of the intensity was approximately 5.7% of the average intensity, and the standard deviation of the purity was approximately 0.8% of the average purity of a default spectrum.

The greater variability in Pb $K\alpha$ fluorescence intensity is thought to be due to several factors. Statistical counting fluctuations were greater in the case of Pb since there were fewer counts (approximately 35000, yielding $\sigma = 187$, or 0.53% of the total) in the $K\alpha$ peaks, compared to the 78000 counts (yielding $\sigma = 279$, or 0.36% of the total) in the $K\alpha$ peaks of Sn. Slight variations in the thickness of the Au fluorescence beam filter due to mechanical wear caused by multiple folding and unfolding cycles may have contributed

significantly. One of the other significant causes appears to be the instability of the x-ray generator at high tube potentials. When run at low tube potentials, the variation in $K\alpha$ intensity between test spectra run consecutively under identical conditions (these spectra should not be confused with default spectra which were not run consecutively) was generally within one standard deviation of the number of counts in the $K\alpha$ peaks. However, when run at high tube potentials, it was not uncommon for variability between consecutively run identical spectra to be 3 or 4 times the standard deviation of the number of counts in the $K\alpha$ peaks.

Chapter 5

Results

All spectra shown in this chapter were obtained using an anode to foil distance (d_1) of 18.3 cm, a fluorescence foil to detector distance (d_2) of 66.7 cm, and 270 mAs.

5.1 Spectra from each of the seven fluorescence foils

The specific parameters used to obtain each spectrum in Section 5.1 are given in Table 5.1. The foil angle ϕ and detector angle θ were held constant at 45° and 110° respectively. In some cases there may be escape peak remnants visible. These occur due to the fact that the equations governing the detector response correction algorithm were applied from lines of best fit.

Table 5.1 Parameters used for each spectrum.

kVp	Primary beam filter	Fluorescence foil	Fluorescence beam filter	Figure
60	none used	0.08 mm Zr	none used	5.1
71	none used	0.10 mm Ag	none used	5.2
82	none used	0.076 mm Sn	0.075 mm Ag	5.3
88	none used	0.10 mm La	none used	5.4
109	none used	0.254 mm Ho	1.72 mm Gd ₂ O ₃ :S:Th	5.5
116	0.12 cm Al	0.20 mm W	none used	5.6
126	none used	0.30 mm Pb	0.05 mm Au	5.7

Figure 5.1 Zirconium spectrum.

Figure 5.2 Silver spectrum.

Figure 5.3 Tin spectrum.

Figure 5.4 Lanthanum spectrum.

Figure 5.5 Holmium spectrum.

Figure 5.6 Tungsten spectrum.

Figure 5.7 Lead spectrum.

5.2 Visual effect of fluorescence beam filtration

Figure 5.8 is a spectrum obtained using Sn as the fluorescence foil. No fluorescence beam filter was used. The spectrum was acquired using the following parameters:

X-ray tube potential - 82 kV

Primary beam filtration - none used

Fluorescence foil thickness - 0.076 mm Sn (K-edge = 29.20 keV)

Fluorescence foil angle (ϕ) - 45°

Detector angle (θ) - 110°

Figure 5.8 Tin spectrum (no filtration of fluorescence beam).

Figure 5.9 is also a Sn spectrum. It was acquired using the same parameters as the spectrum shown in Figure 5.8, except that 0.125 mm Ag was used as fluorescence beam filtration.

Figure 5.9 Tin spectrum (0.125 mm Ag used as fluorescence beam filtration).

The use of 0.125 mm Ag increased the spectral purity from 0.779 in Figure 5.8 to 0.966 in Figure 5.9. The increase in purity must be weighed against the decrease in intensity. The intensity of the K α peaks in Figure 5.9 is 27.5% of that in Figure 5.8.

5.3 Intensity and purity versus the controlling variables for Sn

The following graphs show the experimental results of the effect of the controlling variables on the intensity and purity of the fluorescence x-ray beam generated from a Sn fluorescence foil. The error bars, representing the uncertainty in the measurement of intensity, are approximately the same size as the plotted symbols. In the case of purity, the error bars are much smaller than the plotted symbols. The error bars are applied only for the default value point (see Section 4.3) on each graph since it was under the default conditions that duplicate spectra were generated and then compared to determine variability.

5.3.1 X-ray tube potential

Figure 5.10 shows the effect of x-ray tube potential. We see from Figure 5.10 that the $K\alpha$ fluorescence intensity increases approximately linearly with x-ray tube potential. Recall from Section 2.2.1 that this is expected since the tube potentials used lie well above the K-edge energy of the foil. Thus, the new high energy photons produced will contribute very little towards augmenting intensity. Even when the higher energy photons in the primary spectrum interact, they do so deeper in the foil. Thus, many of the fluorescence photons generated will not be able to get out of the front side of the foil to be detected. We therefore observe an increase in intensity proportional only to the increase in the number of photons which lie just above the K-edge of the foil, which is approximately linear with kilovoltage.

Purity falls only slightly with increasing tube potential. This is due to the fact that, for the average energies of the high and low kV spectra used, the difference in the amount of scattered radiation generated is minimal. For example, the ratio of the scatter to photoelectric cross sections changes from 0.02 at 30 keV, to 0.04 at 50 keV, for Sn.

Figure 5.10: Effect of x-ray tube potential.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.076 mm Sn.

Fluorescence foil angle (ϕ) - 45° .

Detector angle (θ) - 110° .

Fluorescence beam filtration - 0.075 mm Ag.

5.3.2 Primary beam filter thickness

Figure 5.11 shows the effect of a $\text{Gd}_2\text{O}_3\text{S:Tb}$ x-ray screen used as the primary beam filter.

It should be noted that the thicknesses shown in Figure 5.11 and quoted previously are for the $\text{Gd}_2\text{O}_3\text{S:Tb}$ screen which is coated in plastic. The thickness of pure Gd which is equivalent to one layer of screen (0.43 mm) is approximately 0.07 mm.

As expected from Equation 15 in Section 2.2.2, Figure 5.11 shows that the K α fluorescence intensity decreases approximately exponentially with increasing primary beam filter thickness. This is because fewer primary photons are available to irradiate the fluorescence foil.

Purity seems to be unaffected, or even decreases slightly, with increasing x_p . This could indicate that the low and high energy primary photons did not contribute noticeably to the degradation of the purity of the fluorescence beam. However, it could also indicate that the wrong primary beam filter material was chosen. Perhaps a material with a K-edge either further above, or below, that of Gd (K-edge = 50.24 keV) would have increased the overall purity of the fluorescence beam generated.

Fig. 5.11 Effect of primary beam filter thickness.

Tube potential - 82 kV.

Fluorescence foil - 0.076 mm Sn.

Fluorescence foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

Fluorescence beam filtration - 0.075 mm Ag.

5.3.3 Fluorescence foil thickness

Figure 5.12 shows the effect of fluorescence foil thickness.

In agreement with the theory of Section 2.2.3, Figure 5.12 shows that $K\alpha$ intensity increases according to $1 - e^{-\mu x}$ as thickness, x , increases.

The purity of the fluorescence beam is relatively insensitive to the thickness of the fluorescence foil. There is only a slight decrease in purity with increasing foil thickness. This decrease is due to the increased probability that the high energy primary photons will interact with the thicker foil. These higher energy photons are more likely to scatter than those with energies just above the K-edge of the foil (see Table 2.1).

Figure 5.12 Effect of fluorescence foil thickness.

Tube potential - 82 kV.

Primary beam filtration - none used.

Fluorescence foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

Fluorescence beam filtration - 0.075 mm Ag.

5.3.4 Fluorescence foil orientation

Figure 5.13 shows the effect of foil angle (ϕ).

As expected, fluorescence intensity decreases as ϕ increases. From Figure 5.13 we see that the negative slope of the intensity plot is steepest when the foil angle is small. This is because of the more rapid change in the effective thickness of the foil [which is proportional to $(\sin \phi)^{-1}$] when the foil is rotated at small foil angles. There is an 18.9% decrease in path length in going from 35° to 45°, while in going from 65° to 75°, the decrease in the path length through the foil for the primary incident photons is only 6.2%.

The purity of the fluorescence beam emitted is unaffected by fluorescence foil orientation.

Figure 5.13 Effect of fluorescence foil angle (ϕ).

Tube potential - 82 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.076 mm Sn.

Detector angle (θ) - 110° .

Fluorescence beam filtration - 0.075 mm Ag.

5.3.5 Detector orientation

Figure 5.14 shows the effect of detector angle (θ).

We see that $K\alpha$ intensity increases as detector angle increases. This confirms the hypothesis made in Section 2.2.5 that there would be an increase in intensity due to the decreasing heel effect as $\theta-\phi$ tends towards 90° . This increase is most pronounced for smaller detector angles. This is because the path length out of the fluorescence foil to the detector changes most rapidly with the movement of the detector when $\theta-\phi$ is closest to 0° .

Purity reaches a slight maximum at approximately 105° . This may be due to the superposition of incoherent scatter, which has minimum probability at approximately 90° , with coherent scatter, for which the probability decreases as θ tends towards 180° .

Figure 5.14 Effect of detector angle (θ).

Tube potential - 82 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.076 mm Sn.

Fluorescence foil angle (ϕ) - 45°.

Fluorescence beam filtration - 0.075 mm Ag.

5.3.6 Fluorescence beam filter thickness

Figure 5.15 shows the effect of fluorescence beam filter thickness.

As expected, $K\alpha$ intensity falls off exponentially with increasing fluorescence beam filter thickness.

The preferential attenuation of $K\beta$ radiation by the fluorescence beam filter causes the purity of the fluorescence beam to rise quickly as the first layer.. of Ag are applied. The purity then rises more slowly as subsequent layers are applied. This is as expected in Section 2.2.6. It was also mentioned in Section 2.2.6 that there is an optimal fluorescence beam filter thickness which maximizes purity. From Figure 5.15, the optimal thickness appears to be approximately 0.10 mm Ag. The linear attenuation coefficient of Ag at the $K\beta$ energy of Sn is approximately 45.8 mm^{-1} , therefore, only 1% transmission occurs when 0.10 mm of Ag is used. This indicates that almost all of the $K\beta$ radiation has been filtered out. Increasing the fluorescence beam filter thickness further will only serve to decrease the $K\alpha$ intensity, which will decrease purity since the filter will not attenuate the high energy scatter very effectively.

Figure 5.15 Effect of fluorescence beam filter thickness.

Tube potential - 82 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.076 mm Sn.

Foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

5.4 Intensity and purity versus the controlling variables for Pb

The following graphs show the experimental results of the effect of the controlling variables on the intensity and purity of the fluorescence x rays generated from a Pb fluorescence foil. The error bars, representing the variability in purity between default spectra are approximately the same size as the plotted symbols.

5.4.1 X-ray tube potential

Figure 5.16 shows the effect of x-ray tube potential. The horizontal error bars represent the uncertainty in the tube potential.

It is evident from Figure 5.16 that $K\alpha$ intensity increases non-linearly. The equation governing the number of $K\alpha$ photons produced is: $195(kVp - 88)^{1.55}$, where 88 represents the K-edge of Pb. The power 1.55 is not surprising since there will be a nearly linear gain from an increased number of photons just above the K-edge, and some gain from the higher energy photons (since they are not too far above the K-edge) created by increasing the tube potential. Recall that in the case of the irradiation of a Sn foil, there was a linear increase since the high energy primary photons generated well above the K-edge of the Sn foil were not effective in creating K-shell vacancies.

Purity increases as tube potential is increased. This is because the tube potential starts out just above the K-edge energy of the foil. This leads to lower purity spectra since most of the primary beam is unable to create K-shell vacancies but can scatter to the detector lowering fluorescence beam purity.

Figure 5.16 Effect of x-ray tube potential.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.3 mm Pb.

Fluorescence foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

Fluorescence beam filtration - 0.05 mm Au.

5.4.2 Primary beam filter thickness

Figure 5.17 shows the effect of a Cu primary beam filter.

As with the Sn results (Section 5.3.2), $K\alpha$ intensity falls off approximately exponentially with increasing primary beam filter thickness as expected.

The purity of the fluorescence beam increases initially and then levels off. This is due to the elimination of some of the lower energy primary photons which give rise to low energy scatter. As more layers of Cu are added, the effect is diminished since the primary beam will already have hardened as a result of passing through the previous layers.

Figure 5.17 Effect of primary beam filter thickness

Tube potential - 115 kV.

Fluorescence foil thickness - 0.3 mm Pb.

Fluorescence foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

Fluorescence beam filtration - 0.05 mm Au.

5.4.3 Fluorescence foil thickness

Figure 5.18 shows the effect of fluorescence foil thickness.

In agreement with theory of Section 2.2.3, $K\alpha$ intensity increases according to $1-e^{-\mu x}$ growth curve as thickness, x , increases.

The purity is relatively insensitive to changes in fluorescence foil thickness for the thicknesses used in this study. There does seem to be a very slight increase in purity as thickness increases. This could suggest that the increased $K\alpha$ intensity is offsetting some of the lower energy scatter which will occur mainly in the first layers of a fluorescence foil.

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Figure 5.18 Effect of Pb fluorescence foil thickness.

Tube potential - 115 kV.

Primary beam filtration - none used.

Fluorescence foil angle (ϕ) - 45° .

Detector angle (θ) - 110° .

Fluorescence beam filtration - 0.05 mm Au.

5.4.4 Fluorescence foil orientation

Figure 5.19 shows the effect of foil angle (ϕ).

As expected, the intensity of the fluorescence falls off as ϕ is increased. Within the limits of the error bars, the decrease is linear. We actually expect that the decline in intensity will be slower at large foil angles, as discussed in Section 5.3.4.

As was the case with the Sn fluorescence foil, purity is insensitive to fluorescence foil angle.

Figure 5.19 Effect of fluorescence foil angle (ϕ).

Tube potential - 115 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.3 mm Pb.

Detector angle (θ) - 110° .

Fluorescence beam filtration - 0.05 mm Au.

5.4.5 Detector orientation

Figure 5.20 shows the effect of detector angle (θ).

As observed when using a Sn fluorescence foil (Section 5.3.5), $K\alpha$ intensity increases as detector angle increases.

There is a slight maximum in purity similar to that observed when Sn was used as the fluorescence foil. The maximum occurs again at approximately 105° .

Figure 5.20 Effect of detector angle (θ).

Tube potential - 115 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.3 mm Pb.

Fluorescence foil angle (ϕ) - 45° .

Fluorescence beam filtration - 0.05 mm Au.

5.4.6 Fluorescence beam filter thickness

Figure 5.21 shows the effect of fluorescence beam filter thickness.

We see that $K\alpha$ intensity falls off exponentially as expected with increasing fluorescence beam filter thickness.

The use of filtration between the fluorescence foil and the detector has a profound effect on purity, especially for high Z fluorescence foils. The addition of the first 0.025 mm Au increases beam purity from approximately 0.34 to 0.69, due to the elimination of the very intense $L\alpha$ and $L\beta$ radiation from the fluorescence beam. The subsequent addition of layers of Au fluorescence beam filter serves to remove the lower intensity $K\beta$ radiation from the beam, thus, the purity increases more slowly. The K-edge filter thickness which maximizes purity was not reached in this experiment.

Figure 5.21 Effect of Au fluorescence beam filter thickness.

Tube potential - 115 kV.

Primary beam filtration - none used.

Fluorescence foil thickness - 0.3 mm Pb,

Foil angle (ϕ) - 45°.

Detector angle (θ) - 110°.

Chapter 6

Conclusions

6.1 Effect of the variables on intensity

The effect that a given variable has on the $K\alpha$ fluorescence output depends partially on the range of the variable considered. It is therefore difficult to say in absolute terms which variable is most influential.

In terms of the irradiation of a Sn fluorescence foil, the order of importance is:

1) Fluorescence beam filter thickness (Ag)

$K\alpha$ output decreases exponentially with increasing filter thickness. For filter thicknesses of approximately 15 μm , the decrease in the $K\alpha$ output is approximately 1500 counts/ μm . At 115 μm , the count rate decreases at 400 counts/ μm .

2) X-ray tube potential

$K\alpha$ output increases with increasing kV. The increase is approximately linear at 1700 counts/kV.

3) Fluorescence foil thickness

$K\alpha$ output increases according to $1-e^{-\mu x}$ with increasing foil thickness. For thicknesses of approximately 40 μm , the rate of increase is approximately 1100 counts/ μm . For thicknesses of approximately 115 μm , the increase is 200 counts/ μm .

4) Primary beam filter thickness ($\text{Gd}_2\text{O}_3\text{:Tb}$ screen)

$K\alpha$ output decreases approximately exponentially with increasing primary beam filter thickness. The rate of decrease when filter thicknesses are approximately $200\text{ }\mu\text{m}$ is 77 counts/ μm , while when thicknesses are increased to $1100\text{ }\mu\text{m}$, the rate falls to 26 counts/ μm .

5) Fluorescence foil angle (ϕ)

$K\alpha$ output decreases as foil angle increases. The average rate of decrease is approximately 700 counts/degree.

6) Detector angle (θ)

$K\alpha$ output increases as detector angle increases. The average rate of increase is approximately 260 counts/degree.

In the case of the irradiation of the Pb fluorescence foil, the order of importance appears to be:

1) X-ray tube potential

Intensity increases at a superlinear rate governed by the relationship $195(\text{kVp} - 88)^{1.55}$, as tube potential increases. The rate changes from 1200 counts/kV at approximately 100 kV, to 1900 counts/kV at approximately 115 kV.

2) Fluorescence beam filter thickness (Au)

Intensity decreases exponentially as thickness increases. The rate changes from 160 counts/ μm at approximately $15\text{ }\mu\text{m}$, to 120 counts/ μm at approximately $75\text{ }\mu\text{m}$.

3) Fluorescence foil thickness

$K\alpha$ output increases according to $1 - e^{-\mu x}$ with increasing thickness. The rate of increase starts out at 70 counts/ μm for thicknesses of approximately $150\text{ }\mu\text{m}$, and saturates after $300\text{ }\mu\text{m}$.

4) Primary beam filter thickness (Cu)

Intensity decreases exponentially as thickness increases. The rate of decrease changes from 14000 counts/mm at 0.25 mm, to 8500 counts/mm at 1.75 mm.

5) Fluorescence foil angle (ϕ)

Intensity decreases linearly at a rate of 250 counts/degree as foil angle increases.

6) Detector angle (θ)

Intensity increases at a rate of approximately 100 counts/degree as detector angle increases.

There was a change in the order of importance between the Sn and Pb results involving x-ray tube potential and fluorescence beam filter thickness. This is due to the fact that, in the case of the irradiation of the Pb fluorescence foil, the tube potential started out very near its K-edge, and was therefore very influential on $K\alpha$ output.

6.2 Effect of the variables on purity

In terms of the irradiation of a Sn fluorescence foil, only fluorescence beam filter thickness had a significant effect. Purity increased from 0.775 to 0.965 with the addition of 0.12 mm Ag. The others produced only very slight (but interesting) effects. For example, there does appear to be an angle of maximum purity at $\theta = 105^\circ$. This probably indicates that there is a minimum in total scatter at this angle.

In terms of the irradiation of a Pb fluorescence foil, the order of importance appears to be:

1) Fluorescence beam filter thickness (Au)

Purity increases as filter thickness increases. The initial addition of 0.025 mm Au

increased purity very quickly (0.014/ μm on average) due to the elimination of the low energy L and M fluorescence radiation. Subsequent increases in filter thicknesses increased purity at a rate of approximately 0.0013/ μm .

2) X-ray tube potential

Purity increases as tube potential increases. The initial increase is large (0.034/kV) just below 100 kV. By 120 kV the increase has slowed to 0.003/kV.

3) Primary beam filter thickness (Cu)

Purity increases at a rate of 0.078/mm for the first 0.50 mm with increasing filter thickness. There is no increase in purity after this point.

The others produced only slight effects. However, there again appears to be a detector angle of maximum purity which occurs at approximately 105°.

The preceding results yield information useful for optimizing intensity or purity, or it allows one to set the parameters such that a compromise is reached.

6.3 Intensity output factor

As mentioned in Section 1.5.1, many of the intensities reported in the previous investigations are not very useful for making comparisons. The difficulties often arise due to incomplete descriptions of the parameters (such as d_1 , d_2 , and beam area irradiating the foil). Comparisons are also made difficult due to the variation in parameters used among the studies. In an effort to standardize the results of this thesis, an output function, $O_{1,1}$, has been defined as the exposure per mAs applied, per cm^2 of beam area irradiating the foil, at $d_1 = d_2 = 1 \text{ cm}$. The function has units: $\text{mR mA}^{-1} \text{ s}^{-1} \text{ cm}^2$. A typical $O_{1,1}$ value obtained during this thesis for the irradiation of a Sn foil, with no primary or secondary beam filtration, at 82 kV, is approximately $4.0 \times 10^3 \text{ mR mA}^{-1} \text{ s}^{-1}$.

cm², while the irradiation of a Pb foil at 121 kV with no beam filtration, yields an $O_{1,1}$ value of $3.2 \times 10^2 \text{ mR mA}^{-1} \text{ s}^{-1} \text{ cm}^2$.

Given any $O_{1,1}$ value, the following equation (where I is the tube current, t , is the time in seconds, and A_b is the beam area irradiating the foil) allows the reader to calculate the exposure for any d_1 , d_2 , mAs applied, and beam area incident on the foil.

$$X_{d_1, d_2} = \frac{O_{1,1}}{(d_1 d_2)^2} I t A_b \quad (19)$$

6.4 General remarks

The experimental results seem to agree well with both the theoretical calculation of $K\alpha$ intensity expected in Section 2.1.4, and the theory proposed in Section 2.2. The only exception is the case of the $\text{Gd}_2\text{O}_3\text{S:Tb}$ x-ray screen primary beam filter used when irradiating the Sn fluorescence foil. Purity did not increase as a result of using the filter. The experimental results also seem to yield the same trends as those generated in the computer simulation of the experiment performed by A. Dekok [22].

6.5 Future work

There are several areas which could be further explored. It is unclear why the Gd primary beam filter did not increase purity. This could perhaps be explored by using different primary beam filter materials with K-edges slightly above and below the Gd K-edge.

Many of the potential uses of monoenergetic x-ray beams mentioned in Section

1.2 require that the fluorescence intensities generated be much higher than those attained during this investigation. To help maximize the intensity of the fluorescence beam, an x-ray tube with the fluorescence target placed inside the glass envelope next to the x-ray anode (such that d_f is minimized) could be designed. The results of this thesis should be useful determining the optimum position, orientation, and thickness of the fluorescence target inside the x-ray tube.

Appendix 1

Glossary

Term	Definition
Angiography	The x-ray imaging of blood vessels through the use of radiopaque contrast agents
Beam hardening	The preferential removal of low energy photons from a polyenergetic x-ray beam
CT	Computed tomography
Dose	Energy absorbed per unit mass of the absorber (J/kg)
Exposure	Charge liberated per unit mass of air (C/kg)
Heel effect	The term used to describe the radiation emission pattern from an x-ray tube anode. The x rays emitted in the direction nearly parallel to the surface must travel through the longest path to escape the material, and those emitted perpendicular the shortest path. Therefore, the radiation pattern is most intense for photons travelling perpendicular to the surface, and decreases as the photon angle becomes more oblique.
kVp	Peak kilovoltage produced by the x-ray generator
SNR	Signal to noise ratio

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