227
10-3-80
JWA

Doc. 1810

UCRL-52968

Scattering of x rays from low-Z materials

J. L. Gaines
L. D. Kissel
H. C. Catron
R. A. Hansen

MASTER

August 1, 1980

Lawrence
Livermore
Laboratory

Scattering of x rays from low-Z materials

J. L. Gaines
L. D. Kissel
H. C. Catron
R. A. Hansen

Manuscript date: August 1, 1980

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$6.00 per copy • (Microfiche \$3.50)

CONTENTS

Abstract	1
Introduction	1
Technical Background	1
General Theory	1
Calculations	3
Experimental	3
Theoretical	4
Experiment	6
Equipment	6
Procedure	7
Results and Discussion	8
Incident and Scattered X-Ray Spectra	8
Relative Scattering Efficiency	9
Absolute Scattering Efficiency	9
Conclusions	13
References	14

Scattering of x rays from low-Z materials

ABSTRACT

X rays incident on thin beryllium, boron, carbon, and other low-Z materials undergo both elastic and inelastic scattering as well as diffraction from the crystalline or "crystalline-like" structure of the material. Unpolarized monoenergetic x rays in the 1.5- to 3.0-keV energy range were used to determine the absolute scattering efficiency of thin beryllium, carbon, and boron foils. These measurements are compared to calculated scattering efficiencies predicted by single-atom theories. In addition, the relative scattering efficiency versus x-ray energy was measured for other low-Z foils using unpolarized bremsstrahlung x rays. In all the low-Z foils examined, we observed Bragg-like x-ray diffraction due to the ordered structure of the materials.

INTRODUCTION

Low-Z materials are often used or considered for use as scatterers of x-ray beams. These uses may originate from a desire to reduce the intensity of the x-ray beam, e.g., for diagnostic purposes, or may be required as a result of experimental geometry constraints. It is necessary to know the energy distribution and intensity of the x rays scattered from the low-Z material in order to make effective use of it as a scatterer.

Although a considerable amount of work has been done in the area of calculating or predicting single-atom photon scattering,^{1,2} little experimental work has been performed in the 1- to 10-keV energy range to confirm these calculations and predictions.

We have therefore measured the absolute scattering efficiency in this energy range of three thin low-Z foils (Be, C, and B)³ and compared these values with calculated single-atom scattering efficiencies. These measurements were made using intense, nearly monoenergetic, unpolarized x-ray beams in the energy range from 1.5 to 8 keV.⁴ In addition, we have measured the relative scattering efficiency of several other thin, low-Z foils using unpolarized 16-keV bremsstrahlung x rays from Al and Cu targets. High resolution lithium-drifted silicon detectors were used to monitor the incident and scattered x rays.

TECHNICAL BACKGROUND

GENERAL THEORY

In traversing a thin slab of matter, a narrow beam of x rays is absorbed in accordance with the usual exponential equation

$$I = I_0 e^{-\mu x}, \quad (1)$$

where I is the transmitted intensity, and I_0 is the incident intensity of the x-ray beam. The quantity x is the thickness of the material in centimeters, and μ is

the linear absorption coefficient. We may rewrite this equation as

$$I = I_0 e^{-(\mu/\rho)x}, \quad (2)$$

where ρ is the material density. The quantity μ/ρ , the mass absorption coefficient, is more nearly independent of the physical and chemical state of the material than μ . The loss of intensity of a narrow x-ray beam as it traverses the material is actually due to two processes, "true absorption" and "scatter." True absorption involves the transformation

of x rays into kinetic energy of ejected electrons, whereas scattering is a process in which radiant energy is transferred from the primary x-ray beam to scattered beams originating in the atoms of the absorber. The mass absorption coefficient can thus be written as

$$\frac{\mu}{\rho} = (\tau/\rho) + (\sigma/\rho), \quad (3)$$

where τ/ρ is the true absorption coefficient, and σ/ρ is the scattering coefficient. Although this true absorption coefficient accounts for most of the loss of intensity as x rays traverse a substance, in this paper we are primarily concerned with the smaller fraction of beam intensity lost through scattering.

Scattering can be classified as either elastic or inelastic. Elastic scattering involves a change in x-ray momentum but no change in x-ray energy, i.e., a change of direction only. A portion of the elastically scattered radiation comprises the phenomenon of x-ray diffraction, or "Bragg scattering," which will be discussed in more detail later. Inelastic scattering involves both a change in x-ray momentum and x-ray energy. Thus we can write the total scattering cross section for an isolated atom as the sum of the elastic and inelastic scattering cross sections,

$$\sigma_{\text{scat}} = \sigma_{\text{elas}} + \sigma_{\text{inelas}}. \quad (4)$$

If we consider only scattering which is observed in a small solid angle $d\Omega$ at a specified angle θ with respect to the incident x-ray beam, then we can define the differential scattering cross section per unit solid angle as

$$\frac{d\sigma_{\text{scat}}}{d\Omega} = \frac{d\sigma_{\text{elas}}}{d\Omega} + \frac{d\sigma_{\text{inelas}}}{d\Omega}. \quad (5)$$

In principle, it is impossible to distinguish which component of an isolated atom is responsible for elastically scattering a photon since there is no change in the atom after scattering. However, in practice, one usually expresses the total-atom elastic scattering amplitude, for scattering x rays and γ rays, as a sum of amplitudes due to elastic scattering by the:

- (1) Bound atomic electrons (Rayleigh scattering).
- (2) Nuclear charge (nuclear Thomson scattering).
- (3) Structure of the nucleus (nuclear resonance scattering).
- (4) Field of the nucleus (Delbrück scattering).

The total-atom elastic scattering cross section is the square of the total scattering amplitude. For x-ray energies above 100 keV, all of these processes are important. However, the energies of the x rays used in this experiment were in the range 1 to 20 keV, and in this energy region Rayleigh scattering strongly dominates the total-atom elastic scattering cross section. The differential cross section for Rayleigh scattering per unit solid angle is often written in terms of a form-factor-corrected Thomson cross section,⁵

$$\frac{d\sigma_{\text{elas}}}{d\Omega} = |F(q)|^2 \frac{d\sigma_{\text{Thomson}}}{d\Omega}. \quad (6)$$

The form factor $F(q)$ corrects the point-charge Thomson scattering cross section for scattering by an extended charge distribution. The Thomson cross section is given by⁵

$$\frac{d\sigma_{\text{Thomson}}}{d\Omega} = \frac{r_0^2}{2} (1 + \cos^2 \theta), \quad (7)$$

where θ is the scattering angle and r_0 is the classical radius of the electron given as

$$r_0 = \frac{e^2}{mc^2}, \quad (8)$$

with

- e = electron charge,
- m = electron rest mass,
- c = velocity of light.

The atomic form factor $F(q)$ is given for a spherically symmetric electronic charge density by⁵

$$F(q) = 4\pi \int_0^\infty \rho(r) \frac{\sin(qr)}{qr} r^2 dr, \quad (9)$$

where

- $\rho(r)$ = radial electron charge density,
- r = atomic radial coordinate centered on the nucleus,
- $q = 4\pi/\lambda \sin \theta/2$ (θ = scattering angle and λ = photon wavelength).

For x rays with $E < 20$ keV, the inelastic scattering by atoms is due primarily to the contribution made by the atomic electrons and is referred to as bound Compton scattering. The inelastic scattering from an atom containing N bound electrons is often calculated using a scattering function correction to the Klein-Nishina formula⁶:

$$\frac{d\sigma_{\text{inelas}}}{d\Omega} = S(q_{\text{incoh}}) \frac{d\sigma_{\text{KN}}}{d\Omega}, \quad (10)$$

where

$$h q_{\text{incoh}} = 2 K \sin \theta/2 \left[1 + (K^2 + 2K) \times \sin^2 (\theta/2) \right]^{1/2} / \left[1 + 2K \sin^2 (\theta/2) \right],$$

and the Klein-Nishina formula may be written as

$$\frac{d\sigma_{\text{KN}}}{d\Omega} = \frac{r_0^2 (1 + \cos^2 \theta)}{2 [1 + k(1 - \cos \theta)]^2} \times \left\{ 1 + \frac{k^2 (1 - \cos \theta)^2}{[1 + \cos^2 \theta] [1 + k(1 - \cos \theta)]} \right\}, \quad (11)$$

where

$k = h\nu_0/mc^2$ energy of incident x ray,

r_0 = classical radius of electron as given in Eq. (8).

θ = x-ray scattering angle.

As with elastic scattering by atomic electrons, the incoherent scattering function $S(q_{\text{incoh}})$ corrects the free point charge Klein-Nishina formula for scattering by a bound and distributed electronic charge. Tables have been published which give calculated values for the incoherent scattering functions.¹

The phenomenon of x-ray diffraction by crystals results from elastic scattering by a collection of atoms which are fixed in a spatial lattice. Diffraction occurs only when certain geometrical conditions are satisfied, which are expressed for crystals in terms of the Bragg condition⁷:

$$n\lambda = 2d \sin \theta_\beta, \quad (12)$$

where

n = order of reflection,

λ = wavelength in $\text{\AA}$ of incident x ray,

d = interplanar spacing in $\text{\AA}$,

θ_β = angle between the atomic plane and the incident beam.

For well-ordered crystals with known d spacings this relationship is routinely used in most applications of x-ray diffraction systems. However, diffraction is not limited to well-ordered crystalline substances but occurs from most solids when the right geometric conditions are present. It is now evident that most materials act as three-dimensional diffraction gratings for x rays in the 1- to 20-keV energy range. In fact, it appears that a truly amorphous scatterer is an extreme rarity for x rays in this energy range.

Considering all the processes which contribute to the scattering of x rays from materials in the energy region under consideration, Eq. (5) should be modified to include a contribution due to diffraction. However, at the present time we are unable to properly quantify the contribution due to this effect.

CALCULATIONS

Experimental

In this experiment we have measured the absolute scattering efficiency which we have defined as the fraction of x rays of energy E incident on the scatterer and scattered into a solid angle Ω ,

$$\epsilon(E, \Omega) = \frac{\text{No. scattered x rays into solid angle } \Omega}{\text{No. x rays of energy } E \text{ incident}}. \quad (13)$$

Figure 1 illustrates the typical geometry used in this experiment. Referring to this figure, we see that all of the x rays that pass through collimator C_1 strike the scattering foil, and all of the x rays that pass through C_2 strike detector No. 1 which is a windowless lithium-drifted silicon detector. The number of x rays per second striking the foil are related to the number of x rays counted by detector No. 1 by the relation

$$\dot{N}_{C_1} = \frac{N_{C_2}}{t_{e1}} \left(\frac{D_{C_1}}{D_{C_2}} \right)^2 \left(\frac{R_{C_2}}{R_{C_1}} \right)^2, \quad (14)$$

FIG. 1. Experimental geometry.

where

- $\dot{N}_{C1}$ = x rays per second striking the foil,
- D_{C1} = diameter of collimator C_1 in cm,
- R_{C1} = distance from x-ray source to C_1 in cm,
- D_{C2} = diameter of collimator C_2 in cm,
- R_{C2} = distance from x-ray source to C_2 in cm,
- N_{C2} = x rays counted by detector No. 1 in

time t ,

t = counting interval in seconds,

e_1 = efficiency of detector No. 1.

All of the x rays that are scattered from the foil and pass through collimator C_3 of Fig. 1 are counted by detector No. 2. The solid angle subtended by C_3 is given by

$$\Omega = \frac{\text{Area of collimator } C_3}{\text{Distance from scatterer to } C_3}$$

$$= \frac{(\pi/4)(D_{C3})^2}{R_{C3}}, \quad (15)$$

where

- D_{C3} = diameter of collimator C_3 in cm,
- R_{C3} = distance from scatterer to C_3 in cm.

Referring again to Fig. 1, the number of x rays per second scattered through collimator C_3 and counted by detector No. 2, a lithium-drifted silicon detector with a 5.08×10^{-3} -cm-thick beryllium window, is given by

$$\dot{N}_{C3} = \frac{N_{C3}}{t_2 e_2}, \quad (16)$$

where

- N_{C3} = number of x rays counted by detector No. 2 in t_2 seconds,

t_2 = counting interval in seconds,

e_2 = efficiency of detector No. 2.

Thus the number of x rays per second per steradian scattered into detector No. 2 is

$$\dot{N}_{S3} = \frac{\dot{N}_{C3}}{\Omega}, \quad (17)$$

and the measured scattering efficiency is then

$$\epsilon(E, \Omega) = \frac{\dot{N}_{S3}}{\dot{N}_{C1}}. \quad (18)$$

Theoretical

Kissel⁸ relates single-atom elastic and inelastic scattering cross sections to the experimentally observed scattering efficiency for thin foils. We repeat expression 13 from this reference here as

$$\epsilon(E, \Omega) = n t_{\text{elas}} \frac{d\sigma_{\text{elas}}}{d\Omega} + n t_{\text{inelas}} \frac{d\sigma_{\text{inelas}}}{d\Omega}, \quad (19)$$

where

n = scatterer number density in scatterers/cm³,

t_{elas} = effective thickness of material perpendicular to the incident x-ray beam direction for elastic scattering,

$d\sigma_{elas}/d\Omega$ = differential elastic scattering cross section per scatterer,

t_{inelas} = effective thickness of material perpendicular to the incident x-ray beam direction for inelastic scattering,

$d\sigma_{inelas}/d\Omega$ = differential inelastic scattering cross section per scatterer.

The quantities t_{elas} and t_{inelas} are effective thicknesses of material in the x-ray beam. That is, nt_{elas} is the number of scatterers per unit area of incident x-ray beam which effectively contribute to elastic scattering.

For a reflection geometry $\theta > \phi$, the x-ray source and detectors are on the same side of the scattering foil. The effective foil thicknesses are:

$$t_{elas}^{ref} = \frac{1 - \exp \left\{ -n \left[\frac{\sigma(E)}{\sin \phi} + \frac{\sigma(E)}{\sin(\theta - \phi)} \right] t \right\}}{n \left[\sigma(E) + \frac{\sigma(E) \sin \phi}{\sin(\theta - \phi)} \right]}, \quad (20)$$

and

$$t_{inelas}^{ref} = \frac{1 - \exp \left\{ -n \left[\frac{\sigma(E)}{\sin \phi} + \frac{\sigma(E')}{\sin(\theta - \phi)} \right] t \right\}}{n \left[\sigma(E) + \frac{\sigma(E') \sin \phi}{\sin(\theta - \phi)} \right]}; \quad (21)$$

where

E = energy of incident x ray and energy of elastically scattered x ray,

E' = energy of inelastically scattered x ray,

$\sigma(\omega)$ = total cross section for photons of energy ω ,

t = physical foil thickness,

θ = scattering angle,

ϕ = foil angle.

In a transmission geometry, $\phi > \theta$, the x-ray source and detector are on opposite sides of the scattering foil. The effective thicknesses are:

$$t_{elas}^{trans} = \exp \left\{ -\frac{n\sigma(E)t}{\sin \phi} \right\} \times \frac{1 - \exp \left\{ n \left[\frac{\sigma(E)}{\sin \phi} - \frac{\sigma(E)}{\sin(\phi - \theta)} \right] t \right\}}{n \left[\frac{\sigma(E) \sin \phi}{\sin(\phi - \theta)} - \sigma(E) \right]}, \quad (22)$$

and

$$t_{inelas}^{trans} = \exp \left\{ -\frac{n\sigma(E)t}{\sin \phi} \right\} \times \frac{1 - \exp \left\{ n \left[\frac{\sigma(E)}{\sin \phi} - \frac{\sigma(E')}{\sin(\phi - \theta)} \right] t \right\}}{n \left[\frac{\sigma(E) \sin \phi}{\sin(\phi - \theta)} - \sigma(E) \right]}. \quad (23)$$

(See Fig. 1 for definition of θ and ϕ .)

Kissel has written a code called SEFF which calculates the scattering efficiency of Eq. (19) for fixed θ at various E . This code uses Eq. (6) which includes the form-factor-corrected Thomson formula to calculate the contribution from elastic scattering and which uses Eq. (10), the incoherent-scattering-function-corrected Klein-Nishina formula, to calculate the contribution from inelastic scattering. The code obtains the required values of $F(q)$ and $S(q)$ from a private library containing the values published by Hubbell et al.¹ The values of $F(q)$ and $S(q)$ for $Z = 2-6$ were derived from nonrelativistic configuration-interaction calculations which include substantial electron correlation effects. The total cross sections required for the calculation of the effective thicknesses, Eqs. (20) to (23), were obtained from the L Division cross-section library CSLOW3/77.⁹

Precise limitations on the accuracy of the form-factor-corrected Thomson formula, Eq. (6), are not presently available. Recent investigations^{2,10,11} do provide general guidance on regions of expected validity for Eq. (6). It is expected that Eq. (6) will be valid for light elements ($Z \lesssim 20$), for energies well above K shell binding, and for values of the momentum transfer $q \ll 20 \text{ \AA}^{-1}$. That is, Eq. (6) should be generally valid as used here. General limits on the validity of $S(q)$ are not known.

EXPERIMENT

EQUIPMENT

The x-ray facility used to provide the monoenergetic x rays in the 1.5- to 8-keV energy range as well as the bremsstrahlung x-ray beams is a part of the Lawrence Livermore National Laboratory X-Ray Calibration and Standards Laboratory¹² and has been described in detail previously.⁴ The foils which were examined are listed in Table 1 below.

The foils or scatterers were ≥ 0.99 pure in most cases. An oxide coating was present on the beryllium and aluminum as no effort was made to reduce the effects of oxidation, and care was taken only to protect them from physical damage. The foils were placed in a vacuum of $\leq 10^{-6}$ Torr for more than one hour before being used in the experiment.

The thicknesses given are either those specified by the manufacturer or were determined by measuring the mass per unit area through precision weighing. The two beryllium foils were made by differing processes. One was vapor plated (1.16×10^{-3} g/cm²), and the other was rolled to the proper thickness (1.39×10^{-3} g/cm²). The vapor plated foil should be of higher purity because impurities can be introduced by the rolling process. The boron and

carbon foils were fabricated by depositing boron and carbon on thin polyethylene or parylene foils.³ In the case of the boron and carbon on parylene, the parylene foils were measured for their relative scattering efficiency before the boron or carbon was deposited, and then the scattering efficiency for the coated foils was measured. This allowed us to determine the effect of the substrate.

The two liquid-nitrogen-cooled, lithium-drifted silicon detectors were very similar with the exception that one detector had a 5.08×10^{-3} -cm-thick beryllium window, and the other one was used in a windowless mode. These detectors are 100% absorbing for 16-keV x rays and have an energy resolution of 185 eV for the ⁵⁵Fe radiation lines.

The scattering foils were mounted on frames attached to a positioning mechanism that would allow adjustment from outside of the evacuated scattering chamber. The positioning mechanism could hold and position three foils with an empty fourth position to allow the beam a straight-through path. This apparatus can be seen in Fig. 2.

The data was recorded using a multichannel pulse height analyzer system as well as typical counting electronics; and stored on magnetic tape and processed using the Lawrence Livermore National Laboratory LTSS computer facility.¹³

TABLE 1. List of scatterers

Scatterer	Thickness X, cm	ρX , g/cm ²
Aluminum	7.62×10^{-5}	2.06×10^{-4}
Aluminized mylar	5.08×10^{-4}	
Beryllium (vapor deposited)		1.16×10^{-3}
Beryllium (rolled)		1.39×10^{-3}
Boron (on parylene N)		2.27×10^{-3}
Carbon (on parylene N)		$361. \times 10^{-6}$
Carbon (on polyethylene)		$299. \times 10^{-6}$
Mylar	3.81×10^{-4}	$533. \times 10^{-6}$
Nickel	1.0×10^{-4}	8.90×10^{-4}
Parylene C	2.2×10^{-4}	$283. \times 10^{-6}$
Parylene N	2.5×10^{-4}	$278. \times 10^{-6}$
Parylene N (boron substrate)	1.0×10^{-4}	$111. \times 10^{-6}$
Parylene N (carbon substrate)	8.5×10^{-5}	94.4×10^{-6}
Polyethylene	3.54×10^{-4}	$323. \times 10^{-6}$
Titanium	3.05×10^{-4}	1.38×10^{-3}
Saran	1.02×10^{-3}

FIG. 2. Photographic view of scattering apparatus.

PROCEDURE

The scattering foil to be investigated was positioned in the evacuated scattering chamber as shown schematically in Fig. 1. The scattering foil was inclined at an angle of 45° with respect to the incident beam on the horizontal plane and 90° with respect to the incident beam on the vertical plane. The collimator C_1 defined the size of the x-ray beam striking the scatterer and insured that the x-ray beam struck only the scatterer and not the mounting structure.

For the absolute scattering efficiency measurements using monoenergetic x rays, detector No. 2 was kept at a position of 90° with respect to the incident x-ray beam and looked at the front surface of the scattering foil through collimator C_3 . The efficiency of this detector was known, having been measured for the energy range of 1 to 16 keV. Detector No. 1 was located on the axis of the x-ray beam about 8 m from the x-ray source, and when the foil was rotated up out of the beam this detector viewed the x-ray source through collimator C_2 .

The efficiency of this detector is also known for the energy range of 1 to 16 keV. The large distance to this detector and small collimator in front of it were necessary to reduce the x-ray flux to allow counting of the x-ray beam. The procedure was then to place the foil into the monoenergetic x-ray beam, and count the number of scattered x rays as seen by detector No. 2 for a given time period, and at the same time record the data on a multichannel pulse height analyzer. The foil was then removed from the beam and the number of x rays as seen by detector No. 1 were counted for a fixed time as well as also being recorded on a multichannel pulse-height analyzer. By use of Eqs. (14) through (18), the absolute scattering efficiency as defined by Eq. (13) can be determined.

To measure the relative scattering efficiency of the foils, the experimental setup was nearly the same as described above with the exception that detector No. 2 was rotated 90° to monitor the direct x-ray beam when the foil was removed from the beam. In addition, the x-ray beam used was a bremsstrahlung beam rather than a monoenergetic x-ray beam. When the incident bremsstrahlung beam was monitored with the foil out of the way and detector No. 2 positioned on the beam axis, the current to the x-ray tube was reduced to enable the detector to count the incident flux and record the spectrum on the multichannel pulse-height analyzer. When the foil was in the beam, and detector No. 2 was rotated 90° to measure the scattered beam and record the spectrum on the multichannel pulse-height analyzer, the current to the x-ray tube was increased to full value. By changing only the x-ray tube current and not the high voltage, the x-ray spectrum incident on the foil or detector was unchanged except for intensity. The scattered spectrum and the incident spectrum, both recorded on magnetic tape, were then processed by a computer routine which converted the spectra from number of counts versus channel number to counts versus energy, and corrected them for detector efficiency. The corrected and converted scattered spectrum was then divided by the converted and corrected incident spectrum using a computer routine to provide the relative scattering efficiency versus x-ray energy for the foil.

RESULTS AND DISCUSSION

INCIDENT AND SCATTERED X-RAY SPECTRA

The bremsstrahlung x-ray spectra from an aluminum anode and a copper anode are shown in Figs. 3 and 4. These spectra, corrected for detector efficiency, were recorded using Si(Li) detector No. 2 which had a 5.08×10^{-3} -cm-thick beryllium window. Most of the data obtained to determine the relative scattering efficiency was taken using the aluminum bremsstrahlung spectra incident on the various foils. The choice of the aluminum over the

copper spectra was to avoid having scattered fluorescent peaks with their accompanying escape peaks interfere with the Bragg peaks in the scattered spectra. A scattered peak due to the aluminum fluorescent peak did occur, but at least there was no escape peak present. Also, the resolution of the detectors allowed only one fluorescent peak for aluminum to occur, where two fluorescent peaks plus two escape peaks occurred for the scattered copper bremsstrahlung. In cases where the scattered aluminum peak interfered with the Bragg peaks seen in the scattered spectrum, the copper anode was also used to examine that region as it had no peaks in that energy region. Scattered spectra from a couple of the foils using both anodes are shown in Figs. 5-8. These spectra have been corrected for detector efficiency. Figures 5 and 6 are aluminum and copper bremsstrahlung spectra scattered from the rolled beryllium foil. The scattered fluorescent peaks, Bragg peaks, and escape peaks are identified. Figures 7 and 8 are the same bremsstrahlung spectra scattered from a thin aluminum foil. The aluminum foil shows a large fluorescent peak at 1.48 keV, which is much larger than the Bragg peaks and falls on top of the scattered aluminum fluorescent peak from the aluminum bremsstrahlung spectrum in Fig. 7.

FIG. 3. Incident aluminum bremsstrahlung spectrum.

FIG. 4. Incident copper bremsstrahlung spectrum.

FIG. 5. Scattered aluminum bremsstrahlung spectrum from rolled beryllium foil.

FIG. 6. Scattered copper bremsstrahlung spectrum from rolled beryllium foil.

FIG. 7. Scattered aluminum bremsstrahlung spectrum from aluminum foil.

FIG. 8. Scattered copper bremsstrahlung spectrum from aluminum foil.

RELATIVE SCATTERING EFFICIENCY

The relative scattering efficiency of the foils listed in Table I was determined using the procedure described previously. The relative scattering efficiency versus incident x-ray energy for most of these scatterers is shown in Figs. 9-22. For some of the scatterers, fluorescent peaks as well as Bragg peaks are evident. The parylene-C and saran scatterers both exhibit chlorine fluorescent peaks at approximately 2.6 keV due to the chlorine in their composition. The aluminum, aluminized mylar, nickel, and titanium scatterers also exhibit fluorescent peaks at the appropriate k-shell energy for aluminum, nickel, and titanium.

The spectra shown in Figs. 9-22 are plotted out to 16 keV. However, since the incident bremsstrahlung spectra shown in Figs. 3 and 4 tail off to zero at 16 keV, the statistics beyond 10 or 12 keV are fairly poor. Likewise, at energies lower than approximately 1.5 keV the data is not as reliable because the beryllium window on Si(Li) detector No. 2 cuts off the low energy x rays, and the electronic noise of our counting system becomes a more predominant effect.

ABSOLUTE SCATTERING EFFICIENCY

The absolute scattering efficiency was determined for four of the scatterers. These were the two beryllium foils, the carbon on parylene foil, and the boron on parylene foil. The procedure as described previously is very time consuming since some of the count rates as measured by Si(Li) detector No. 2 were very low, and the time required to accumulate a good spectrum exceeded 6 hours for a single energy point. Since eight energy points in the region from 1.5 to 8 keV were used for each scattering efficiency measurement, the absolute scattering efficiency was measured for only four foils. Figures 23-26 show the measured scattering efficiency as well as the calculated scattering efficiency as described previously. In addition the relative scattering efficiency normalized at one energy point is also shown. The normalization was done at an energy point which was not affected or influenced by a Bragg peak. After normalization, the agreement between the relative scattering efficiency curves and the measured absolute scattering efficiency at distinct energy points is remarkably

FIG. 9. Relative scattering efficiency for aluminum.

FIG. 10. Relative scattering efficiency for aluminized mylar.

FIG. 11. Relative scattering efficiency for plated beryllium.

FIG. 12. Relative scattering efficiency for rolled beryllium.

FIG. 13. Relative scattering efficiency for boron on parylene.

FIG. 14. Relative scattering efficiency for carbon on parylene.

FIG. 15. Relative scattering efficiency for carbon on polyethylene.

FIG. 18. Relative scattering efficiency for parylene C.

FIG. 16. Relative scattering efficiency for mylar.

FIG. 19. Relative scattering efficiency for parylene N.

FIG. 17. Relative scattering efficiency for nickel.

FIG. 20. Relative scattering efficiency for polyethylene.

FIG. 21. Relative scattering efficiency for titanium.

FIG. 22. Relative scattering efficiency for saran.

FIG. 23. Absolute scattering efficiency for plated beryllium.

FIG. 24. Absolute scattering efficiency for rolled beryllium.

FIG. 25. Absolute scattering efficiency for boron on parylene.

FIG. 26. Absolute scattering efficiency for carbon on parylene.

good. The brackets on the calibration points at distinct energy points represent an estimated uncertainty in the measurements of approximately 25%. This is due primarily to a small uncertainty involved in determining the number of x rays in the incident fluorescent peak and a much larger uncertainty involved in determining the number of x rays in the scattered fluorescent peak. Since the incident filtered fluorescent x-ray spectra is not 100% monoenergetic but only 89-98% spectrally pure, a small amount of contaminant that happens to be Bragg scattered can become a much more significant feature of the scattered spectrum than the scattered fluorescent peak. Due to the 185 eV resolution of the Si(Li) detector, these Bragg-scattered contaminant peaks often partially overlap the scattered fluorescent peaks, making it difficult to determine their magnitude.

CONCLUSIONS

All of the scatterers examined in this experiment exhibited Bragg-like x-ray diffraction. The number of diffraction peaks was generally greater for the metallic scatterers than for the others. As was mentioned previously, some of the scatterers also produced fluorescent x-ray peaks in the energy region of interest when x rays were incident on them. Since the present calculational model for scattering efficiency does not account for these effects, it only gives an approximate value when compared to

The effects of Bragg scattering are very evident in these figures. As can be seen in Figs. 23 and 24, the Bragg scattering peaks from two different pieces of beryllium are different. This might be expected since they were fabricated differently and since the orientation of the crystal planes was not considered when they were mounted on their holders. By reorienting the foils a change in the Bragg scattering peaks could be accomplished. The calculated scattering efficiency, which does not include Bragg scattering, agrees with the measurements fairly well for one of the beryllium foils, and not too badly for the carbon foil. However, the measured scattering efficiency for the vapor-plated beryllium foil, although in agreement with the calculation at higher energies, disagrees with the calculation considerably at the lower energies (1-7 keV).

the measured scattering efficiency. If the scatterers were truly amorphous, the agreement should be quite good with the exception of possible fluorescent peaks.

Since even the same types of scatterers may have different crystalline-like orientations, the only valid method of determining the scattering efficiency of a particular scattering foil is to experimentally measure it.

REFERENCES

1. J. H. Hubbell, W. J. Veigele, E. A. Briggs, R. T. Brown, D. T. Cromer, and R. J. Howerton, *Journal of Physical and Chemical Reference Data* **4**, 471 (1975).
2. L. Kossel and R. H. Pratt, *Phys. Rev. Lett.* **40**, 387 (1978).
3. T. C. Froehle, *Large-Area Boron and Carbon Scatterers and Filters*, Lawrence Livermore National Laboratory, Livermore, CA, report UCID-18077 (1979).
4. J. L. Games, *Nucl. Inst. and Method.* **102**, 7 (1972).
5. E. L. Condon and H. Odishaw, Eds., "Nuclear Physics," in *Handbook of Physics*, 2nd ed. (McGraw-Hill, New York, 1967), Part 9, pp. 116-119.
6. A. T. Nelms, *National Bureau of Standards Circular 542* (1953).
7. H. P. Klug and L. E. Alexander, *X-Ray Diffraction Procedures* (John Wiley & Sons, Inc., New York, 1954) p. 122.
8. L. Kissel, *On the Scattering of Photons by Matter*, Lawrence Livermore National Laboratory, Livermore, CA, internal report XRM-78-125 (1978).
9. E. Lent, *Updated Low-Energy X-Ray Cross Section*, Lawrence Livermore National Laboratory, Livermore, CA, internal report DAG-77-22 (1977).
10. L. Kissel, *Rayleigh Scattering Update Number One*, Lawrence Livermore National Laboratory, Livermore, CA, internal report XRM-79-7 (1979).
11. L. Kissel and R. H. Pratt, *Rayleigh Scattering by Neutral Atoms 100 eV to 10 MeV*, Lawrence Livermore National Laboratory, Livermore, CA, report UCRL-82507 (1979).
12. J. Gaines, *IEEE Transactions on Nuclear Science* **NS-26**, 1420 (1978).
13. J. Fletcher, *Livermore-Time-Sharing System*, Lawrence Livermore National Laboratory, Livermore, CA, report LTSS-6 (1970).