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Measurements of Filtered X-Ray Spectra

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MEASUREMENTS OF FILTERED X-RAY SPECTRA

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ABSTRACT

A compilation of measured x-ray spectra is presented for three x-ray tubes operating at potentials of 60 to 300 kV with various thicknesses of aluminum, copper, molybdenum, lead, and uranium filters. The measurements were made with silicon and germanium semiconductors, sodium iodide scintillators, and a xenon proportional counter. The attenuation coefficients computed from the measured spectra are compared with those from theory. Because of Compton scattering, the energy region in which measurement and calculation agree within 10% is limited to above $(1/6) E_0$ for the beryllium-windowed tube and above $(1/4) E_0$ for the more heavily filtered tubes. Agreement is also limited to below $(3/4) E_0$ because of counting statistics.

I. INTRODUCTION

Radiation detectors are calibrated at the Los Alamos Scientific Laboratory with fluorescent x-ray sources below 100 keV. Because there are few monochromatic gamma-ray emitting isotopes available in the 100- to 300-keV range, detectors are also calibrated with filtered continuous x-ray spectra. To characterize the calibrating beam properly, a detailed knowledge of the spectrum is required. Consequently, spectral measurements were made with four different kinds of detectors, and three x-ray units were used to calibrate the radiation detectors. This report is a compilation of 55 measured spectra for tubes operating at potentials of 60 to 300 kV with various thicknesses of aluminum, copper, molybdenum, lead, and uranium filters. Drexler and Gossrau¹ recently published a similar compilation containing 87 germanium-measured spectra for tubes operating at potentials of 25 to

300 kV with various thicknesses of aluminum, copper, tin, and lead filters.

The filtered spectra can be calculated from the measured unfiltered spectrum and published photon-attenuation coefficients. However, because of detector distortions, differences would be expected between the calculated and measured spectra. Instead of comparing the measured with the calculated spectra directly, it is more informative to calculate attenuation coefficients from the measured spectra and compare them with the published values.

II. EXPERIMENTAL ARRANGEMENT

Three commercial x-ray units were used in the measurements: (1) A North American Philips Company 300-kV constant potential Norelco x-ray unit containing a Müller MÖ 301/10 tube with tungsten anode, 22° target angle, and 4-mm aluminum-equivalent inherent filtration. (2) A Picker X-Ray Corporation

Fig. 1. Experimental arrangement for measurement of filtered x-ray spectra.

100-kV self-rectified x-ray unit with a Machlett MR-100 tube with tungsten anode, 20° target angle, and 0.4-mm aluminum-equivalent inherent filtration. (3) A Picker X-Ray Corporation 60-kV constant-potential x-ray unit containing a Machlett OEG-60G tube with tungsten anode, 45° target angle, and 0.025-mm beryllium inherent filtration.

The essential features of the experimental arrangement are shown in Fig. 1. Except for the exit window, the x-ray tubes were completely encased in lead shielding to prevent radiation leakage. To reduce the counting rate to a measurable level, the detectors were placed approximately 50 m from the target. An evacuated pipe was placed between the x-ray tube and the detectors to reduce air attenuation. A beam-limiting aperture was placed in front of the detector.

Four types of detectors were used in the measurements: a silicon semiconductor, a germanium semiconductor, a sodium-iodide scintillator, and a xenon proportional counter. The detectors were calibrated with fluorescent x-ray sources and isotope gamma rays.

Metal foils of aluminum, copper, molybdenum, lead, and uranium were used as filters. The foils were placed in front of the detector aperture, although it was confirmed that the same results would be obtained if the foils were placed in front of the target aperture.

III. RESULTS

A. Measured Spectra

The measured unfiltered spectra and the spectra filtered by several thicknesses of aluminum, copper, molybdenum, lead, and uranium are shown in Figs. 2 through 12. The notation E_0/E_{om} , where E_0 is the actual operating potential and E_{om} is the maximum tube potential, is used throughout this report to identify accelerating potential and x-ray unit.

Figures 2 and 3 give the silicon and xenon proportional-counter measurements of the 60/60 kV spectra. Because the tube has a beryllium window, the tungsten target L lines (10 keV) are present and preferentially absorbed as filtration is added.

Figure 4 gives the silicon-measured 60/100-kV spectra, and Figs. 5 and 6 give the silicon- and germanium-measured 100/100-kV spectra. The tungsten L lines do not appear in the measurements, because they are absorbed by the heavier (equivalent to 0.4 mm aluminum) inherent filtration of the tube. The tungsten K lines appear in the 100/100-kV spectral silicon and germanium measurements.

Figures 7 through 11 give the germanium-measured 100-, 150-, 200-, 250-, and 300/300-kV spectra, and Fig. 12 gives the sodium iodide-measured 250/300-kV spectra. Again, the tungsten L lines are absorbed by the heavy (equivalent to 4 mm aluminum) inherent filtration of the tube. However, the tungsten K lines are present in both the sodium iodide and germanium measurements, and the germanium detector has separated the K_α (59 keV) and K_β (68 keV) components. The ratio of the K_α to K_β intensity is about 3.6, but as filtration is added, the K_α line is preferentially absorbed, and the K_β exceeds the K_α intensity at the larger filtrations.

B. Attenuation Coefficients

The attenuation coefficients were calculated by a least-square method computer program. For a given detector, accelerating potential, and photon energy, the fraction

of photons transmitted through a filter was computed from the unfiltered and filtered spectral measurements for each filter thickness. The log transmission was plotted as a function of filter thickness and a least-square curve was put through the points. The attenuation coefficient is given by the slope of the curve.

The aluminum attenuation coefficients in units of cm^2/g are plotted in Fig. 13 as a function of photon energy for the four detector types. Similar curves are given for copper, molybdenum, lead, and uranium in Figs. 14, 15, 16, and 17, respectively. Solid lines represent measured attenuation coefficients, and dashed lines represent those from theory.

The K absorption edges of molybdenum (20 keV), lead (88 keV), and uranium (115 keV) are evident in the silicon and germanium measurements. Because of detector distortion, the drop in the coefficient does not appear sharply at the ionization potential, but spreads 2 to 5 keV on each side of the absorption energy. The L-edge structure of lead (13 to 16 keV) and uranium (17 to 22 keV) is suggested in the silicon measurements.

IV. DISCUSSION OF RESULTS

Figures 13 through 17 show that for a given detector and accelerating potential, measurement and calculation are in poor agreement in both the lower and upper parts of the spectrum. The discrepancy in the lower-energy region is caused by the inherent filtration of the tube and by Compton photons scattered by the detector. The inherent filtration of the 100- and 300-kV units is sufficient to absorb most of the photons below 10 and 20 keV, respectively.

Thus, the counts observed below 25 keV are caused primarily by Compton photons. This may be seen in Fig. 18, where the silicon-measured 100/300-kV spectrum filtered by different thicknesses of molybdenum is plotted as a function of photon energy. Four peaks appear in the measurements: The Compton peak near 10 keV, the continuum peak which increases from 35 to 80 keV as the filtration increases from 0 to 1 g/cm^2 of molybdenum, and the K_α and K_β lines at 59 and 68 keV. As the thickness of molybdenum increases, the Compton photons make up a greater percentage of the total number of measured photons. With the thickest filters, the Compton component becomes separated from the continuum and lines.

The energy region in which measurement and theory agree within 10% is limited to above $(1/6) E_0$ for the beryllium-windowed tube and above $(1/4) E_0$ for the more heavily filtered tubes, where E_0 is the accelerating potential. The discrepancy in the upper energy region is caused by poor statistics and poor detector efficiency. At the higher photon energies, the counting rates are low and the fluctuations large. Also, the energy region in which measurement and theory agree within 10% is restricted to below about $(3/4) E_0$. The upper range is further restricted by poor detector efficiency. The xenon and silicon detectors, which are considerably less efficient than the germanium and sodium iodide detectors, are limited in performance to below 50 and 100 keV, respectively.

V. REFERENCE

1. G. Drexler and M. Gossrau, Report GSF - Beucht S45 (Institut für Strahlenschutz, Neuherberg bei München), 1968.

Fig. 2. Silicon-detector measurements of 60/60-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

60/60 kV, Xe

Fig. 3. Xenon-detector measurements of 60/60-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

Fig. 4. Silicon-detector measurements of 60/100-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

100/100kV, Si

Fig. 5. Silicon-detector measurements of 100/100-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

100/100 kV, Ge

Fig. 6. Germanium-detector measurements of 100/100-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

Fig. 7a.

Fig. 7. Germanium-detector measurements of Al-filtered 100/300 to 300/300-kV spectra.

Fig. 7b.

Fig. 8a.

Fig. 8. Germanium-detector measurements of Cu-filtered 100/300 to 300/300-kV spectra.

Fig. 8b.

Fig. 9a.

Fig. 9. Germanium-detector measurements of Mo-filtered 100/300 to 300/300-kV spectra.

Fig. 9b.

Fig. 10a.

Fig. 10. Germanium-detector measurements of Pb-filtered 100/300 to 300/300-kV spectra.

Fig. 10b.

Fig. 11a.

Fig. 11. Germanium-detector measurements of U-filtered 100/300 to 300/300-kV spectra.

Fig. 11b.

Fig. 12a.

Fig. 12. Sodium Iodide detector measurements of 250/300-kV x-ray spectra filtered by Al, Cu, Mo, Pb, and U foils.

250/300kV, NaI

Fig. 12b.

Fig. 12c.

Fig. 13a.

Fig. 13. Aluminum attenuation coefficients as a function of energy. (Solid lines represent measured attenuation coefficients; dashed lines represent those from theory.)

Al - Ge DETECTOR

Fig. 13b.

Fig. 13c.

Fig. 14a.

Fig. 14. Copper attenuation coefficients as a function of energy. (Solid lines represent measured attenuation coefficients; dashed lines represent those from theory.)

Fig. 14b.

Fig. 14c.

Fig. 15a.

Fig. 15. Molybdenum attenuation coefficients as a function of energy. (Solid lines represent measured attenuation coefficients; dashed lines represent those from theory.)

Mo - Ge DETECTOR

Fig. 15b.

Fig. 15c.

Fig. 16a.

Fig. 16. Lead attenuation coefficients as a function of energy. (Solid lines represent measured attenuation coefficients; dashed lines represent those from theory.)

Fig. 16b.

100/100kV

Fig. 16c.

Fig. 17a

Fig. 17. Uranium attenuation coefficients as a function of energy. (Solid lines represent measured attenuation coefficients; dashed lines represent those from theory.)

Fig. 17b.

Fig. 17c.

Fig. 18. Silicon-detector measurements of 100/300-kV x-ray spectrum filtered by different thicknesses of molybdenum. With the thickest filters, the scattered Compton component, centered near 10 keV, became separated from the continuum.