Photoelectric cross sections for 6–20-keV photons in beryllium, carbon, magnesium, aluminum, silicon, copper, silver, and lead

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Photoelectric cross sections for low-energy photons in the energy range of 5.9 to 20.16 keV in beryllium, carbon, aluminum, magnesium, silicon, copper, silver, and lead have been determined experimentally through photon-transmission measurements performed under narrow-beam counting geometry with Si (Li) as a photon detector. The photoelectric-cross-section values reported in this work are found to be in agreement with the values computed theoretically by E. Storm and H. I. Israel [Nucl. Data Tables A 7, 565 (1970)].

I. INTRODUCTION

Accurate values of photoelectric cross sections for photon radiation in several materials are needed in solving various problems in radiation physics and radiation dosimetry. The photon cross-section data which are most often used are the compilation of the National Bureau of Standards.[1] It is important to note that much of the data is based on theoretical work and only few experimental results are available for comparison. Such comparison is necessary to ensure that the theoretically predicted values do indeed agree with experimental results.[2] This is particularly true in the case of low-energy photons. Although a number of experimental measurements are reported in the literature,[3] the work therein actually carried out is limited to a few energy points and materials. Further, the experimental techniques used by different workers are not identical and hence it is difficult to intercompare the experimental results.[4] It was therefore decided to carry out accurate measurements of photon attenuation data covering the 6–20 keV energy range in selected pure materials and then determine from the attenuation data the photoelectric cross sections for comparison with theoretical values. Photoelectric cross sections are determined either by counting the photoelectrons emitted during photoelectric absorption or by detecting those photons which have not undergone any interaction within the material.[5,6] In the earlier work, the photoelectrons were detected by organic scintillators and total-absorption-proportional counters. The accuracy of the final results was limited by the poor efficiency of either of these detectors. A good photon detector with high-energy-resolution characteristics as used in the present measurements is an essential requirement for higher accuracy. Solid-state detectors have the high-energy-resolution characteristics necessary for such measurements to be performed accurately.

II. EXPERIMENTAL PROCEDURE

In the present work the photoelectric-cross-section values for low-energy photons in the range of 5.89 to 20.16 keV are determined in eight elemental solids of atomic numbers ranging from 4 to 82 through photon-transmission measurements. The monoenergetic photon radiation required for these measurements was derived from pure ^{55}Fe and ^{238}Pu radionuclides and from photon-excited sources available as variable-energy photon sources. The ^{55}Fe and ^{238}Pu radionuclides decay to ^{55}Mn and ^{234}U through electron capture (EC) and α emission and during the process, photons of 5.89 and 20.16 keV are emitted as Mn-K and U-$L\gamma$ x rays, respectively. The variable-energy photon source is a compact cylindrical assembly of steel consisting of a sealed circular primary source of ^{241}Am of 10 mCi radioactive strength. The 60-keV photons emitted from the ^{241}Am source in turn excite K-orbital electrons of Rb and Mo targets incorporated in the source assembly resulting in the emission of 13.37- and 17.44-keV x rays, respectively. These sources (Table I) of varying radioactive strength from 5 to 10 mCi were procured as sealed sources from Radiochemical Centre, Amersham (UK).

The photon transmission measurements were done under a narrow-beam counting geometry employing high-resolution Si (Li) as a photon detector (Fig. 1). The Si (Li) detector utilized in this work had 6 mm diameter with 0.9 ml as active volume. A thin beryllium window (0.3 mil) provided at the entrance allowed maximum transmission of incident photons even at low energies. The detector was operated at liquid-nitrogen temperature and had good stability over the entire range of photon energy. The energy resolution of the detector at 5.9 keV from ^{55}Fe was about 3.0% with full width at half maximum (FWHM) being 178 eV.

The experimental system consists mainly of two aluminum collimators of about 12 cm long, having internal and external diameters of 10 and 60 mm, respectively. These collimeters were internally lined with 4-mm-thick perspex so as to provide a scatter-free collimated photon beam 2 mm in diameter. With the present experimental system, it was established from the photon spectrum that the energy of transmitted photons did not change appreciably due to scatter or fluorescent radiation from the collimators. A provision was made midway between the collimators to introduce absorbers which were in the form of thin foils. The entire system was arranged verti-

TABLE I. Nuclear properties of isotopes used as low-energy photon sources.

Isotope	Half-life (y)	Principal photon energy (keV)	Emission probability
^{55}Fe	2.7	Mn-K x ray 5.89	28%
^{238}Pu	87.75	U-$L\gamma$ x ray 20.16	13%
^{241}Am (photon-excited source[a])	433	Rb-K x ray 13.37	
^{241}Am (photon-excited source[a])	433	Mo-K x ray 17.44	

[a]Available as variable energy photon source.

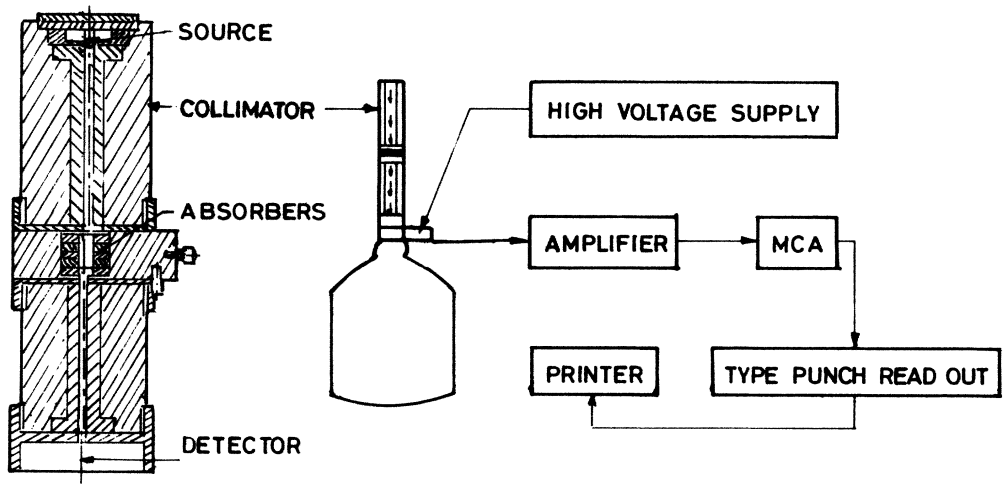

FIG. 1. Block diagram of photon-counting system.

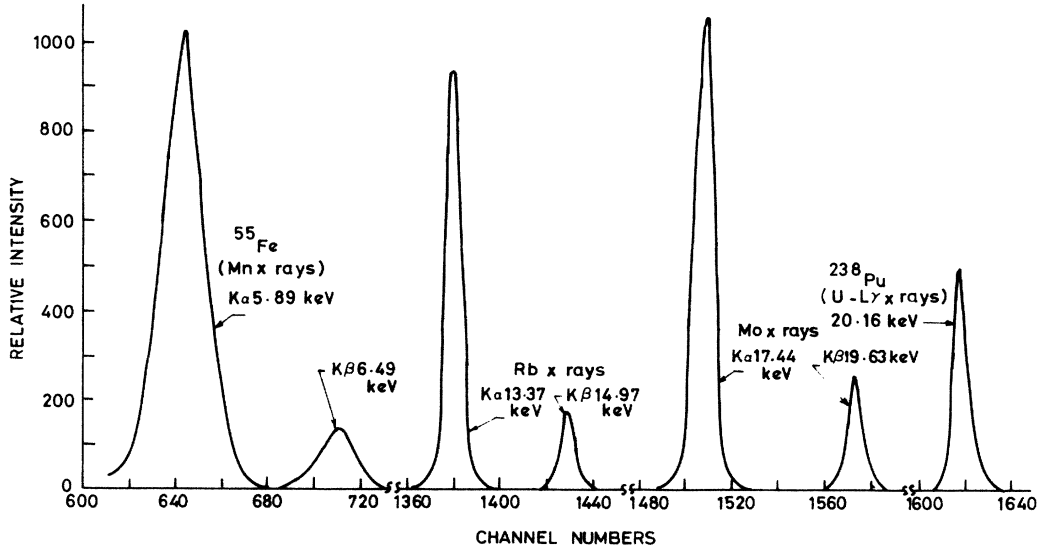

FIG. 2. Photon spectrum of Mn, Rb, Mo-K x rays, and U-$L\gamma$ x rays.

TABLE II. Source of availability and purity of the elemental absorbers.

Absorber	Purity (%)
Beryllium (Be)[a]	99.99
Carbon (C)[b]	99.99
Magnesium (Mg)[a]	99.97
Aluminum (Al)[c]	99.98
Silicon (Si)[b]	99.99
Copper (Cu)[c]	99.99
Silver (Ag)[a]	99.99
Lead (Pb)[c]	99.95

[a]Obtained from Good Fellow Metals Ltd., U.K.
[b]Obtained from International Union of Crystallography, Australia.
[c]Obtained from Bhabha Atomic Research Centre, India.

cally over the Si (Li) detector, ensuring that the central axis of the collimators coincided with the central axis of the detector.

Radioactive sources of ^{55}Fe and ^{238}Pu had thin beryllium windows for the exit of photon radiations. Each source in turn was kept in a lead container which was provided with an aperture for the exit of photons. The source container assembly was then kept over the collimator so as to allow a narrow, well-collimated photon beam from the collimator incident normally on the absorbers. The source and the detector were well aligned with the collimators. The incident energy of photon radiations from each source was known accurately from the photon spectrum taken with a calibrated γ spectrometer. The chosen absorbers include thin and uniform foils of high purity of beryllium, carbon, magnesium, aluminum, silicon, copper, silver, and lead (Table II). These foils were weighed accurately on an analytical balance (Stanton F5P), and from their measured area the thickness proportional to the areal density in g cm^{-2} was determined. The absorbers had varying thicknesses of a few mg cm^{-2} and higher thicknesses were obtained by stacking the foils together. All the foils used were of nuclear grade of specified purity of the order of 99.9%. No attempt was made to ascertain further purity of these absorbers. Each foil of the specified absorber was interposed in the beam such that the primary photon beam was incident normally on its surface. The transmitted photons were recorded without a source, with a source alone, and with a source and an absorber in sequence identical to that of Conner *et al.*[7] The Si (Li) detector was coupled to a 1024-channel analyzer [Bhabha Atomic Research Centre (BARC)] for recording the photon spectrum of each source.

Figure 2 shows the photon energy spectrum of Mn, Rb, Mo, and U-L_γ x rays from ^{55}Fe, photon excitation from Rb and Mo targets, and ^{238}Pu, respectively. The transmitted photon spectrum of each source had an energy width characteristic of the full energy absorption peak, identical with that of primary photon beam. The thickness of the absorbers was increased in steps by additional foils as stated earlier. The counts under the full energy absorption peak of the recorded photon spectrum were determined (following the method of Kokta[8]). The photon spectra were recorded several times for each added foil thickness and an average of counts under the full energy absorption peak was obtained. If I and I_0 are the transmitted and incident photon intensity for a thickness t of the absorber, then the total atomic cross section is given by the following expression:[9]

$$\mu_a = A/N[\log(I_0/I)/t] ,$$

where A and N are the atomic weight and Avogadro number of the absorber, respectively.

III. RESULTS AND DISCUSSION

The values of the atomic cross section μ_a were obtained for photons at 5.9, 13.37, 17.44, and 20.16 keV and are shown in Table III for each of the eight elemental solids covering the atomic number range from 4 to 82. This atomic cross section is composed of the photoelectric and the scattering cross sections. The scattering cross section is the sum of the cross sections due to coherent and incoherent scattering which have been calculated by Storm and Isreal[10] for a wide range of photon energies and elements. The photoelectric cross sections are obtained by subtracting the scattering cross sections from the measured total atomic cross sections as shown

TABLE III. Total atomic cross sections. Numbers in parentheses are theoretical values shown for comparison.

Photon energy (keV)	Total atomic cross sections (b/atom)							
	Beryllium	Carbon	Magnesium	Aluminum	Silicon	Copper	Silver	Lead
5.89	37.5±0.5 (35.0)	233±3 (240)	3980±40 (3900)	5750±60 (5800)	7280±80 (7400)	12 000±100 (11 800)	85 800±900 (86 000)	166 200±2000 (166 000)
13.37	4.9±0.2 (5.0)	21.9±0.3 (18.5)	327±4 (320)	460±5 (430)	630±8 (640)	10 100±100 (10 000)	8850±80 (8900)	51 000±500 (50 900)
17.44	3.9±0.1 (3.9)	11.9±0.2 (11.5)	165±2 (155)	225±3 (220)	350±4 (330)	5000±50 (4900)	4850±40 (4800)	42 200±400 (43 800)
20.16	3.4±0.1 (3.5)	7.7±0.2 (8.2)	89±1 (95.0)	120±2 (135)	180±3 (190)	2850±40 (3000)	2500±30 (2450)	24 800±300 (24 400)

TABLE IV. Photoelectric cross sections. Numbers in parentheses are theoretical values shown for comparison.

Photon energy (keV)	Photoelectric cross section (b/atom)							
	Beryllium	Carbon	Magnesium	Aluminum	Silicon	Copper	Silver	Lead
5.89	32.5±0.5 (32)	225±4 (235)	3930±40 (3900)	5700±60 (5680)	7200±80 (7250)	11 800±120 (11 800)	85 500±900 (86 000)	164 000±2000 (160 000)
12.27	1.95±0.05 (2.0)	16.5±0.2 (15.5)	310±4 (320)	440±5 (450)	600±8 (605)	9900±100 (10 000)	8900±100 (9000)	49 700±500 (50 000)
17.44	1.00±0.05 (0.92)	6.8±0.1 (6.5)	150±2 (145)	210±3 (205)	305±4 (300)	5000±50 (5100)	4650±40 (4600)	41 500±400 (40 500)
20.16	0.60±0.03 (0.56)	3.5±0.1 (3.6)	70±2 (75)	115±2 (120)	160±3 (175)	2770±30 (2900)	2270±25 (2400)	23 000±300 (23 500)

in Table IV. The overall uncertainty of the measured values was estimated to be around 1% and had following components: The counting statistics for I and I_0 measurements, thickness uniformity of the absorbers, and error in the least-square fitting of the experimental data, all added in quadrature. The contribution to the error due to counting statistics was 0.2% corresponding to the accumulated counts in the analyzer. The uncertainty due to the thickness measurements of the absorber was determined to be 0.5%. Contributions to the error due to impurities of the absorbers was negligible as the absorbers were of nuclear grade of high specified purity. The magnitude of the estimated total error have been indicated for each value in Tables III and IV.

As stated earlier, the photoelectric cross section is determined by subtracting the scattering cross-section values available from the literature[10] from the total cross section measured in this work. At photon energies where the total atomic and scattering cross sections are comparable, the difference of these two numbers of the same magnitude has large errors. Thus, the photoelectric-cross-section values in Table IV for low-Z materials like carbon, beryllium, and magnesium, as determined in the present work, have large uncertainties due to the fact that the total scattering cross section is comparable to the atomic cross section. The experimentally determined values of photoelectric cross sections have been compared with theoretically computed values due to Storm and Isreal[10] which are shown in parentheses for each value in the same table. These computed values were obtained by interpolating the data of Storm and Isreal to the photon energies of present work. Most of the experimental values agree with the values calculated theoretically if the uncertainty values of 10% mentioned in the Storm and Isreal data are considered. Since the data on experimental measurements at identical energies and materials are not available in literature, no comparison of these values is possible with previous measurements.

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