Attenuation-coefficient measurements for 3.3- to 165.8-keV photons: Analysis in terms of total photoelectric cross sections

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Total photon interaction cross sections at 22 energies in the region between 3.3 and 165.8 keV are determined in the elements Al, V, Cu, Mo, Sn, Ta, Au, and Pb, using high-energy resolution Si(Li) and Ge(Li) detectors on a "good geometry" setup. An analysis of the experimental data in terms of total photoelectric cross sections is presented.

I. INTRODUCTION

The interest in the study of the photoelectric effect has been recently focussed on very low photon energies (<10 keV) in view of the scarcity of, as well as the discrepancies in, the experimental data,[1-3] and of the difficulties associated with the theoretical developments. In a recent review article published by Pratt *et al.*[4] definite conclusions are drawn only for photon energies above 10 keV. Especially at low photon energies, the photoelectric cross sections can be obtained from the total attenuation coefficient, as the contributions due to the coherent and incoherent scattering processes are very small. Only a few experiments using solid-state detectors for total attenuation measurements at low photon energies ($E > 9$ keV) have been described.[5-7] Hence, in the present investigations, systematic measurements are made on the total photon interaction cross sections for eight elements ($13 \leq Z \leq 82$) in the energy region from 3.3 to 165.8 keV (22 energies) using high-energy resolution Si(Li) and Ge(Li) detectors.

II. EXPERIMENTS

The total photoelectric cross sections are determined by measuring the total photon interaction cross section and subtracting the calculated contributions due to coherent and incoherent scattering. The investigations have been restricted to only those cases where the amount due to coherent plus incoherent scattering does not exceed 10% of the total. Measurements were performed with the transmission technique on a "good geometry" setup, as already described elsewhere.[8-11] The photon energies used and their origin are shown in Table I. The radioactive sources were prepared by drop deposition onto metal-coated VYNS foils of about 180-μg/cm^2 total thickness or by vacuum evaporation onto a 1-mm-thick copper disk. The strength of the sources was between 20 and 50 μCi. Disks of Al, Cu, and Pb having a central hole of between 0.4- and 0.8-cm diameter were used as collimators. Their thickness was between 0.25 and 1.0 cm. Various of these disks, with different appropriate distances between them, were suitably arranged, depending on the energy of the photon, its origin, and the source strength, in order to define the "good geometry." About 150 foils of the elements Al, V, Cu, Mo, Sn, Ta, Au, and Pb were used as attenuators. They had a diameter of 1.8 cm, and their thicknesses ranged from 100 μg/cm^2 to 500 mg/cm^2. They were fixed between two Al rings, and could be placed reproducibly into the photon beam. The photons were measured with a Si(Li) (Fig. 1) or a Ge(Li) detector in combination with an appropriate electronic circuit and a 1024-channel analyzer. The energy resolution of the detectors was 260 eV at 5.9 keV for the Si(Li), and 1.8 keV at 165.8 keV for the Ge(Li) crystal. Typical examples of the pulse distribution of the

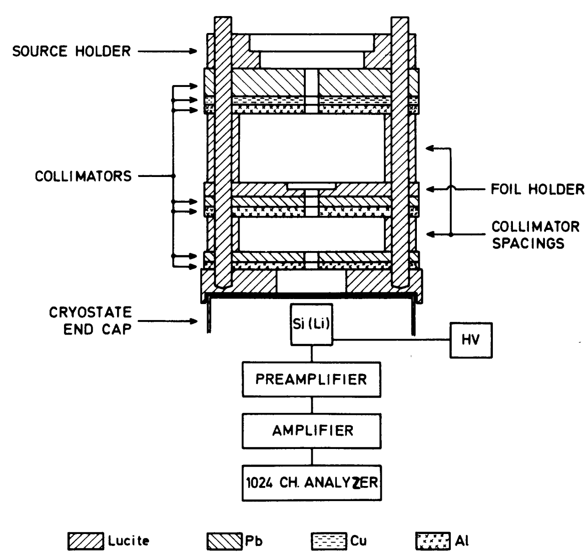

FIG. 1. Scheme of the experimental arrangement. As an example, the scale model of the "good geometry" setup for a 20-μCi ^{57}Co source is shown.

TABLE I. Energy and origin of the photons used.

Photon energy E_{ph}(keV)	Photons	Origin and remarks
3.3	Np $M\alpha$ x rays	^{241}Am; average energy [a]
4.8	Ba L x rays	^{137}Cs; average energy
5.9	Mn K x rays	^{55}Fe
6.4 7.1	Fe K x rays	^{57}Co
8.0 8.9	Cu K x rays	Secondary Cu x rays originating from the backing of the ^{241}Am source
13.9 17.8 20.8	Np L x rays	^{241}Am
26.4	γ rays	^{241}Am
32.1 36.5	Ba K x rays	^{137}Cs
41.3 47.3	Eu K x rays	^{153}Gd
59.6	γ rays	^{241}Am
84.3	γ rays	^{170}Tm
97.3 103.4	γ rays	^{153}Gd
122.1 136.4	γ rays	^{57}Co
165.8	γ rays	^{139}Ce

[a] Reference 13.

different photons used (of $E_{ph}< 10$ keV), measured with the Si(Li) detector, are given in Fig. 2.

Spectra were measured with and without an attenuator foil placed in between the source and the detector yielding the transmitted and the original photon intensities. As a measure of the intensity, the sum of all pulses belonging to a photopeak was taken. This integrated counting rate was corrected for dead time and background events. Corrections for decay time were applied when necessary. In general, the error introduced by these corrections and by counting statistics did not exceed 1%. Furthermore, events from the interference of fluorescence x rays due to higher energetic photons, the influence of photon attenuation in air, and of possible material impurities of the attenuator foils, and the included scattering events have been considered. The corrections for these effects were calculated as usual.[8-11]

The total photon interaction cross sections were calculated from the expressions

$$\mu = -\frac{\ln(I/I_0)}{t}, \quad \sigma_{tot} = \mu\frac{A}{N}\times 10^{+24},$$

where I_0 is the photon intensity without the foil, I is the transmitted photon intensity, t is the foil thickness in g/cm^2, A is the atomic mass of the element used, N is Avogadro's number (6.024 $\times 10^{23}$ mole^{-1}), μ is the mass attenuation coefficient and σ_{tot} is the total photon interaction cross section in b/atom. The photoelectric cross section τ is obtained from σ_{tot} by subtracting the coherent and incoherent scattering cross sections as interpolated from the tables of Storm and Israel.[12] These authors claim an accuracy of within 3% for their calculated values. Thus, as in the present study, these contributions were always lower than

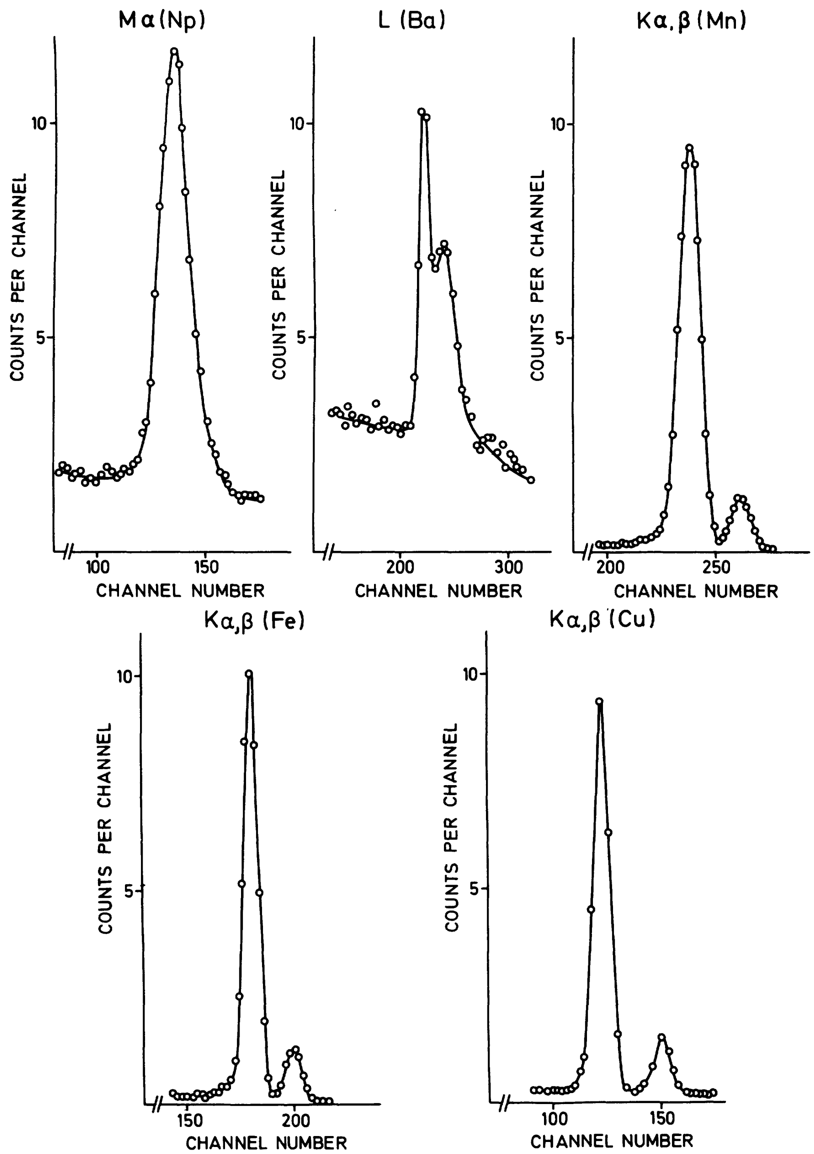

FIG. 2. Typical spectra of photons with $E_{ph} < 10$ keV, as recorded with the Si(Li) detector in a "good geometry" setup. Counts per channel in arbitrary units are plotted versus channel number. The sources used and their emitted photons are described in Table I.

10%; an additional error of $\leq 0.3\%$ has to be considered for the photoelectric cross sections.

III. RESULTS AND DISCUSSION

In Table II the results obtained in this investigation are shown for different photon energies and different attenuator materials. One set of results comprehends three values: the experimental total photon interaction cross section σ_{tot} (exp), with its overall error; the corresponding theoretical value σ_{tot} (th), according to Storm and Israel[12]; and the experimentally obtained total photoelectric cross section τ (exp). It can be seen from Table II that the agreement between experimental and theoretical values is in general satisfactory. For photon energies above 8.9 keV, the expression $|\sigma_{tot}(\text{exp}) - \sigma_{tot}(\text{th})| / \sigma_{tot}(\text{th})$ is usually less than 5%.

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TABLE II. Photon total interaction and photoelectric cross sections (b/atom). The results for each photon energy and element are given as a set of three values representing the experimental and theoretical total interaction and the experimental photoelectric cross sections: $\sigma_{tot}(\text{exp}) \pm \Delta\sigma_{tot}(\text{exp})$, $\sigma_{tot}(\text{th})$, $\tau(\text{exp})$.

Energy (keV)	Al	V	Cu	Mo	Sn	Ta	Au	Pb
3.3							575 000 ± 23 000 568 300 572 000	
4.8	10 000 ± 400 9560 9530		23 860 ± 960 22 150 23 540				256 000 ± 10 000 237 800 253 000	
5.9	5530 ± 120 5320 5090	48 510 ± 970 41 530 48 370	12 660 ± 250 12 570 12 390	60 300 ± 2400 55 660 59 700	105 200 ± 2100 108 600 104 400	111 500 ± 2200 105 200 109 400	139 800 ± 2900 140 900 137 400	
6.4		34 950 ± 700 33 500 34 800		49 100 ± 2200 44 730 48 540	93 100 ± 1900 87 890 92 300	93 700 ± 1900 86 040 91 800	120 100 ± 2400 114 800 117 800	
7.1		25 990 ± 780 25 500 25 870		37 300 ± 2000 33 850 36 800	66 400 ± 1700 66 920 65 680	68 000 ± 2000 66 130 66 200	93 200 ± 2800 88 700 91 100	
8.0	2530 ± 50 2180 2200	18 980 ± 380 18 450 18 870	5700 ± 110 5400 5490	26 160 ± 520 24 270 25 710	49 200 ± 970 48 160 48 520	49 700 ± 990 47 990 48 100	65 100 ± 1300 65 380 63 100	80 300 ± 1600 76 130 78 200
8.9	1880 ± 40 1610 1590	14 370 ± 290 14 120 14 270	4230 ± 90 4130 4050	19 420 ± 390 18 470 19 000	35 300 ± 700 36 730 34 740	38 300 ± 770 37 100 36 700	51 260 ± 1030 50 730 49 480	62 100 ± 1200 58 880 60 200
13.9	449 ± 9 440 427	4160 ± 80 4150 4096	9670 ± 190 9550 9558	5570 ± 110 5550 5298	11 320 ± 230 11 000 10 930	49 900 ± 1000 49 000 48 897	54 310 ± 1090 56 387 53 142	48 120 ± 960 46 000 46 896
17.8	218 ± 4 214 201	2080 ± 40 2060 2031	4940 ± 100 4800 4859	2860 ± 60 2800 2694	5390 ± 100 5600 5091	26 830 ± 540 25 500 26 132	34 530 ± 690 34 000 33 643	40 960 ± 820 39 500 39 990
20.8		1370 ± 30 1340 1327	3430 ± 70 3250 3359	12 270 ± 250 12 000 12 108	4000 ± 80 3775 3754	16 730 ± 340 17 000 16 125	23 080 ± 460 22 900 22 356	27 900 ± 560 27 000 27 177
26.4		687 ± 14 675 652	1770 ± 35 1700 1707	6220 ± 120 6250 6092	2060 ± 40 2050 1880	9710 ± 190 9300 9260	12 140 ± 240 12 300 11 592	15 120 ± 300 14 500 14 573

TABLE II *(Continued)*

Energy (keV)	Al	V	Cu	Mo	Sn	Ta	Au	Pb
32.1		403 ± 8	954 ± 19	3780 ± 80	7050 ± 140	5745 ± 115	7710 ± 150	8770 ± 175
		395	945	3750	6800	5500	7500	8600
		375	909	3684	6904	5388	7293	8352
36.5					4820 ± 100	3780 ± 80	5390 ± 110	
					4800	3800	5250	
					4699	3486	5031	
41.3					3550 ± 70	2865 ± 60	3990 ± 80	
					3480	2790	3850	
					3446	2631	3695	
47.3					2500 ± 50	2140 ± 45	2790 ± 60	
					2420	2050	2700	
					2407	1947	2528	
59.6					1305 ± 13	1109 ± 11	1485 ± 15	1745 ± 17
					1317	1080	1475	1730
					1236	963	1300	1536
84.3						1990 ± 20	2620 ± 25	
						2000	2610	
						1889	2499	
97.3						1394 ± 14	1805 ± 20	2015 ± 20
						1370	1800	2040
						1311	1708	1908
103.4						1175 ± 12	1546 ± 15	1740 ± 17
						1160	1540	1750
						1099	1456	1643
122.1						785 ± 8	1027 ± 10	1160 ± 12
						780	1020	1160
						720	952	1078
136.4						597 ± 6	784 ± 8	867 ± 9
						600	780	870
						539	722	794
165.8							475 ± 5	534 ± 5
							480	540
							419	476

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