Coherent scattering of 59.54-keV γ rays by Al, Cu, Zn, Cd, and Pb

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Differential cross sections for coherent or Rayleigh scattering of photons on atoms were measured using a 59.54-keV ^{241}Am source. Scattering angles ranging from 20° to 107° were studied, corresponding to a momentum transfer of 0.8 to 4.0 Å^{-1}. At angles greater than 60° the results are compared with values of other authors. The measurements are in agreement with calculations of second-order perturbation theory within the experimental error of 4—10 %.

I. INTRODUCTION

Rayleigh scattering is the contribution of bound atomic electrons to elastic scattering of photons by atoms and it predominates over elastic scattering for energies less than 1 MeV. In recent years great progress has been achieved in understanding this process which, except in the forward direction, is increasingly dominated by scattering from the inner atomic shells.[1–3] Kissel *et al.*[2,3] have developed a prescription for the evaluation of Rayleigh scattering amplitudes where the contributions of inner shells are evaluated using second-order S-matrix elements and outer-shell contributions are calculated using modified relativistic form-factor theories. Theories more simple than the above are based on the form-factor[4,5] and the modified-form-factor approximation.[4–6]

Experiments on Rayleigh scattering were performed by several groups[7–11] but the comparison between theory and experiment is far from complete. Nevertheless with available data a relatively good agreement exists between experiments and the theory[2,3] in the 100-keV region.[12] The measurements were made in general above 45° or 60° and only experiments at 662 keV (Ref. 13) and 145 keV (Refs. 9 and 10) exist below these angles. Although great discrepancies are found between the two 145-keV measurements, one of them[9] is in agreement with the theory.

In this paper, experiments at scattering angle between 20° and 107° are reported using a 59.54-keV γ-ray source. This energy is in the vicinity of the K-shell absorption edge of atoms, where dispersion effects occur. Comparison between experimental and theoretical data can now be made at angles from 20° to 150° at the energy measured, which corresponds to a momentum transfer of 0.8 to 4.6 Å^{-1}.

II. EXPERIMENT AND RESULTS

In this experiment a ^{241}Am source of 100 mCi with photons of 59.54 keV was used. The source with a lead shielding was mounted on a fixed arm of about 20 cm length, which could be rotated around the target center. The whole system was mounted in a prevacuum chamber with a plastic window. The detector was placed outside of the chamber. With vacuum in the chamber, background was very small even under the Compton peak. The detector had nearly the same distance from the target as the source. A Ge(Li) crystal with 25% photopeak efficiency with 900-eV resolution at 59.54 keV was used as the detector. The signals from the detector were amplified and processed with usual multichannel analyzer system. Typical measuring times were several hours to one or two days. Target foils with the dimensions of about 1.5×4

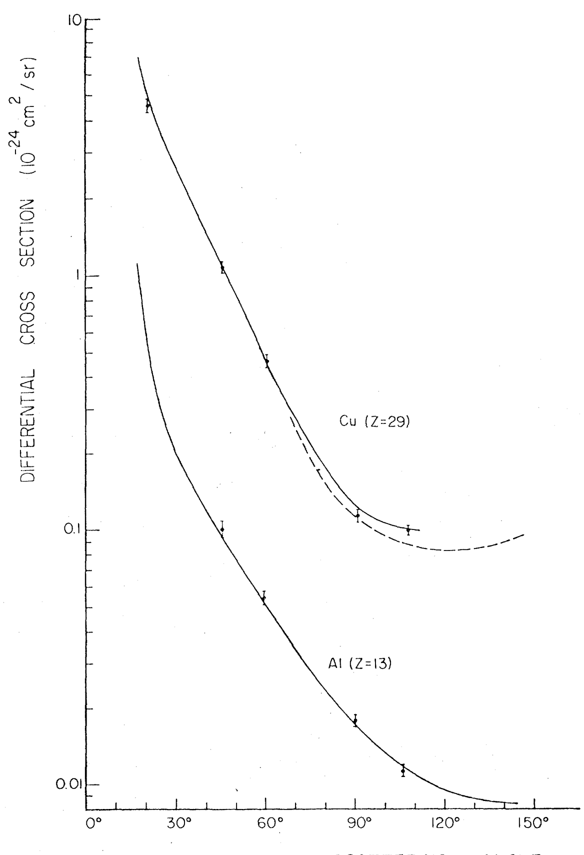

FIG. 1. Experimental differential cross section for Rayleigh scattering at 59.54 keV by Cu and Al compared with the results of second-order perturbation theory (Ref. 14) (solid curves) and relativistic-form-factor theory (Ref. 5) (RFF) (broken curves).

TABLE I. Experimental and theoretical results for the differential cross section for Rayleigh and nuclear Thomson scattering at 59.54 keV: expt., experimental results; theory, results of second-order perturbation theory (Ref. 14); %, relative difference in percent of experimental and theory; NFF (Ref. 4); RFF (Ref. 5); MRFF (Ref. 13). All theoretical results were taken from Ref. 14. In four cases marked by footnote indicators the sum of Rayleigh plus Compton scattering cross section $(d\sigma/d\Omega)$ (expt.$_{R+C}$) was measured. The Rayleigh cross section $(d\sigma/d\Omega)$(expt) in these cases was derived using theoretical Compton cross sections from Ref. 4.

			$d\sigma/d\Omega$ (b/sr)					
Atom	θ (deg)	$\lambda^{-1}\sin(\theta/2)$ (Å^{-1})	Expt.	Theory	%	NFF	RFF	MRFF
^{13}Al	45.0	1.837	0.103	0.0964	6.8	0.0990	0.0978	0.0964
	60.0	2.401	0.0561	0.0511	9.8	0.0518	0.0517	0.0508
	90.0	3.396	0.0176	0.0165	6.7	0.0169	0.0166	0.0162
	107.0	3.860	0.0116	0.0113	2.7	0.0124	0.0113	0.0110
^{29}Cu	20.6	0.859	4.6[a]	5.07	−9.3	4.91	4.99	4.90
	45.0	1.838	1.09	1.13	−3.5	1.09	1.10	1.07
	60.0	2.401	0.459	0.436	5.3	0.416	0.424	0.407
	90.0	3.396	0.111	0.118	−5.9	0.112	0.111	0.104
	107.0	3.860	0.097	0.0946	2.5	0.0907	0.0875	0.0815
^{30}Zn	20.6	0.859	6.0[b]	5.54	8.3	5.35	5.47	5.37
	30.0	1.243	2.45	2.81	−12.8	2.72	2.78	2.72
	45.0	1.838	1.24	1.24	0	1.19	1.21	1.18
	60.0	2.401	0.52	0.497	4.6	0.470	0.483	0.463
	90.0	3.396	0.132	0.132	0	0.124	0.124	0.117
^{48}Cd	45.0	1.838	3.90	3.66	6.6	3.55	3.55	3.32
	60.0	2.401	1.66	1.70	−2.4	1.55	1.61	1.49
	90.0	3.396	0.70	0.748	−6.4	0.622	0.679	0.619
	107.0	3.860	0.54	0.607	−11.0	0.499	0.532	0.483
^{82}Pb	20.6	0.859	82.0[c]	80.9	+1.3	86.2	88.8	84.1
	30.0	1.243	35.9[d]	36.8	−2.4	39.4	42.0	39.0
	45.0	1.838	13.2	13.5	−2.2	15.5	16.4	14.7
	60.0	2.401	6.7	6.87	−2.5	7.78	8.71	7.72
	90.0	3.396	2.24	2.27	−1.3	2.64	3.14	2.68
	107.0	3.860	1.66	1.61	3.1	2.10	2.36	1.93

[a]$(d\sigma/d\Omega)(\mathrm{expt})_{R+C}=6.0$ b/sr.
[b]$(d\sigma/d\Omega)(\mathrm{expt})_{R+C}=7.4$ b/sr.
[c]$(d\sigma/d\Omega)(\mathrm{expt})_{R+C}=84.7$ b/sr.
[d]$(d\sigma/d\Omega)(\mathrm{expt})_{R+C}=38.9$ b/sr.

cm^2 were used. The thicknesses were 47 mg/cm^2 (Al), 77 mg/cm^2 (Cu), 102 mg/cm^2 (Zn), 46 mg/cm^2 (Cd), and 59 mg/cm^2 and 21 mg/cm^2 (Pb).

In the scattered spectra the elastic (Rayleigh) and inelastic (Compton) peaks were separated reasonably for angles greater than 45°. For smaller angles a separation was not possible only for four measuring points. In these cases, marked in Table I by footnote indicators, the measured sum of the Rayleigh plus Compton cross section is given at the end of the table. The Rayleigh cross section was obtained from these values subtracting theoretical Compton cross sections based on the incoherent scattering function.[4] The contribution of the Compton process to the measured sum is between 3% and 23%. Thus, possible errors due to theory have a small effect on the result of the Rayleigh cross section. Measurements for angles smaller than 20° show strong fluctuations of the scattered intensity due to solid-state interference effects and the measurements of Rayleigh cross section are difficult with crystalline targets.

The system was calibrated measuring the Compton line on Al at 45° and comparing the result with the theoretical differential cross section. Later, this calibration was rechecked measuring the product of source intensity and detector efficiency at a zero-degree experiment yielding absolute values for the cross sections. From the counting rate of the photons scattered elastically the differential cross section $d\sigma/d\Omega$ for Rayleigh scattering was evaluated. Corrections were applied for absorption of the incident and the scattered beams. As a test of the corrections, results were obtained for lead at some angles with targets of different thickness. The results were in good agreement with each other. The differential cross sections obtained are listed in Table I. The experimental errors are 10% or less. In Figs. 1—3 the experimental results are shown together with values of Ref. 8 for larger angles.

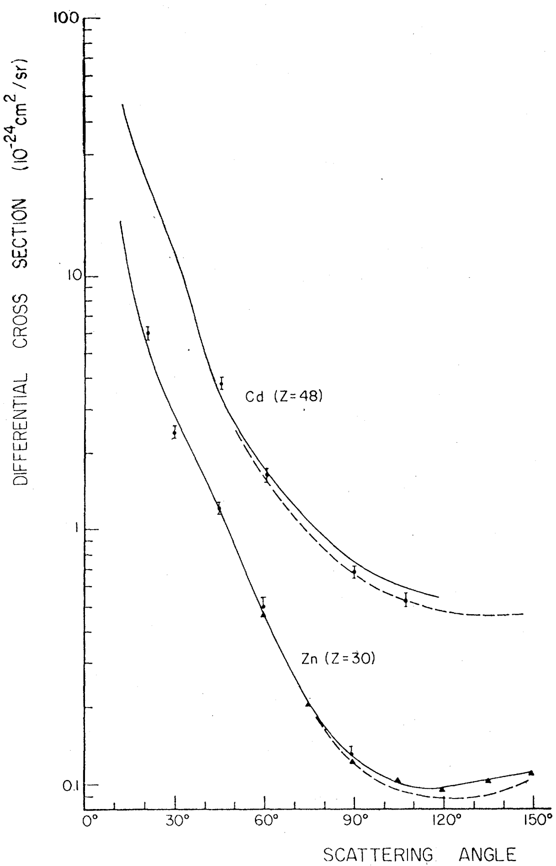

FIG. 2. Experimental differential cross section for Rayleigh scattering at 59.54 keV by Zn and Cd compared with the results of the second-order perturbation theory (Ref. 14) (solid curves). The broken curves are the result of relativistic-form-factor theory (RFF). For Zn some experimental results of Ref. 8 (▲) are added.

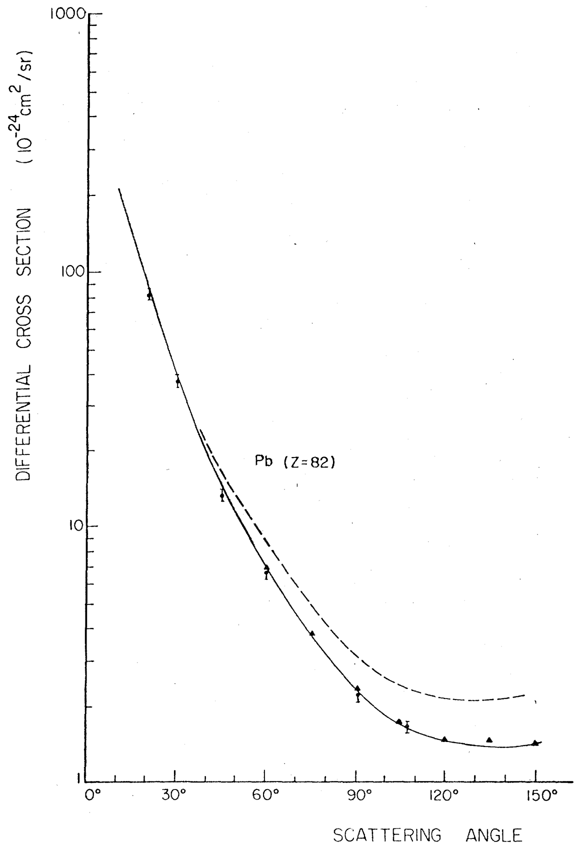

FIG. 3. Experimental differential cross section for Rayleigh scattering at 59.54 keV by Pb compared with the results of the second-order perturbation theory (Ref. 14) (solid curves) and relativistic-form-factor theory (RFF) (broken curve). For higher angles experimental results of Ref. 8 (▲) are added.

III. DISCUSSION

Numerical values for Rayleigh cross section at 59.54 keV were calculated by Kissel.[14] These data are shown in Figs. 1—3 as solid curves and these values are included in Table I. The agreement with the measurements is within the experimental error of 5—10 % and no systematic deviations can be seen. The relative difference (in %) of each measuring point and theory is also shown in Table I. The relativistic form factor[5] (RFF) is also shown as a broken curve in Figs. 1—3. For ^{13}Al these results are nearly equal to the results of second-order perturbation theory. Discrepancies between both theories in our case exist for heavier atoms, especially at large scattering angles. The differences between the relativistic[5] (RFF) and nonrelativistic[4] (NFF) can be seen in Table I. Numerical results of the modified-form-factor theory (MRFF) in comparison with the other form-factor theories give better agreement with experiments for Pb only. We may conclude from our data and the calculations of Kissel[14] that second-order perturbation theory gives good results for the differential elastic cross sections at 59.54 keV. Form-factor theories are approximations, which are valid for light elements and small scattering angles only.

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