Comparison of Compton and Rayleigh scattering at 145 keV

J. Eichler,* S. de Barros, O. Gonçalves, and M. Gaspar
Instituto de Física, Universidade Federal do Rio de Janeiro, 21944 Rio de Janeiro, Brazil
(Received 20 December 1982)

Differential cross sections for Rayleigh and Compton scattering of 145-keV γ rays by Cu, Cd, and Pb have been measured from 25° and 80°. The ratio of these cross sections, which can be determined with higher precision than absolute values, is given. The experimental cross sections, which complement earlier results, are compared with the theories of the relativistic and modified form factor and the incoherent scattering function. Agreement exists for the Compton cross section and scattering function theory showing the influence of the binding energy of the electrons. The Rayleigh differential cross sections are found to be lower than the results of the relativistic form-factor theory. Better agreement is found with the modified form-factor theory.

INTRODUCTION

In recent years, numerous experiments on 100-keV-region Rayleigh scattering have been performed[1-3] and compared with the relativistic form factor[4] and more sophisticated theories.[5-7] The experiments of different authors are in agreement with each other only within the general trend, showing deviations in detail. Tabulated results for differential cross sections of the second-order perturbation theory, which give numerical data for all elements, energies, and angles, do not exist. For Compton scattering, experimental material is scarce. Thus we measured simultaneously differential cross sections for Rayleigh and Compton scattering for angles between 25° to 80°. The ratios of both cross sections have higher precision than absolute differential cross sections, since these values are independent from some geometrical parameters and calibration. The experimental data are compared with available theoretical results[4,8] and calculations using the modified form factor.[9]

EXPERIMENTAL METHOD

In the experiment, a ^{141}Ce source, with an initial activity of 100 mCi and a half-life of 32 days, was used. The source consisted of about 2 g of CeO_2 pressed into a Lucite cylinder with an inner diameter of about 6 mm. The irradiation was performed with the research reactor of São Paulo. The source had a distance of 63.6 cm from the target, which had dimensions of 6×2 cm^2. A Ge-Li detector with a resolution of about 2 keV for the ^{60}Co lines and a relative photopeak efficiency of about 25% was used, which had a distance of 76.7 cm from the target. For angles larger than 40° the target-detector and target-source distances were reduced to 36.5 cm and the targets had an area of 4×2 cm^2. In front of the detector a 20-mm vertical slit of lead was mounted. The precision in the determination of the scattering angle θ is about $\pm 15'$. A conventional electronic equipment with a 4K multichannel analyzer was used.

In the detected spectra the Rayleigh and Compton lines are well separated. For determining the areas of the lines and the counting rates for Rayleigh and Compton scattering, the background without target was measured for each angle. At the Compton energy a small peak appears, probably due to Compton scattering from the air and the target holder. This background was subtracted in the determination of the Compton counting rate. The half-width of the Compton line varied between 2.5 keV for 25° and 6 keV for 80°. Due to the electronic momentum distribution, the Compton line has a complicated profile with inner-shell distribution at lower energies from the line center. In addition, a background is produced by the Compton effect in the detector. These facts were taken into account in the determination of the Compton counting rate. Special care was also undertaken to detect impurities of the incident beam with energies in the region of the Compton line, which are produced by inelastic scattering from the lead shielding and the source holder.

The differential cross sections $(d\sigma/d\Omega)_R$ and $(d\sigma/d\Omega)_C$ for Rayleigh and Compton scattering were evaluated as described earlier,[3,10] taking into account the absorption of the incident and scattered beams, using the absorption coefficients of Refs. 11 and 12. Since elastic and inelastic scattering were measured simultaneously, the ratio of the differential cross sections for Compton and Rayleigh scattering can be given by

$$\frac{(d\sigma/d\Omega)_C}{(d\sigma/d\Omega)_R}=A_C f_C E_R / A_R f_R E_C \ , \quad (1)$$

where A_R and A_C are the counting rates of the Rayleigh and Compton lines. The absorption in the target at the energy of the elastic and inelastic scattered line is given by f_R and f_C, and the corresponding efficiency of the detector by E_R and E_C. For small angles from 25° to 40°, the right-hand side of Eq. (1) reduces to A_C/A_R and can be measured with an accuracy of a few percent. Thus the cross-section ratio is free of systematic geometric and calibration errors.

For investigation of double scattering, some measurements were performed for angles of 25° and 40° varying the target thickness from 0.2 to 5.5 g/cm^2. The results are shown in Fig. 1 for Cu and Cd. The elastic and inelastic differential cross sections show a systematic increase of about 10% for the thick targets. Measuring the cross-section ratio, this effect cancels out and we get a value independent with the target thickness within experimental errors. The experiments were performed with target thickness obeying a compromise between double scattering and count-

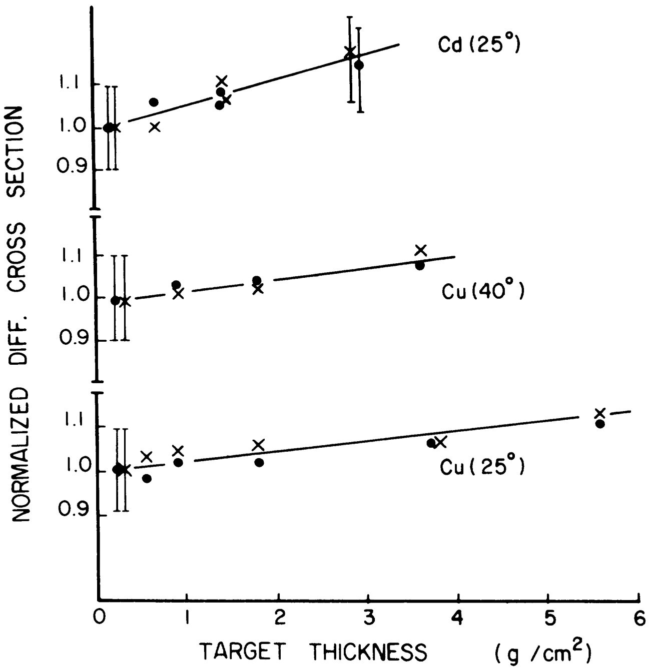

FIG. 1. Investigation of double scattering. Variations of the differential Compton cross section (×) and Rayleigh cross section (●) as a function of the target thickness for Cu at 25° and 40° and Cd at 25°. Normalization was made for the thinnest target.

ing rate. For Cu, Cd, and Pb, targets with 0.7, 1.8, and 1.0 g/cm^2 thickness were used.

RESULTS AND DISCUSSION

The experimental results are shown in Table I for angles from 25° to 80°, giving absolute values for the Rayleigh and Compton differential cross section and the ratio of both cross sections. The estimated errors for the cross-section ratios are smaller by nearly a factor of 2, compared with absolute cross-section values. In Fig. 2 the experimental result of the cross-section ratio is plotted together with theory, which uses the relativistic form factor[4] and incoherent scattering function,[8] both tabulated by Hubbell. All experimental points lie above the theoretical curve. Using calculations with the modified form-factor theory for Rayleigh scattering,[9] reasonable agreement exists for the

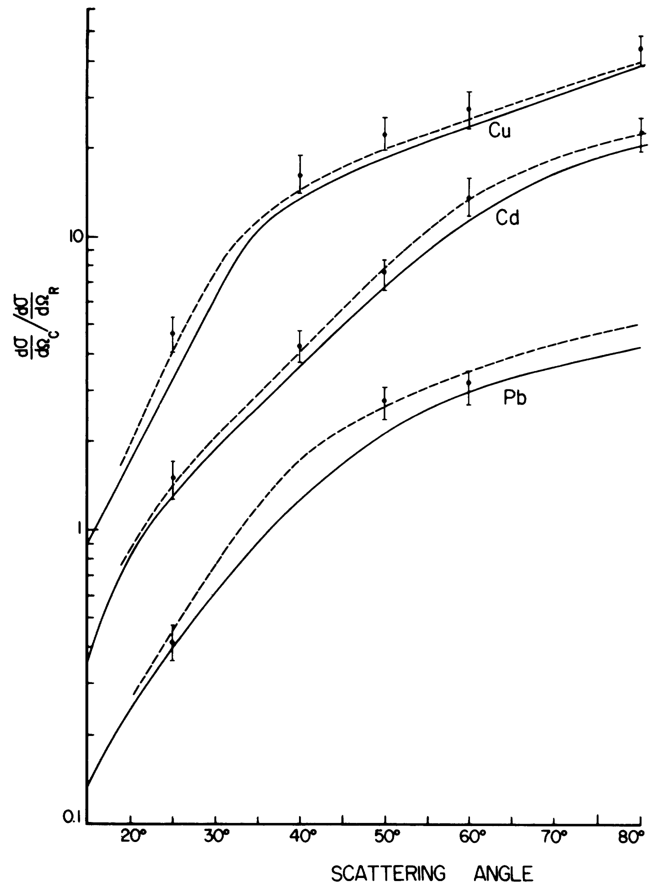

FIG. 2. Ratio of the differential cross section for Compton and Rayleigh scattering as a function of scattering angle for Cu, Cd, and Pb. The solid curves give the ratio of the results of the relativistic form-factor theory (Ref. 4) and the incoherent scattering function theory (Ref. 8). The broken curves use the modified form-factor theory (Ref. 9) for Rayleigh scattering.

TABLE I. Experimental results for the ratio of the differential cross sections for inelastic (Compton) and elastic (Rayleigh) scattering $(d\sigma/d\Omega)_C/(d\sigma/d\Omega)_R$ and absolute values for $(d\sigma/d\Omega)_R$ and $(d\sigma/d\Omega)_C$ for copper, cadmium, and lead.

	Cu			Cd			Pb		
θ	Inelastic / Elastic	$\frac{d\sigma}{d\Omega}$ (10^{-24} cm^2) Elastic	Inelastic	Inelastic / Elastic	$\frac{d\sigma}{d\Omega}$ (10^{-24} cm^2) Elastic	Inelastic	Inelastic / Elastic	$\frac{d\sigma}{d\Omega}$ (10^{-24} cm^2) Elastic	Inelastic
25°	4.7	0.39	1.86	1.5	1.81	2.66	0.41	10.4	4.24
40°	16.6	0.095	1.58	4.3	0.55	2.36			
50°	22.5	0.062	1.41	7.6	0.29	2.19	2.81	1.16	3.25
60°	27.9	0.039	1.08	13.8	0.11	1.54	3.25	0.88	2.85
80°	43.7	0.018	0.79	22.5	0.054	1.20			
Error	±(8–10)%	±15%	±15%	±(8–10)%	±15%	±15%	±(8–10)%	±15%	±15%

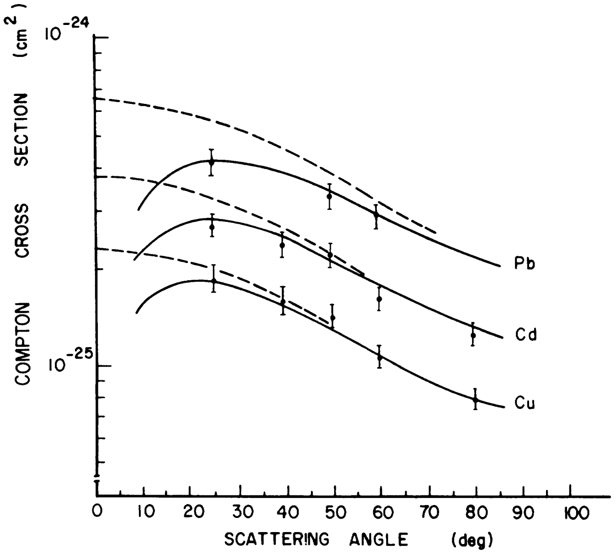

FIG. 3. Experimental results for the differential cross section for Compton scattering as a function of scattering angle for Pb, Cd, and Cu. The solid curve gives the incoherent scattering function theory (Ref. 8). The broken curve is the Klein-Nishina free-electron differential cross section.

cross-section ratios. The measurements of the differential Compton cross section are shown and compared with available theoretical results in Fig. 3. The solid curve is the theory[8] and the broken curve is the free-electron Klein-Nishina value. Corrections for double scattering, which lower the experimental points by about 1–8% according to Fig. 1, were applied. The agreement with the incoherent scattering factor theory[8] is reasonable. Further experiments of smaller scattering angles and energies are required for a more rigorous test of this theory. In Fig. 4, the Rayleigh cross section is compared with the relativistic form-factor[8] and modified form-factor calculations.[9] For Cd and Pb, some results published previously[1,3] are added. The experimental values are generally smaller than form-factor calculations but show agreement with modified form-factor calculations that coincide for light elements in this region with second-order perturbation calculations. More precise experiments on the Rayleigh scattering are required for establishing the validity domain of the form-factor theory.

Note added in proof. Recent results of second-order perturbation theory for Pb (Ref. 13) are about 0–20% higher than the values of the modified form-factor calculations shown in Fig. 4, giving better results with experiments.

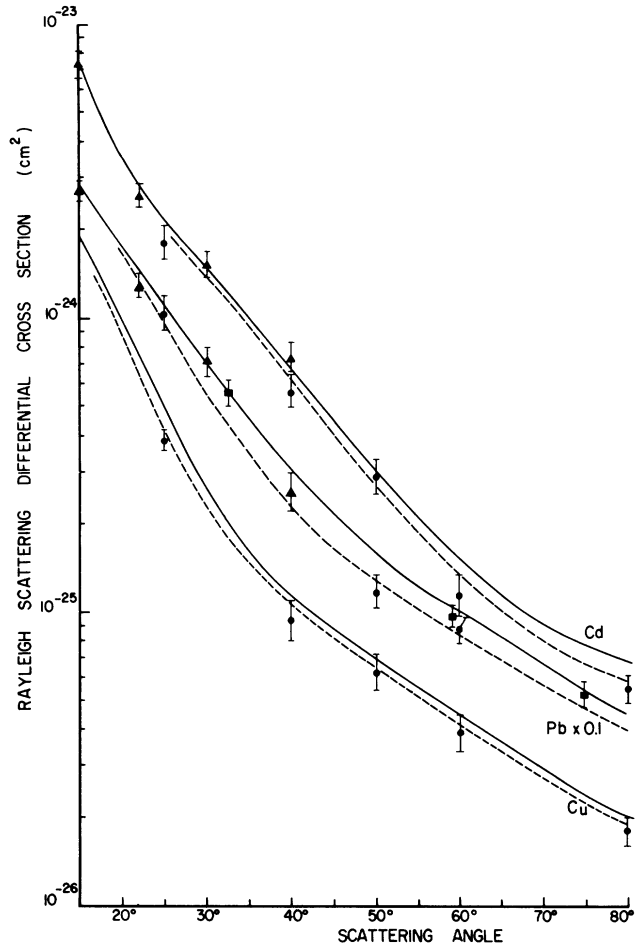

FIG. 4. Experimental results for the differential cross section for Rayleigh scattering as a function of scattering angle for Cd, Cu, and Pb. The solid curves give the relativistic form-factor theory (Ref. 4) and the broken curve the modified form-factor theory (Ref. 9). For Cd and Pb, additional measuring points are added (▲ Ref. 3, ■ Ref. 1).

The authors would like to thank the Financiadora de Estudos e Projetos (FINEP), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and the Foundation VW for their financial support.

*Present address: Technische Fachhochschule Berlin, 1000 Berlin, 65, Germany.

[1]F. Smend, M. Schuhmacher, and I. Borchert, Nucl. Phys. A213, 309 (1973); M. Schuhmacher, Phys. Rev. 182, 7 (1969).

[2]W. Chitwattanagorn, R. B. Taylor, P. Teansompiason, and I. B. Whittingham, J. Phys. 6, 1147 (1980).

[3]S. de Barros, J. Eichler, M. Gaspar, and O. Gonçalves, Z. Naturforsch. 36A, 595 (1981).

[4]J. H. Hubbell and I. Overbo, J. Phys. Chem. Ref. Data 8, 69 (1979).

[5]W. R. Johnson and K. Cheng, Phys. Rev. A 13, 693 (1976).

[6]L. Kissel and R. H. Pratt, University of Pittsburgh Report No. PITT-218, 1979 (unpublished).

[7]L. Kissel and R. H. Pratt, Phys. Rev. Lett. 40, 387 (1978).

[8]J. H. Hubbell, W. J. Veigele, E. A. Briggs, R. T. Brown, D. T. Cromer, and R. J. Howerton, J. Phys. Chem. Ref. Data 4, 471 (1975).

[9]D. A. Liberman and T. D. Cromer, R. Phys. Commun. 2, 107 (1971).

[10]S. De Barros, J. Eichler, M. Gaspar, and O. Gonçalves, Phys. Rev. C 24, 1765 (1981).

[11]A. L. Conner *et al.*, Phys. Rev. A 1, 539 (1970).

[12]K. Siegbahn, *Alpha-, Beta-, and Gamma-Ray Spectroscopy* (North-Holland, Amsterdam, 1968), p. 892ff.

[13]L. Kissel (private communication).