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Rayleigh scattering of 145- and 279-keV γ rays in Al, Cu, Sn, and Pb at forward angles

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The integral Rayleigh scattering (RS) cross sections of γ rays for Al, Cu, and Sn at 145 keV energy and for Al, Cu, Sn, and Pb at 279 keV energy have been determined at angles below 7° by a new method, and are compared with the theoretical integral RS cross sections computed using the nonrelativistic form factors (NRFF) of Hubbell *et al.*, the relativistic form factors (RFF) of Hubbell and Overbo, and the modified form factors (MFF) of Schaupp *et al.* The present experimental results are in fairly good agreement with each of these NRFF, RFF, and MFF theoretical values below 6° within the uncertainties quoted. However, the experimental integral RS cross sections for medium- and high-Z elements appear to be consistently closer to the MFF theoretical values as the scattering angle increases.

I. INTRODUCTION

Previously[1], we reported a new method for measuring the integral Rayleigh scattering (RS) cross sections of γ rays at forward angles. The method is simple and just involves the measurement of the scattered intensity superposed as a small addition to the direct transmitted beam. There is no need to determine the source strength and the geometrical factor as required in the conventional shadow-cone method. Several approximations are made[2-5] to overcome these difficulties in estimating the absolute scattering cross sections by the latter method, which introduce large uncertainties in the measured values. The integral RS cross sections of 661.6-keV γ rays for Cu, Zn, Sn, and Pb at angles below 7° were measured by the new method and were presented earlier.[1] We have noted good agreement between the experimental values and the theoretical integral RS cross sections calculated using the nonrelativistic form factors (NRFF) tabulated by Hubbell *et al.*[6] In addition, we have pointed out that the relativistic form factors (RFF) compiled by Hubbell and Overbo[7] were slightly large. This indicated that a reevaluation of the RFF values, taking into account the effect of the binding energy of the intermediate states, was necessary.

In the present experiment, the measurements were extended to lower photon energies and determined the integral RS cross sections of γ rays for Al, Cu, Sn, and Pb at 279 keV, and for Al, Cu, and Sn at 145 keV energy at angles less than 7°. The experimental results thus measured are compared with the theoretical integral RS cross sections based on NRFF (Ref. 6) and RFF (Ref. 7) theoretical calculations. Very recently, the relativistic modified atomic form factors (MFF) have been tabulated by Schaupp *et al.*[8] for all elements ($Z=1-100$) and for momentum-transfer values from $x=0$ to 100 Å^{-1}. It is expected that these MFF values represent the atomic RS amplitudes with good accuracy at energies well above the K-shell binding energies and small-momentum-transfer values.[10] It is also the purpose of this work to check the validity of the MFF values in the low-momentum-transfer region.

II. EXPERIMENT

The principle and the details of the experimental method used in the present study have already been reported.[1] For the sake of clarity, the experimental arrangement used in the present study is given in Fig. 1. C, C_1, C_2, C_3, and C_4 are lead collimators each of about 7 cm in thickness, E is the lead shielding around the detector, S is the source position, and D is the $2\times 1\frac{3}{4}$-in.^{2} NaI(Tl) crystal. The collimators C_2 and C_3 with collimating holes of diameter less than 4 mm were used and they were separated by a distance of 73 cm, in order to obtain a fine narrow beam of γ rays. The collimator C_4, kept in front of the detector, had a step 0.5 cm in depth and a diameter slightly greater than the diameter of the NaI(Tl) crystal, cut symmetrically around its collimating hole of diameter 4.18 cm, so that the crystal can be fitted into the step groove correctly with its centroid coinciding with the center of the crystal. The γ-ray sources used were 47 mCi of ^{141}Ce and 38 mCi of ^{203}Hg, and were obtained in the form of steel-welded radiographic capsules from the Isotope division, Bhabha Atomic Research Centre, Bombay, India. Scatterers of Al, Cu, Sn, and Pb of 99.9% purity in the form of circular foils of uniform thickness were used. The thickness t of each scatterer was chosen such that $\mu t \sim 1$, where μ is the attenuation coefficient. Aluminum ($Z=13$) was also included in the present set of elements for the investigation because we have used the lower-energy photon sources. The spectra were accumulated in an Ortec 7150 multichannel analyzer.

In this method, we have slightly modified the experimental setup used in the total attentuation cross-section measurements so that when the scatterer is placed at position P_1, only the direct transmitted beam intensity is recorded by the detector by eliminating as far as possible all the scattered photons using lead collimators having very narrow collimating holes. When the scatterer is placed at position P_2, the photons scattered within a cone of half-angle θ are also recorded in addition to the direct transmitted photon beam. The integral scattering cross sections $\Delta\sigma_{\text{sc}}$ were obtained from the intensities (background subtracted) I_1 and I_2 measured by placing the

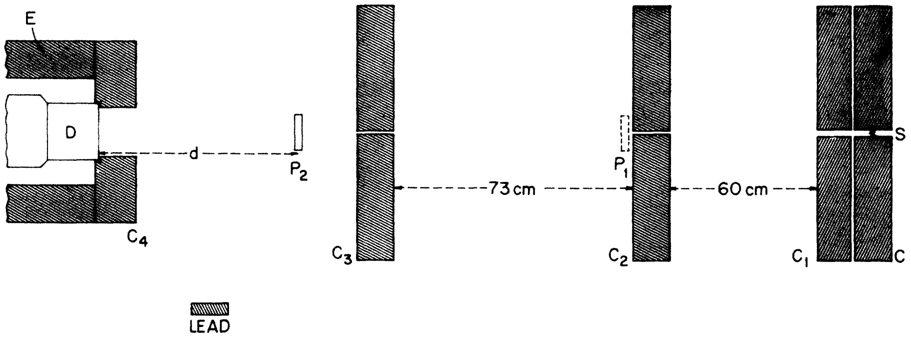

FIG. 1. Experimental arrangement (not to scale). S is the source, D is the NaI(Tl) detector, C, C_1, C_2, C_3, and C_4 are lead collimators. E is the lead shielding around the detector. P_1 and P_2 are the scatterer positions.

scatterer at positions P_1 and P_2, respectively, using the relation[1]

$$\Delta\sigma_{sc}=(A/N\rho t)\ln(I_2/I_1)\ \mathrm{cm}^2/\mathrm{atom}\ , \qquad (1)$$

where A is the atomic weight, ρ is the density, t is the thickness of the scatterer, and N is Avagadro's number.

The angle of scattering θ is taken as the half-angle of the cone of acceptance of the detector at the scatterer. The outer front edge of the detector was shielded using the lead collimator C_4 in order to minimize the edge effect (discussed in our earlier publication[1]). The scattering angle θ was defined in terms of the distance d between the scatterer and the detector by the relation $\theta=\tan^{-1}\{2.09/[d\ (\mathrm{cm})]\}$. The distance from the middle of the scatter to the front surface of the NaI(Tl) crystal was taken for the purpose. The angle θ was varied here too, as was done earlier,[1] by moving the scatterer between the collimator C_3 and the detector.

At each photon energy, the γ-ray spectra were recorded by keeping each of the scatterers at position P_1 and at different positions P_2 (corresponding to the angular range selected). The area of the photopeak was noted each time and was taken to be proportional to the intensity. The time for each spectrum was adjusted to get the intensity of the order of 10^5 or more, in order to reduce the statistical error. The experiment was repeated at least five times for each of the elements, for each photon energy, and for each position. The intensity of the background at each photon energy was measured by placing a lead absorber of thickness 15 cm in the path of the γ ray beam. Corrections were made for the decrease in intensities due to the short half-lives of the sources used. The integral scattering cross sections were then obtained for each of the elements used, at each angle and energy using Eq. (1). The experimental errors were calculated, as in our earlier studies,[1] taking into account the error due to counting statistics and the error in the measurement of the thickness t of the scatterer. The error in the measured integral RS cross sections has maximum value of around 18% at the smallest angle investigated. In addition to this, there is about 4—5 % error in the measurement of the scattering angle θ mainly due to the finite width of the incoming γ-ray beam.

III. RESULTS AND DISCUSSION

The integral scattering cross sections thus measured comprise both the coherent (Rayleigh) and incoherent (Compton) scattering cross sections. Since the Compton contribution is quite small and can be described[4,5] with good accuracy by the NRFF theory[6] at these forward an-

TABLE I. Integral Rayleigh scattering cross sections of 145-keV γ rays (b/atom).

Element (Z)	Distance d (cm)	Angle θ (deg)	$(\Delta\sigma_{sc})_{theor}$			$(\Delta\sigma_{sc})_{expt}$
			NRFF	RFF	MFF	
Al	76.7	1.6	0.023	0.023	0.023	0.031±0.005
(13)	48.6	2.5	0.045	0.045	0.045	0.053±0.005
	28.5	4.2	0.093	0.093	0.092	0.085±0.005
Cu	76.7	1.6	0.132	0.132	0.130	0.14 ±0.02
(29)	48.6	2.5	0.279	0.279	0.274	0.26 ±0.03
	28.5	4.2	0.576	0.576	0.565	0.55 ±0.03
	19.9	6.0	0.818	0.818	0.804	0.83 ±0.03
Sn	76.7	1.6	0.384	0.385	0.380	0.38 ±0.07
(50)	48.6	2.5	0.817	0.821	0.808	0.81 ±0.08
	28.5	4.2	1.752	1.758	1.726	1.71 ±0.08
	19.9	6.0	2.639	2.653	2.601	2.58 ±0.08

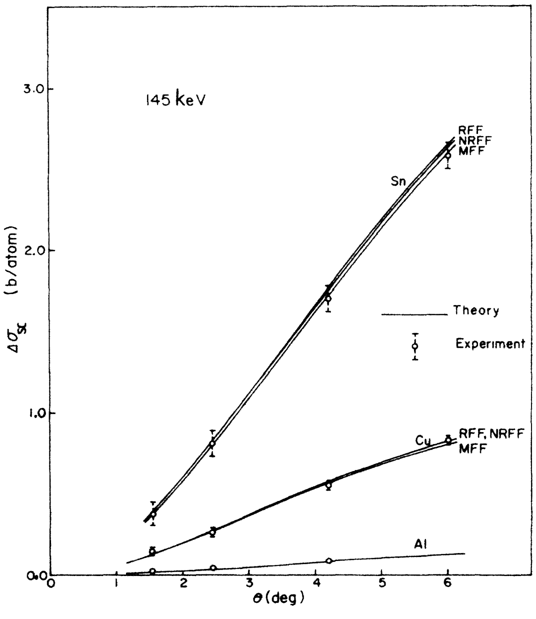

FIG. 2. Comparison of the experimental and theoretical integral Rayleigh scattering cross sections of 145-keV γ rays for Al, Cu, and Sn. Solid curves represent the theory and the circles (with the error bars) indicate the experimental values.

gles, the integral Rayleigh scattering cross sections are obtained by subtracting the theoretically calculated[6] integral Compton scattering cross sections from the measured total integral cross sections. The integral RS cross sections of 145-keV γ rays for Al, Cu, and Sn, and of 279-keV γ rays for Al, Cu, Sn, and Pb thus obtained at angles of 1.6°, 2.5°, 4.2°, and 6.0° are given in Tables I and II, respectively, along with the theoretical integral RS cross sections based on NRFF, RFF, and MFF calculations for comparison. The theoretical integral Rayleigh and Compton scattering cross sections were calculated using the tabulated $F(x,Z)$ (Refs. 6–8) and $S(x,Z)$ (Ref. 6) values using a TDC 316 computer as described in our earlier publication.[1] There are no similar experimental studies measuring the integral scattering cross sections of γ rays available in the literature for comparison except the work of Belskii and Starodubtsev,[9] which is outdated.

In Fig. 2, we have plotted the integral RS cross sections of 145-keV γ rays for Al, Cu, and Sn against the scattering angle θ. The solid curves represent the theories whereas the circles (with the error bars) denote the experimental values. Errors are not shown in the case of Al, as they are smaller than the sizes of the respective circles. We have not made the measurements for Pb at 145 keV because the thickness needed to get sufficient scattered intensity leads to more than 90% attenuation by photoelectric absorption at that low energy. For low-Z elements (Al and Cu), there is no appreciable change in the theoretical integral scattering cross sections based on NRFF, RFF, and MFF theory. As is evident from Table I and Fig. 2, our experimental values for Al, Cu, and Sn at 145-keV energy are in overall agreement with each of the NRFF,[6] RFF,[7] and MFF (Ref. 8) theoretical calculations throughout the angular region studied ($\leq 6°$). However,

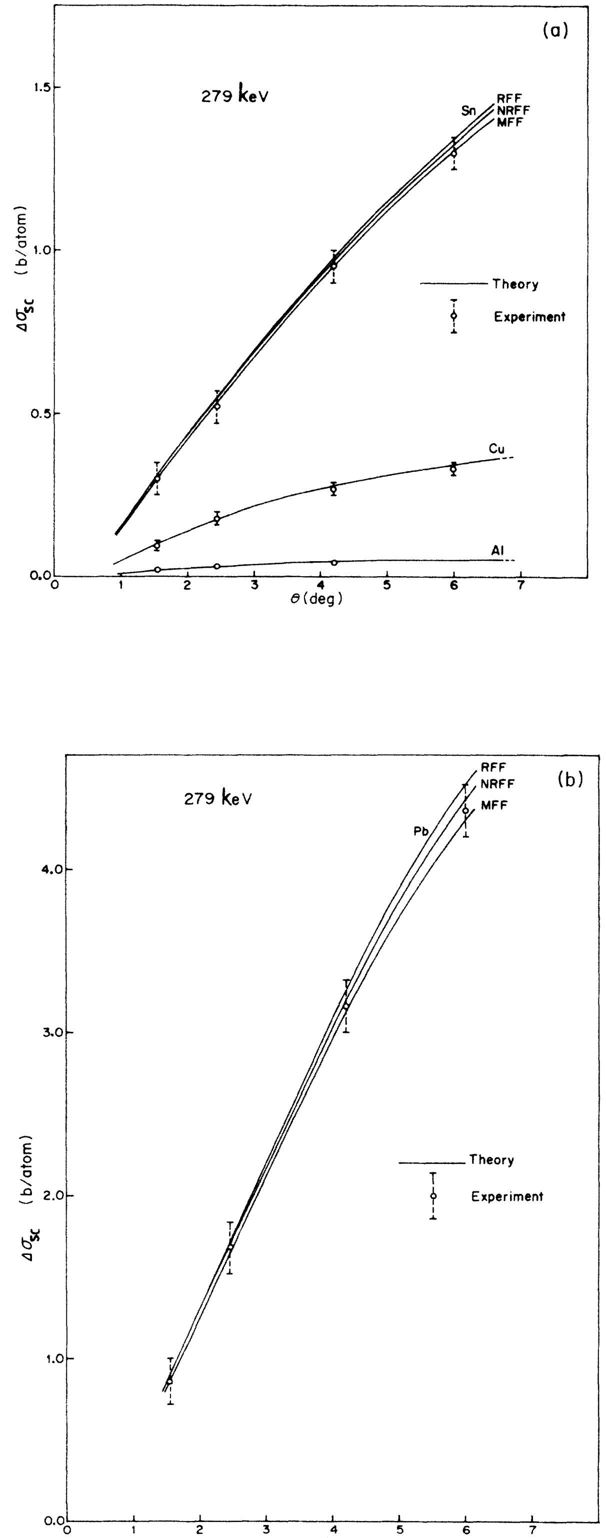

FIG. 3. Comparison of the measured and calculated integral Rayleigh scattering cross sections of 279-keV γ rays (a) for Al, Cu, and Sn, and (b) for Pb. Solid curves represent the theory and the circles (with the errors bars) indicate the experimental values.

TABLE II. Integral Rayleigh scattering cross sections of 279-keV γ rays (b/atom).

Element	Angle θ		$(\Delta\sigma_{\mathrm{sc}})_{\mathrm{theor}}$		
(Z)	(deg)	NRFF	RFF	MFF	$(\Delta\sigma_{\mathrm{sc}})_{\mathrm{expt}}$
Al	1.6	0.016	0.016	0.016	0.022±0.004
(13)	2.5	0.029	0.029	0.028	0.030±0.004
	4.2	0.045	0.045	0.044	0.045±0.004
Cu	1.6	0.102	0.101	0.099	0.095±0.015
(29)	2.5	0.178	0.177	0.173	0.18 ±0.02
	4.2	0.277	0.278	0.274	0.27 ±0.02
	6.0	0.349	0.350	0.345	0.33 ±0.02
Sn	1.6	0.300	0.299	0.294	0.30 ±0.05
(50)	2.5	0.549	0.549	0.538	0.52 ±0.05
	4.2	0.961	0.972	0.951	0.95 ±0.05
	6.0	1.326	1.342	1.308	1.30 ±0.05
Pb	1.6	0.884	0.883	0.857	0.85 ±0.15
(82)	2.5	1.706	1.713	1.657	1.68 ±0.16
	4.2	3.188	3.247	3.121	3.16 ±0.16
	6.0	4.426	4.515	4.311	4.36 ±0.16

the NRFF, RFF, and MFF theoretical cross sections differ slightly $[\sigma(\mathrm{MFF}) < \sigma(\mathrm{NRFF}) < \sigma(\mathrm{RFF})]$ and in the case of Sn, the experimental values are seen to be consistently closer with the MFF theory as the scattering angle increases.

The variation of the integral RS cross sections of 279-keV γ rays for Al, Cu, and Sn with the scattering angle is shown in Fig. 3 (a) and the same for Pb in Fig. 3(b). Here too, the solid curves represent the theories and circles (with the error limits) indicate the experimental values. It is observed from Table II and Fig. 3(a) that the experimental integral RS cross sections of 279-keV γ rays for Al, Cu, and Sn are in fairly good agreement with each of the NRFF, RFF, and MFF theories. Figure 3(b) shows that the results for Pb are also in overall agreement with each of the theories within the uncertainties quoted. However, the results for Sn and Pb at 279 keV are closer to the MFF values as the scattering angle increases.

In conclusion, we may infer from the present study that in the low-momentum-transfer region, each of the NRFF, RFF, and MFF theories is as good as the others in predicting the RS amplitudes for all elements below 6° within the error limits. However, we can notice from Figs. 2, 3(a), and 3(b) that in the case of medium- and high-Z elements (Sn and Pb), the experimental values seem to be consistently closer to the MFF values as the scattering angle θ increases. It can be seen that the deviation between the theories increases with increasing scattering angle and the experimental errors remain practically the same. This indicates the possibility that the measurements extended to higher angles ($>6°$) may lead to differentiate at least between RFF and MFF values. The measurements may be extended to higher angles by using a larger dimension NaI (Tl) crystal in order to avoid the possible edge effect discussed in an earlier paper.[1]

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