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Effect of Bragg reflection on Rayleigh scattering experiments on polycrystalline targets

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Scattering of 59.5-keV γ rays from Zn, Cd, and Pb foils at angles from 3.5° to 30° has been measured. The influence of Bragg scattering on the determination of differential Rayleigh cross sections has been investigated. It has been shown that interference effects occur in polycrystalline targets for angles $\leq 20°$ and some care has to be taken in the measurement of Rayleigh cross sections for momentum transfer less than 2 Å^{-1}.

I. INTRODUCTION

Rayleigh scattering of γ rays is due to the elastic interaction between photons and the atomic electrons. The scattering from different parts of the atomic charge distribution is coherent and interference of waves scattered from one atom occurs. The differential cross section can be calculated with high precision using second-order perturbation theory.[1] For small momentum transfer and for energies above the K-shell threshold, form-factor approximations can be used.[2–5] In all these works it is assumed that the atoms are free and no interference effects arise between different atoms.

Generally, in experiments on differential Rayleigh cross sections, polycrystalline targets are used.[6–9] It is known that in crystals the radiation scattered from different atoms interferes. This gives rise to crystalline reflections with constructive interference only in the directions given by Bragg's law. In polycrystals small monocrystalline regions are oriented randomly. This assures that Bragg reflection occurs for all angles of incidence on the target. For an "ideal" polycrystal the radiation scattered elastically shows sharp reflections at angles which are related to the Miller indices. For other angles destructive interference occurs and the photons will pass through the target without Rayleigh scattering. In less perfect polycrystals some Rayleigh scattering may occur in this region because of deviations of the periodicity. An example is thermal diffuse scattering. The situation described is valid for small momentum transfer.

For large momentum transfer the density of the Bragg reflections rises. The angular resolution of the incident beam and the finite solid angle of the detection system make the separation of single reflections impossible. In addition, the contribution of incoherent scattering due to departures of periodicity of the solid rises. As a consequence, the effect of interference cancels. Thus for large scattering angles the differential elastic cross section measured on polycrystalline targets approaches the free-atom Rayleigh value.

In this paper, an experiment on small-angle scattering is performed at 59.5 keV with the aim of establishing the region of momentum transfer where interferences are measured. Knowledge of this is important in experiments investigating differential Rayleigh cross sections. We are aware of very few discussions of the influence of Bragg reflection on Rayleigh cross-section measurements.[10]

II. EXPERIMENTAL ARRANGEMENT

A ^{241}Am source of 100 mCi emitting 59.5-keV photons with an active diameter of 7.5 mm was used (Amersham Company). The source with its lead shielding and the target were mounted on a rotatable arm (Fig. 1). The targets were perpendicular to the incident beam. The photons scattered were detected with a hyperpure Ge detector with about 30 mm diameter, which had an efficiency of nearly 100% for 59.5 keV. The following distances were used: source-target, 50 cm; and target-detector, 64 cm. The angular dispersion is determined by the source diameter, the target dimension of about 5×28 mm^2, and a slit of 5 mm in front of the detector: Targets of laminated metallic sheets of Zn (80 mg/cm^2), Cd (48 mg/cm^2), and Pb (59 mg/cm^2) were investigated. The

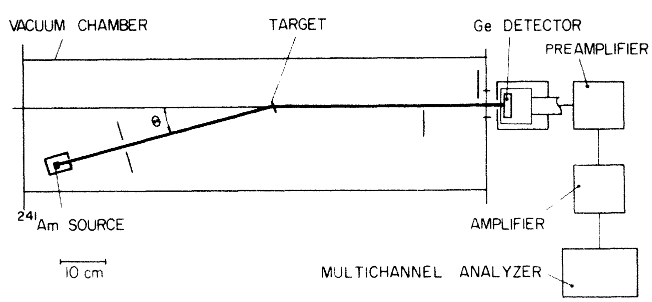

FIG. 1. Experimental arrangement for studying small-angle scattering of 59.5-keV photons.

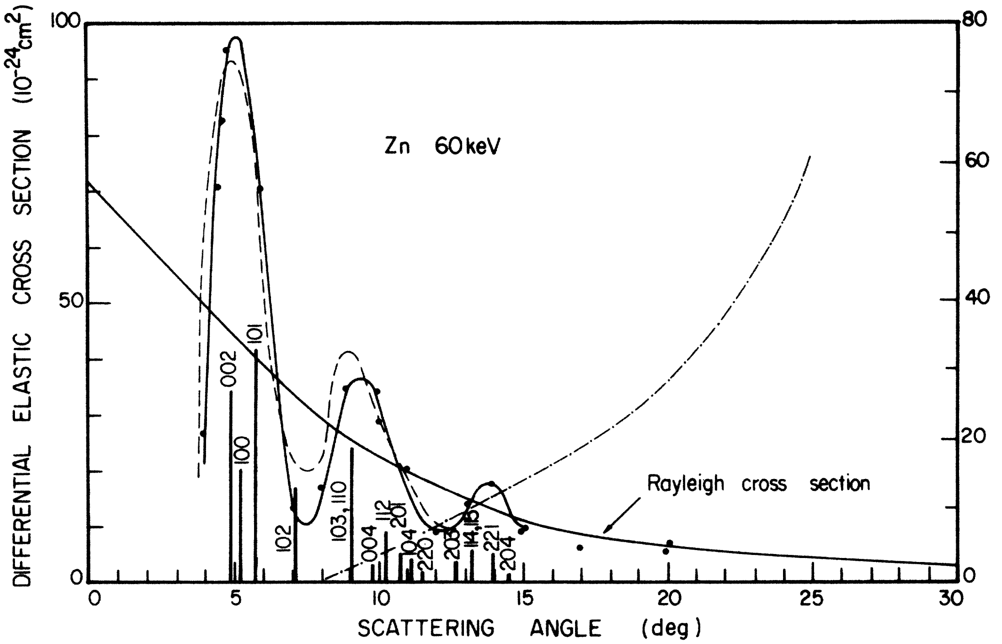

FIG. 2. Angular distribution of 59.5-keV radiation scattered elastically from Zn. The experimental values are shown by data points, which are connected by a solid oscillating curve. The results oscillate around the Rayleigh cross section calculated from form-factor theory (4). The vertical lines are Bragg reflections with the corresponding Miller indices, measured with $K\alpha$ radiation and recalculated for 59.5 keV. By superposition of these reflections the dashed oscillating curve (— — —) is obtained, taking into account the limited angular resolution of the experimental setup. The contribution of Compton scattering is shown by the curve (—· —· —·) using the right-hand scale.

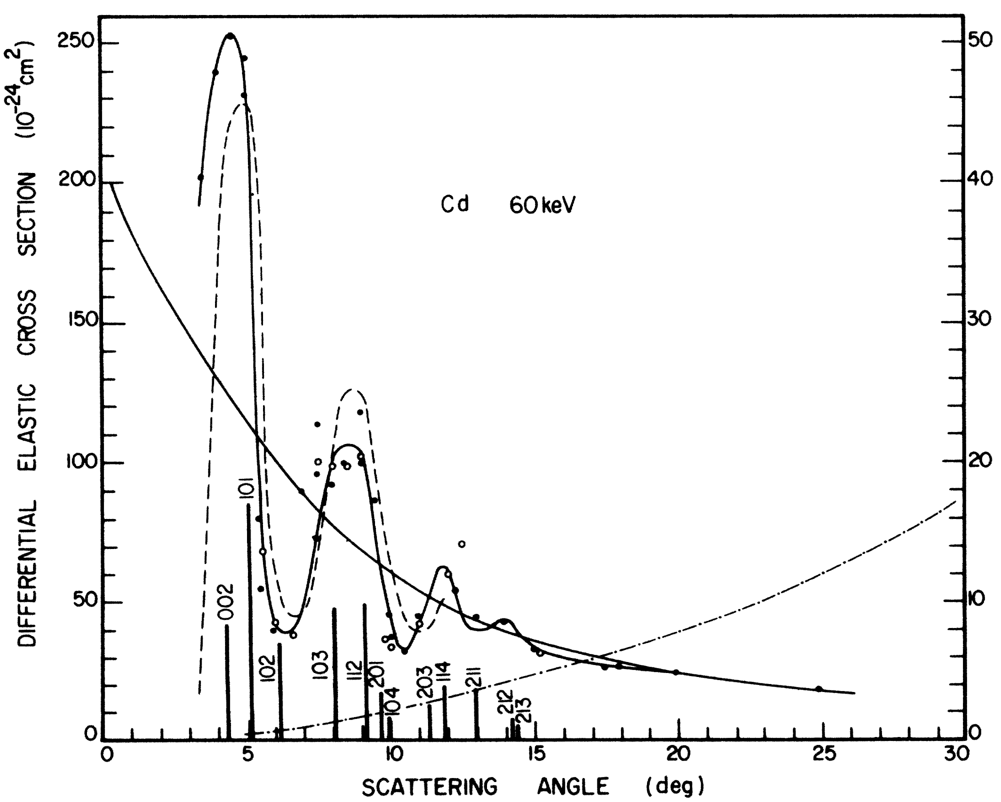

FIG. 3. Same as Fig. 2, scattering from Cd (●, target perpendicular to the γ beam; ○, target inclined by 30° from perpendicular position).

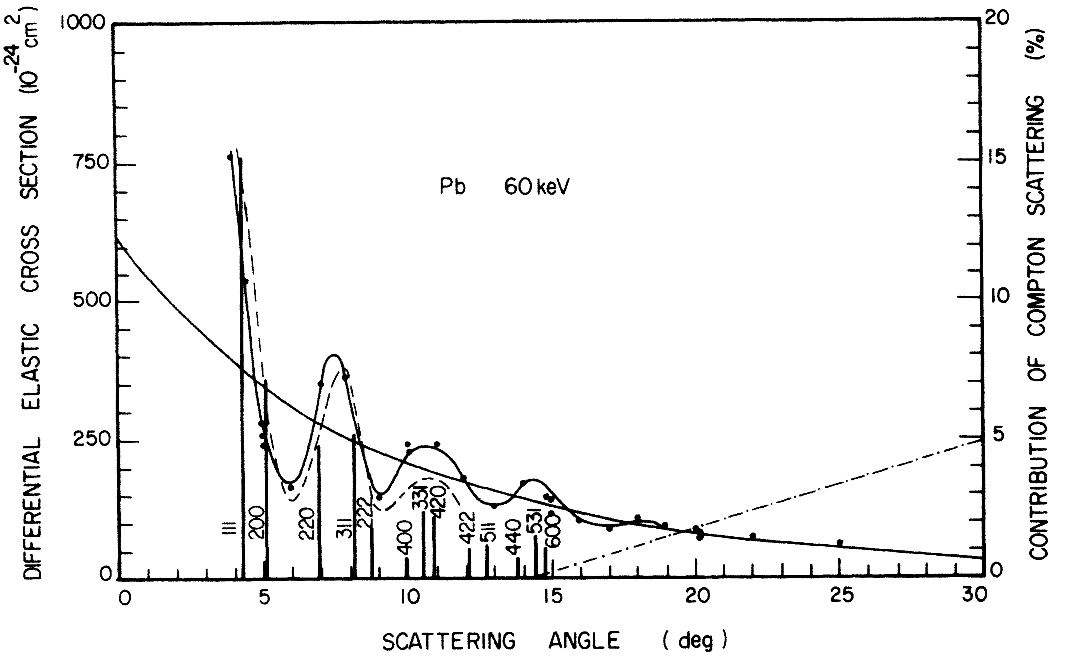

FIG. 4. Same as Fig. 2, scattering from Pb.

transmission for the 59.5-keV photons was between 70% (for Cd) and 85% (for Zn).

For small angles the volume irradiated and "seen" by the detector is relatively large. To prevent Compton scattering in the air, the system was mounted in a prevacuum tube with a pressure of about 10^{-2} mbar. The detector was installed outside the tube in front of a 0.5-mm Mylar window. A conventional electronic system for γ spectroscopy with a 4000-channel analyzer was used. The accumulation of the spectra took about one hour for small angles of about 5° and one day, for 20°. The measurements were performed between 3.5° and 25° in steps of 1° or less with a precision of 0.3°. The measured spectra consist of a superposition of elastic and inelastic scattering. Due to the limited resolution of the Ge detector, the Compton peak is not completely separated from the elastic line for angles less than 25°. Corrections for Compton scattering were applied using the incoherent-scattering-factor theory.[3] The contribution of Compton scattering in the experiment is given by the dashed curves and the right-hand scale in Figs. 2–4. Absolute values of the differential cross section were obtained performing an experiment without target at 0°. Corrections due to the absorption in the target are included.

III. RESULTS AND DISCUSSION

The experimental results for the differential cross sections for elastic scattering are shown as data points in Figs. 2–4 for Zn, Cd, and Pb. For comparison with theory for Rayleigh scattering, calculations based on the relativistic form-factor theory[4] are given as solid curves in Figs. 2–4. These values are nearly equal to the results of second-order perturbation theory in this region.[1] The experimental points oscillate around the theoretical curve. The oscillations decrease with the scattering angle and disappear at about 20° within the precision of the experiment. This angle corresponds to a momentum transfer of 0.9 $Å^{-1}$.

For explaining the measurements, experiments on x-ray diffraction were performed with Cu $K\alpha$ radiation ($\lambda = 0.154$ nm, $E = 8.0$ keV). Specimens of the targets were mounted in an x-ray goniometer (Siemens-Kristallofex IV). The 8-keV $K\alpha$ radiation is strongly absorbed in the targets. Thus the target surface was installed at $\theta/2$, where θ is the scattering angle. (In papers about diffraction, 2θ is used for the scattering angle.) The targets were rotated periodically within ±2° around $\theta/2$. The scattered intensity was measured with a gas counter varying continuously the angle θ between 8° and 150°. The relative intensity of the various Bragg reflections was determined graphically. Corrections were applied for the dependence of x-ray absorption on scattering angle. The energy position of the Bragg reflections at 8.0 keV ($K\alpha$) was transformed for 59.5 keV (Co) using the equation

$$\sin\theta_{Co}/2 = (\sin\theta_{K\alpha}/2)\lambda_{Co}/\lambda_{K\alpha} .$$

The results for the relative intensities of the Bragg reflections are shown in Figs. 2–4 in arbitrary units. The reflections are characterized by the Miller indices. The full-width angular dispersion of the scattering angle in the experiment is ±1.2°. Supposing a triangular probability distribution of the scattering angle, the dashed oscillating curve results. The scale of this curve was normalized to fit the experimental data points. The agreement with the experimental results at 60 keV is reasonable, taking into account the following facts: the error of the measured angle is $\pm 0.3°$; the error of the x-ray intensity is about 5–10 %, the orientation of the crystals was different in both experiments. For investigating the influence of the texture of the polycrystalline foils, measurements were performed rotating the target (30°) (see Fig. 3). Variations of the counting rate of about 10% was observed.

It may be concluded that elastic-scattering intensity is affected by Bragg interference effects in the polycrystalline target. Thus measurements of the differential Rayleigh cross section should be performed with great care for momentum transfer smaller than about 1 $Å^{-1}$. Some experiments exist in this region of momentum transfer.[6–9] Due to the interference effects discussed in this paper, it may not be useful to compare these results in all cases with the free-atom differential cross section. It is well known that interference effects in small-angle scattering yield important information in crystallography[11] using γ sources instead of x-ray tubes.

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