Determination of integral Compton-scattering cross sections of 662-keV γ rays from K-shell electrons in intermediate Z elements

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Integral Compton-scattering cross sections of 662-keV γ rays from K-shell electrons in Y, Zr, Mo, Ag, Cd, and Sn have been determined. The results, when compared with theory, suggest that the K-shell electrons in the elements under investigation behave as free electrons.

I. INTRODUCTION

Differential Compton-scattering cross sections of 662-keV γ rays from K-shell electrons in some elements have been measured by many workers[1-7] at scattering angles ranging from 20° to 160°. The measured cross sections are found to be smaller (larger) than the theoretical Klein-Nishina values for free and stationary electrons at small (large) scattering angles. In an attempt to estimate the integral Compton-scattering cross sections in tin and gold relative to that in aluminum in which the Klein-Nishina assumptions of free and stationary electrons are considered to be valid, from the extrapolation of their measurements to scattering angles below 20° and above 110°, Motz and Missoni[3] concluded that the observed decrease at small angles and increase at large angles would compensate each other, making the integral cross sections equal to the Klein-Nishina value within ~20%. However, Sujkowski and Nagel[4] showed that the integral cross sections are smaller than Klein-Nishina values. Therefore, it was considered desirable to determine the integral Compton-scattering cross sections of 662-keV γ rays from K-shell electrons in different elements in the range $39 \leq Z \leq 50$ using a method which did not depend upon the differential cross-section measurements. Traditionally, the incoherent differential scattering cross sections for bound electrons have been determined by measuring the scattered photons in coincidence with K x rays, which involves many experimental complexities inherent in coincidence measurements. The method of measurements and the results are reported in this communication.

II. METHOD OF MEASUREMENT

The Compton and photoelectric interaction of photons with K-shell electrons of the target atom result in K vacancies which are filled by the emission of fluorescence x rays or Auger electrons. Thus the knowledge of fluorescence yield and the measurement of the intensity of the fluorescence x rays emitted from a target when it is irradiated with a known flux of γ rays, provides a method for the determination of the cross sections for Compton and photoelectric interactions. The relative contribution of Compton or photoelectric interaction to the creation of K vacancies and thus emission of K-shell fluorescent x rays depends upon the energy of photons and Z value of the target element. For low-energy photons and high- and intermediate-Z target elements the emission of fluorescence x rays is almost entirely due to photoelectric interaction and this fact has been utilized[8-13] to measure K-shell photoelectric cross sections of photons of energies ranging from 18 to 280 keV. However, in the present measurements the photon energy and the target elements are such that the contributions of Compton and photoelectric interactions are comparable and information about the integrated Compton cross sections can be obtained within 15% to 30%, as explained in Sec. III., from the measurement of total fluorescence x-ray intensity. In order to avoid the need for the absolute measurements of source strength, counter efficiencies, and solid angles, etc., the Compton cross sections at 662 keV are measured relative to the photoelectric cross sections of the barium K-conversion x rays which are emitted along with γ rays from ^{137m}Ba.

A composite beam of 662-keV γ rays and Ba K-conversion x rays of weighted mean energy 32.890 keV (Ref. 14) from an ~200-mCi ^{137}Cs radioactive source was allowed to fall upon targets of Y, Zr, Mo, Ag, Cd, and Sn of thicknesses ranging from 10–40 mg/cm^2. The resulting K-shell fluorescence x rays were counted under photopeak by a thin NaI(Tl) crystal scintillation counter coupled to ND series 1100 analyzer. The intensity of the composite beam was then reduced by passing it through an iron absorber before irradiating the target, and the emitted fluorescence x rays were again counted. A typical run is shown in Fig. 1. The experimental arrangement and other details were the same as reported in an earlier paper.[11] It can be seen that if $N(\gamma+x)$ and $N^*(\gamma+x)$

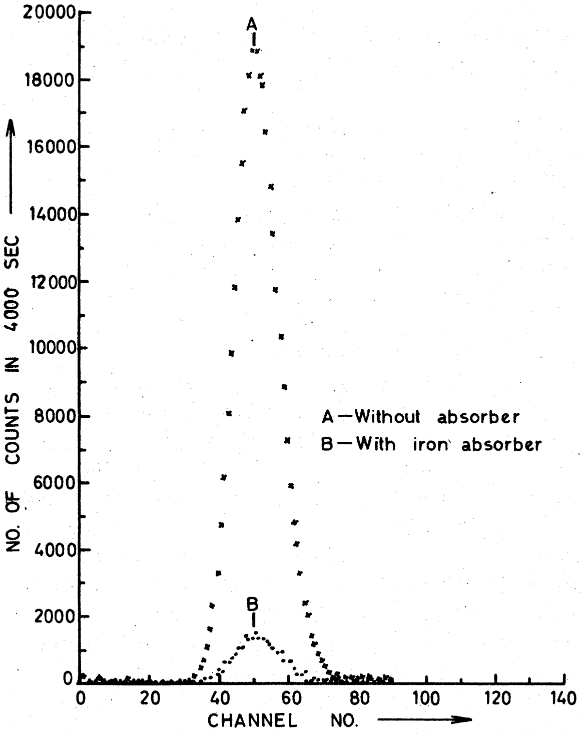

FIG. 1. Tin K x-ray spectra recorded with thin NaI(Tl) scintillation spectrometer when the target was irradiated with a ^{137}Cs source. A—target irradiated with γ rays and conversion x-rays without iron absorber; B—target irradiated with γ rays and conversion x rays after absorption in an iron absorber.

are the intensities of the K-shell fluorescence x rays of the target elements in two cases (see Fig. 1), the integrated Compton-scattering cross section for K-shell electrons $\sigma_C(\gamma)$ is given by

$$\sigma_C(\gamma)=\frac{S(x)a(x)}{S(\gamma)a(\gamma)}\;\frac{1-N(\gamma+x)S^*(x)/N^*(\gamma+x)S(x)}{N(\gamma+x)S^*(\gamma)/N^*(\gamma+x)S(\gamma)-1}\times\frac{\beta(x)}{\beta(\gamma)}\sigma_p(x)-\sigma_p(\gamma)\,, \quad (1)$$

where the subscripts C and p stand for Compton and photoelectric interactions, respectively. All other terms in Eq. (1) have the same meanings as in Eqs. (3) and (7) of our earlier paper.[11] It may be mentioned that $\sigma_C(x) \ll \sigma_p(x)$ and has been neglected in the derivation of Eq. (1). It is clear from the equation that determination of $\sigma_C(\gamma)$ is reduced to measurements of the ratios $S(x)a(x)/S(\gamma)a(\gamma)$, $S^*(x)/S(x)$, $S^*(\gamma)/S(\gamma)$, $N(\gamma+x)/N^*(\gamma+x)$, and $\beta(x)/\beta(\gamma)$ which can be determined more conveniently than the absolute values of the intensities of the radiation incident on and emitted from the target. The present method is thus simpler than our earlier method[9] in which ^{137}Ba K x rays were completely filtered and total (photoelectric plus Compton) integral cross sections were measured

TABLE I. Measured values for internal Compton-scattering cross sections of 662-keV photons from K-shell electrons. The theoretically calculated (Ref. 2) value from the Klein-Nishina formula is 0.512 b/atom.

Element	Z	Measured cross section (b/atom)
Y	39	0.56 ± 0.08
Zr	40	0.43 ± 0.08
Mo	42	0.55 ± 0.10
Ag	47	0.40 ± 0.12
Cd	48	0.51 ± 0.14
Sn	50	0.56 ± 0.16

with a counter of known effective detection efficiency which had to be determined in a separate experiment using coincidence techniques.

As explained in the earlier paper[11], using known values[15,16] of $\alpha_K = 0.094 \pm 0.02$ and $\omega_K = 0.895 \pm 0.012$, the values of $S(x)a(x)/S(\gamma)a(\gamma)$ was experimentally determined to be $(9.31 \pm 0.47)\times 10^{-3}$. $S^*(x)/S(x)$ and $S^*(\gamma)/S(\gamma)$ were determined to be equal to $(5.56 \pm 0.11)\times 10^{-2}$ and $(9.50 \pm 0.19)\times 10^{-1}$, respectively, by measuring the counts under the Ba K x ray and 662-keV γ-ray photopeaks with and without iron absorber. The $\beta(x)/\beta(\gamma)$ were calculated using known values of absorption coefficients.[17]

The probability of K-shell ionization by photo- and Compton electrons is known[18,19] to be $\sim 10^{-4}$. The contribution[18,20] of ionization and bremsstrahlung caused by them in the region of K-shell fluorescence x-ray peak (Fig. 1) was estimated for the experimental targets to be not more than 0.1% which is much less than the overall errors (15%

TABLE II. Uncertainties in the quantities used to evaluate $\sigma_C(\gamma)$ from Eq. (1).

Quantity	Nature of uncertainty	Uncertainty
$\frac{N(\gamma+x)}{N^*(\gamma+x)}$	Statistical	~2%
$\frac{S^*(x)}{S(x)}$	Statistical	~2%
$\frac{S^*(\gamma)}{S(\gamma)}$	Statistical	~2%
$\frac{S(x)a(x)}{S(\gamma)a(\gamma)}$	Statistical and due to errors in α_K and ω_K	~5%
$\frac{\beta(x)}{\beta(\gamma)}$	Due to errors in the absorption coefficients at incident and emitted photon energies	~4%
$\sigma_p(x)$	Interpolation	~3%
$\sigma_p(\gamma)$	Interpolation	~3%

to 30%) involved in the present measurements and has therefore been neglected.

III. RESULTS AND DISCUSSION

The values of integrated K-shell Compton-scattering cross sections as determined from Eq. (1) are listed in Table I. Since no other experimental data are available, the measured values are to be compared with the theoretical[21] Klein-Nishina value of 0.512 b/atom. The uncertainties shown in the experimental values are due to counting statistics and the uncertainties involved in other quantities used for evaluation of various terms in Eq. (1). The uncertainties in the various terms are shown in Table II. The errors in the measured values of $\sigma_C(\gamma)+\sigma_p(\gamma)$ were ~7%–8% which increase from 15% to 30% in $\sigma_C(\gamma)$ for different elements depending upon the relative contribution of $\sigma_p(\gamma)$ to $\sigma_C(\gamma)+\sigma_p(\gamma)$. Within the experimental uncertainties, the measured values agree with the theoretically calculated values and thus support the conclusion of Motz and Missoni[3] and contradict that of Sujkowski and Nagel.[4] The present measurements show that for incident 662-keV photons, the K-shell electrons in elements with Z ranging from 39 to 50 behave as free electrons and integral incoherent scattering function comes out to be unity.

The measured average integral Compton cross section per electron is 0.25 ± 0.02 b as compared to theoretical Klein-Nishina value of 0.256 b.

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