PHYSICAL REVIEW A VOLUME 33, NUMBER 4 APRIL 1986

Measurement of *K*-shell photoelectric cross sections by the indirect method

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(Received 16 October 1985)

K-shell photoelectric cross sections are measured by the indirect method in Tb, Ho, Er, and Pt at 84.26 keV. A high-resolution, hyperpure germanium detector and a good-geometry setup are used to conduct a transmission experiment. The superiority of the indirect method over the direct method at low energies is discussed. The results are compared with available theoretical and other experimental values and are in good agreement. The results show a close agreement with the recent and accurate calculations of Scofield.

I. INTRODUCTION

Shell photoelectric cross sections can be measured by two methods: (a) the indirect method (subtraction technique) and (b) the direct method. Method (b) is suitable at higher energies where the scattering contribution is high and measurement involves the simultaneous detection of the *K* x-ray and the incoherently scattered γ-ray spectra. A comparison of these two intensities gives[1] the *K*-shell photoelectric cross section. But at low energies where the relative contribution of scattering cross sections to the total cross section will be less the indirect method is suitable. The principle of this method is to obtain the total γ-ray cross sections by conducting a transmission experiment on a good (narrow-beam) geometry setup. The contributions due to coherent and incoherent scattering are subtracted to get the total photoelectric cross sections. These are then divided by the ratios of the total to *K*-shell photoelectric cross sections to get the *K*-shell photoelectric cross sections.

Most of the data available on *K*-shell photoelectric cross sections are obtained by using a NaI(Tl) detector. The data available using solid-state detectors are meager where the x-ray intensities can be measured more accurately in view of their high resolution. Hence, an attempt is made to determine the *K*-shell photoelectric cross sections by the indirect method using a high-resolution hyperpure germanium (HPGe) detector for comparison with available theoretical and other experimental values. In the present investigation, *K*-shell photoelectric cross sections for 84.26-keV γ rays in the elements Tb, Ho, Er, and Pt are obtained.

II. EXPERIMENTAL DETAILS

The most important aspect in the determination of the total cross sections in a transmission experiment is the geometrical arrangement. The arrangement usually used is a good-geometry setup. A variety of good-geometry setups have been used by several investigators.[2–5] In the present investigation a geometrical arrangement similar to that used by Radhkrishna Murty *et al.*[5] is developed. As the detector used is a horizontal-mounting type, a horizontal-type good-geometry setup is used.

The detecting system consists of an Ortec hyperpure germanium detector with associated electronics in combination with a Nuclear Data 512 channel analyzer. The HPGe coaxial detector is of horizontal configuration with an effective volume of 80 cm^3. Preliminary studies are carried out systematically and the detector is operated at the best conditions (2500 V). The resolution of the detector at 1332 keV is 2 keV. Suitable arrangements are made to maintain the stability in the operating temperature as well as in the line voltage.

The experimental procedure consists of recording the direct as well as transmitted spectra without and with absorbers at the target slit. The experimental data are collected with at least four absorber thicknesses for the given energy in the transmission range from 5% to 20%. The spectra are taken by progressively increasing the thickness and then again decreasing the thickness, measuring, alternatively, the direct photon spectrum. The entire set is repeated three more times so that there will be four trials finally for each element. The time of collection is adjusted so that the statistical error in the direct and transmitted intensities never exceeds 0.2% and 0.7%, respectively.

An accurate determination of the total cross sections requires that the photopeak areas evaluated must be free from interfering radiations as well as background. This can be accomplished by the Gaussian fitting of a few points on either side of the full-energy peak which are free from other contributions. The full-energy-peak areas are therefore determined using a computer program of Rester.[6] This program consists of two parts. The first part

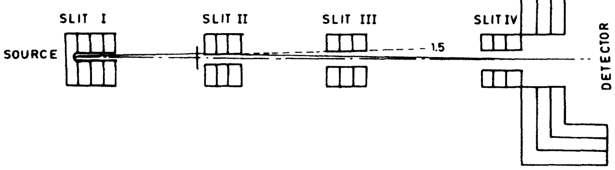

FIG. 1. Scattering in good-geometry setup. Source, ^{170}Tm; detector, HPGe detector; θ_{max}, 1.5°; slits I—IV, graded shielding.

TABLE I. Coherent and incoherent scattering (CI) and measured total gamma-ray (T) cross sections (barns/atom). The CI cross sections are taken from the data of Hubbell *et al.*

Energy (keV)	Cross section	Element			
		Tb	Ho	Er	Pt
84.26	CI	77.4	82.3	84.82	112.38
	T	1311±13	1463±15	1536±15	2446±25

fits the general background under the photopeaks to a second- and third-degree polynomial by the method of least squares. The data points are fitted to a Gaussian in the second part of the program after calculating and subtracting the polynomial-fitted background under each data point. Any possible interferences in the tail part of the full-energy peaks can be easily corrected for by conveniently selecting the peak points which are free from other contributions. The computer program gives the area of the full-energy peak along with the error and the χ^2 factor.

After obtaining the areas of the direct and transmitted spectra as described above, corrections are made for the small-angle scattering which arises because of the scattering of the incident γ rays in the absorber into the detector at the maximum angle $\theta_{\max}$ as shown in Fig. 1. The corrections due to coherent and incoherent scattering can be made[3] using the following expression:

$$I_R = I(e^{-\sigma_s N x / A}) , \tag{1}$$

where I_R is the transmitted intensity after correction, I the observed transmitted intensity, σ_s the scattering atomic cross section included in the maximum scattering angle $\theta_{\max}$ (coherent or incoherent as the case may be), x the thickness of the absorber in g/cm^2, N Avogadro's number, and A the atomic weight of the absorber.

σ_s can be calculated knowing $\theta_{\max}$ and the theoretical differential cross sections of the coherent and incoherent scattering reported by Hubbell *et al.*[7] In the present investigations the effect due to incoherent scattering is negligible and that due to coherent scattering never exceeds 1% under the good-geometry conditions employed (in the present investigation $\theta_{\max}$ is 1.5°). After correcting for the transmitted intensity, the atomic cross section μ_a can be obtained by the following expression:

$$\mu_a = \frac{\ln(I_0/I)}{x} \bigg/ \frac{N}{A} , \tag{2}$$

where I_0 is the intensity without absorber, I the transmitted intensity after correcting for small-angle scattering, and x, N, and A are as above.

Since the experiment is conducted with different absorber thicknesses (in the present case, four absorbers), the cross section can be calculated by the method[2] of least squares. The standard deviation is found to be of the order of 0.7%.

From the measured total γ-ray cross section, the coherent and incoherent scattering cross sections reported by Hubbell *et al.*[7] are subtracted to get the total photoelectric cross sections. These are divided by the experimental total to K-shell photoelectric cross-section ratios to get the K-shell photoelectric cross sections. Systematic investigations are carried out[8–10] in these laboratories on total to K-shell photoelectric cross-section ratios. These are extrapolated on either side of the K edge towards the edge energy and are used in the present study.

The radioactive ^{170}Tm source in liquid form with high specific activity is obtained from the Bhaba Atomic Research Centre, Bombay, India. 99.99%-pure foils obtained from Chempure (Pvt.) Limited, Calcutta, India are used.

III. ERROR ANALYSIS

The overall error in the measured values includes the following factors: (1) the statistical error, which is of the order 0.7%, (2) the error in the correction for the scattering corrections included in the detector which is very small since the correction itself is less than 1%, (3) the error in the measurement of the thickness of the absorbers which is small as all the weights are measured on an electrical balance, (4) the error due to impurities in the absorbers which is negligible as they are of 99.99% purity, and (5) the error in the background fittings, also very small since a high-resolution detector is used.

The effect due to multiple scattering is negligible because of the small $\theta_{\max}$ and also due to the energy-

TABLE II. K-shell photoelectric cross sections (barns/atom) in comparison with theoretical values. Source: ^{170}Tm.

Energy (keV)		Element			
		Tb	Ho	Er	Pt
84.26	Expt[a]	1028±31	1141±34	1206±35	1871±64
84.26	SP[b]	1039	1153	1213	1972.4
84.26	Sco[c]	1050	1165	1224	1886

[a] Experimental values.

[b] Smickley and Pratt (Ref. 11).

[c] Scofield (Ref. 12).

TABLE III. *K*-shell photoelectric cross sections (barns/atom) in comparison with other experimental values and theoretical values. Source: ^{170}Tm.

Energy (keV)	Element: Ta Experimental	Theory
84.26	1514±45[a]	1540[b]
	1569±100[c]	1547[d]

[a] Interpolated value from the present measurements.
[b] Scofield (Ref. 12).
[c] Kusaraju (Ref. 1).
[d] Schmickley and Pratt (Ref. 11).

TABLE IV. Total to *K*-shell photoelectric cross section ratios at 84.26 keV (error is $<2\%$).

Element	Z	Ratio
Tb	65	1.1995
Ho	67	1.2010
Er	68	1.2020
Pt	78	1.2470

selecting device used for the detection process. The effects due to secondary interference events such as fluorescent radiation originating in the absorber is also negligible because of the small $\theta_{\max}$. The effect due to bremsstrahlung radiation produced in the absorber is also negligibly small. In addition, its effect is negligible because of its continuous nature which can be eliminated as continuous background. However, taking all factors into consideration, the total error in the measured total γ-ray cross sections is found to be of the order of 1%.

The contribution due to coherent and incoherent scattering cross sections is around 10% of the total at 84.26 keV in the present investigation. Hence, the additional error included in the extrapolated total photoelectric cross sections is about 0.3% as the scattering cross sections are accurate within 3%. The error in the total to *K*-shell photoelectric cross-section ratios used is less than 2%. Hence, taking the above factors into account, the overall error in the experimental *K*-shell photoelectric cross sections is less than 3%.

IV. RESULTS AND DISCUSSION

In Table I the theoretical values of combined coherent and incoherent scattering cross sections taken from the data of Hubbell along with the measured total cross sections are given. In Table II the measured *K*-shell photoelectric cross sections are given along with the theoretical values of Smickley and Pratt[11] and Scofield.[12] In Table III the *K*-shell photoelectric cross section at 84.26 keV in Ta ($Z=73$) obtained by the Z interpolation of the present data is compared with the value of Kusaraju *et al.*[1] obtained by the direct method and with the theoretical values at this energy. In Table IV the total to *K*-shell photoelectric cross-section ratios that are used in the present study are given.

It can be seen from Table III that the present interpolated value is in agreement with that of Kusaraju within the range of errors. However, it is seen that the error in the present value is smaller than that of Kusaraju.[1] Thus it may be noted in this connection that the indirect method is more suitable at low energies and does not yield accurate values at higher energies because of the domination of the scattering cross sections over the photoelectric cross section. For example, at 661.65 keV in Au the contribution due to coherent and incoherent scattering is of the order of 60% of the total. The theoretical scattering cross sections are accurate within 3%. Thus a 3% error in the scattering cross sections includes an additional error of 4.5% in the extracted total photoelectric cross sections. Adding the error in the measured total gamma-ray cross sections (1%) and that in the used total to *K*-shell photoelectric cross-section ratios at 662 keV ($\sim 2\%$), the error in the finally obtained *K*-shell photoelectric cross sections will be of the order of 7.5%. Thus it may be concluded that the direct method is more suitable at higher energies, whereas the indirect method is more suitable at low energies where the photoelectric cross section dominates. However, the accuracy of the indirect method decreases rapidly as the energy increases because of the relative increase of the contribution due to the scattering cross section to the total. It can be seen from Table II that the measured *K*-shell photoelectric cross sections are in agreement with theoretical values within the range of experimental errors except in Pt with the value of Smickley and Pratt where the agreement is within 2% beyond the experimental errors. The data obtained show the expected variation with atomic number. A close observation shows that the data obtained are in a better agreement with the recently reported accurate data of Scofield.

ACKNOWLEDGMENTS

One of the authors (R.S.P.) is thankful to G. Basavaraju, Department of Physics, Indian Institute of Technology, Bombay, for the kind suggestions and the University Grants Commission for providing the financial assistance to carry out this work.

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