Attenuation measurements in the x-ray region

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Attenuation coefficients have been measured for aluminum for x rays in the energy region 7–15 keV. The x rays were obtained by proton excitation of copper, tantalum, and lead targets. A new method has been used to extract the attenuation coefficients of the individual components of the copper K x rays and the L x rays of tantalum and lead without necessitating an analysis of the component peaks of the x-ray spectrum for each absorber.

I. INTRODUCTION

The need for accurate experimental values for the x-ray attenuation coefficients (μ) has been increasingly demonstrated over the past few years consequent to the rapid advances made in the analytical methods using x rays. The proton-induced x-ray-emission (PIXE) technique of trace-element analysis is one excellent example[1,2] of these methods. Also, it has been shown[3] that careful measurements of the attenuation coefficients give important information about the composition of materials like alloys, glasses, and biological tissues, e.g.

There have been several compilations[4–6] of theoretical values of the attenuation coefficients for x rays and γ rays. Analytical fits to these theoretical values also have been proposed by several authors[7–11] for purposes of interpolation. The typical accuracy of the theoretical compilations lies in the range 1–10 % depending on the atomic number of the absorber and the x-ray or γ-ray energy. The analytical interpolation formulas have accuracies of 1–2 % with respect to the compiled theoretical data.

Experimental data on the x-ray attenuation coefficients are rather sparse as compared to theoretical data. It would be preferable to have as much experimental information as possible, not only for comparison with and checking of the theoretical calculations, but also as independent data which could be reliably used for analytical work using x rays.

There have been several attenuation measurements[12–24] on x rays. Some of the workers used radioactive x-ray sources while others have used characteristic x rays as well as bremsstrahlung from x-ray machines. In the present measurements, proton-induced x rays were used with copper, tantalum, and lead targets and aluminum absorbers. K x rays were used for copper and L x rays for the other two targets. Values for μ for the individual components of the various x-ray lines were extracted using a new method. The details are presented in this paper.

II. EXPERIMENTAL METHOD

X rays for the present measurements were obtained by proton bombardment of thick targets of copper, tantalum, and lead using the PIXE setup at the Indian Institute of Technology, Kanpur.[1,2,25–27] The experimental arrangement is shown in Fig. 1. Accelerated by the 2-MV Van de Graaff machine at IIT, Kanpur, 1.8-MeV protons were allowed to fall on the targets mounted at the center of a specially designed PIXE chamber made of aluminum. The targets were mounted at 45° to the proton beam. Proton currents of about 100 nA were used. The proton charge incident on the targets was monitored and measured using an ORTEC current integrator. X rays emitted from the targets at 90° to the incident proton beam were collimated by a graphite collimator on the wall of the PIXE chamber and allowed to emerge from the chamber through a 10-μm-thick Mylar window. The x rays were then incident on the absorber placed outside the PIXE chamber perpendicular to the x-ray beam. A lead block, 7 cm in length and having a central hole, with a diameter of 0.8 cm and coaxial with the x-ray beam provided a narrow-beam geometry for the attenuation measurements. The maximum angle of in scattering was 2°. The transmitted x rays were detected by an ORTEC Si(Li) detector having a resolution of 180 eV at 6.4 keV. The output pulses from the detector were amplified and fed to a ND512 multichannel analyzer.

The absorbers used were in the form of thin aluminum foils of dimensions 3×2 cm^2. The absorber dimensions were such that multiple-scattering effects were negligible.[28] The purity of the foils was 99.9%. The foil thickness was measured by accurate weighing of the foils on a

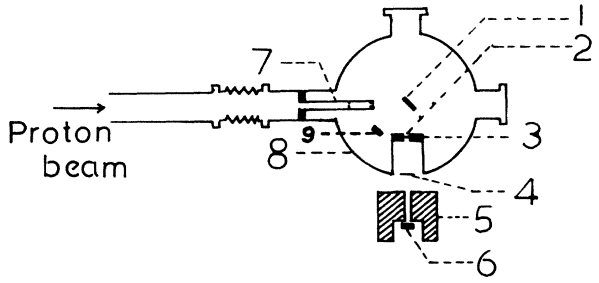

FIG. 1. Experimental arrangement for x-ray attenuation measurements. 1, Cu, Ta, or Pb target. 2, Mylar window. 3, Graphite collimator. 4, Al absorber. 5, Lead shielding. 6, Si(Li) detector. 7, Collimator assembly for proton beam. 8, PIXE chamber. 9, Surface barrier detector.

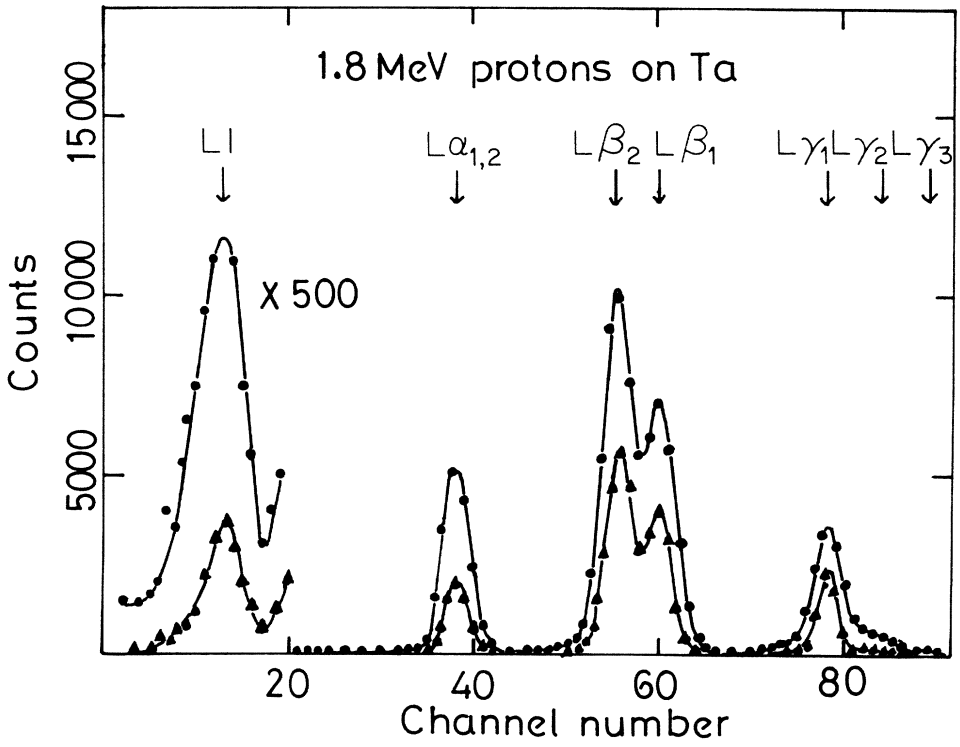

FIG. 2. X-ray spectrum from Ta target bombarded with 1.8 MeV protons. ●, with no absorber; ▲, with 16.3 mg/cm^2 Al absorber.

microbalance. The average thickness was 4.705 mg/cm^2.

The flux of x rays incident on the absorber was indirectly monitored in two ways. The x-ray flux is proportional to the proton charge on the target measured by the current integrator. It is also proportional to the proton flux backscattered from the target. These backscattered protons were detected by means of a surface-barrier detector mounted inside the PIXE chamber, facing the target at 135° to the incident proton beam. They were counted in a single-channel-analyzer—scalar combination. The proton charge measured by the current integrator was found to be proportional to the backscattered proton counts within the statistical error proving the internal consistency in the two methods of monitoring the incident x-ray intensity.

Typical spectra of the Ta L x rays are given in Fig. 2 for zero absorber thickness and for an absorber thickness of 16.3 mg/cm^2. Background spectra were taken in two ways: Firstly, without any target, but with the proton beam on and secondly, with target and with the proton beam on, but with the incident x-ray channel blocked by a 2-cm-long lead block, which completely absorbs the incident x rays. In both cases the background was found to be negligible.

III. METHOD OF ANALYSIS

The Ll line is a singlet. For this line, the observed x-ray intensities (I) are fitted to a straight line in the usual logarithmic scale, by the least-squares method

$$\ln I = mx + c \ , \tag{1}$$

where the slope $m = -\mu$ in appropriate units and x is the absorber thickness.

The $K\alpha$, $K\beta$, $L\alpha$, and $L\beta$ lines consist of two components each. The $L\gamma$ line comprises three components. For these multicomponent lines, the observed intensities can be written as

$$I(x) = \sum_i I_i e^{-\mu_i x} \ , \tag{2}$$

where $i = 1,2,3$ for L_γ and $i = 1,2$ for the other lines.

The μ_i's of the individual components of a particular x-ray line do not differ by more than about 8%. Also, one of the components will be comparatively more intense than the others. Hence it is possible to define an average value for the attenuation coefficient for the components. Thus, one can again fit the logarithms of the observed intensities to a straight line with slope $\bar{\mu}$ and y intercept C_0. One can write

$$y(x) = \frac{I(x)}{I_0 e^{-\mu x}} = \sum_i f_i e^{-\delta_i x} \ , \tag{3}$$

where $I_0 = e^{C_0}$, $f_i = I_i / I_0$, and $\delta_i = \mu_i - \bar{\mu}$. Now $|\delta_i| \ll \bar{\mu}$ and $|\delta_i x| \ll 1$. Thus a linear expansion for

TABLE I. Results of least-squares fitting for Cu $K\alpha$ line.

$\bar{\mu}$ (cm^2/gm)	c_0	δ_1	δ_2	χ^2 (min)
49.83	9.956	−1.0	+0.35	7.7×10^{-3}

the exponential in Eq. (3) can be used,

$$y(x)=\sum_i f_i(1-n\delta_i x)\ . \tag{4}$$

In the above equation, different sets of values of δ_i, $i=1,2,3$, are assumed and the corresponding values of f_i are obtained by least-squares fitting. The optimum set giving minimum χ^2 is selected and the individual μ_i are calculated accordingly.

The results of a typical least-squares fitting are given in Table I and Fig. 3 for the copper $K\alpha$ line.

In Fig. 3, the experimental points are represented by the black circles. The upper solid curve is the average straight-line fit to the experimental points obtained by the least-squares analysis. The lower two curves are the individual contributions of the $K\alpha_1$ and $K\alpha_2$ lines obtained by the least-squares fitting using Eq. (4), as outlined above.

The method was found to work well for the two component x-ray lines. However, for the three-component $L\gamma$ line, the method could not be easily applied, when all the three lines are considered. However, the method could still be applied in this case, if it is assumed that the $L\gamma$ line consists of two components ($L\gamma_1$ and $L\gamma_{2,3}$). Thus, the attenuation coefficient for $L\gamma_1$ and the average attenuation coefficient for $L\gamma_{2,3}$ have been extracted.

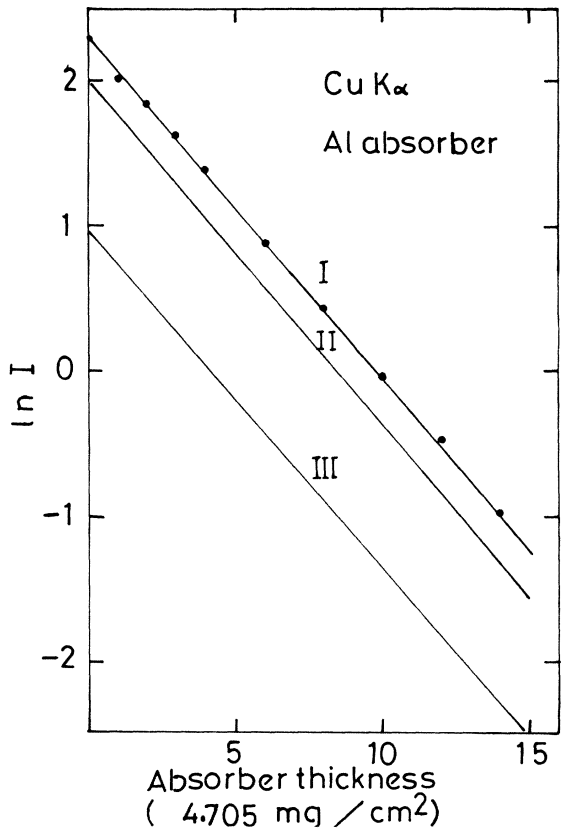

FIG. 3. Attenuation curve for Cu $K\alpha$ x rays in Al. ●, experimental points: curve I, least-squares-fitted line (average); curves II and III, curves for the individual components $K\alpha_1$ and $K\alpha_2$.

TABLE II. X-ray attenuation coefficients for aluminum.

Target	X-ray line	Energy keV	μ (cm^2/g) Present meas.	Theory[a]
Cu	$K\alpha_2$	8.027	50.2± 0.5	48.83
	$K\alpha_1$	8.047	48.8± 0.5	48.47
	$K\beta_1$	8.904	37.2± 0.4	36.07
	$K\beta_2$	8.976	36.0± 0.4	35.23
Ta	Ll	7.171	65 ±19	64.94
	$L\alpha_2$	9.087	47.8± 0.5	47.78
	$L\alpha_1$	8.145	46.8± 0.5	46.79
	$L\beta_2$	9.341	32.2± 0.3	31.35
	$L\beta_1$	9.649	29.4± 0.3	28.51
	$L\gamma_1$	10.892	19.9± 0.2	20.00
	$L\gamma_2$	11.215	18.5± 0.2	18.36
	$L\gamma_3$	11.276		18.07
Pb	Ll	9.184	33.3± 2.7	32.94
	$L\alpha_2$	10.448	22.6± 0.2	22.59
	$L\alpha_1$	10.549	22.1± 0.2	22.08
	$L\beta_2$	12.611	13.2± 0.2	13.03
	$L\beta_1$	12.620	13.0± 0.2	13.00
	$L\gamma_1$	14.762	8.3± 0.2	8.24
	$L\gamma_2$	15.097	7.7± 0.2	7.72
	$L\gamma_3$	15.218		

[a]Reference 8.

The fitting procedure discussed above was found to have an accuracy of ±0.01 cm^2/g irrespective of the x-ray energy. This amounts to much less than 0.1% error in the attenuation coefficients of the individual lines in all the cases considered. The statistical error of the observed intensities was less than 1% except for the Ll lines for the tantalum and lead, where the errors were, respectively, about 22% and better than 9% due to the comparatively lower-count rates.

Calculations of the corrections for the in-scattering were done using the form-factor tabulations of Hubbel and Øverbø[29] for the coherent scattering and the Klein-Nishina formula for incoherent scattering. The effect was found to be less than 0.1%. Therefore, no correction has been applied to the final results for this effect. The correction for the small (0.1%) impurities in the absorber

TABLE III. Comparison of experimental results for Cu $K\alpha$ line.

Reference	μ (cm^2/g)
12	51.15
14	49.7
15	51.6
16	50.3
17	49.1
18	50.6
19	50.04
23	56.5
Present result (Average)	49.83

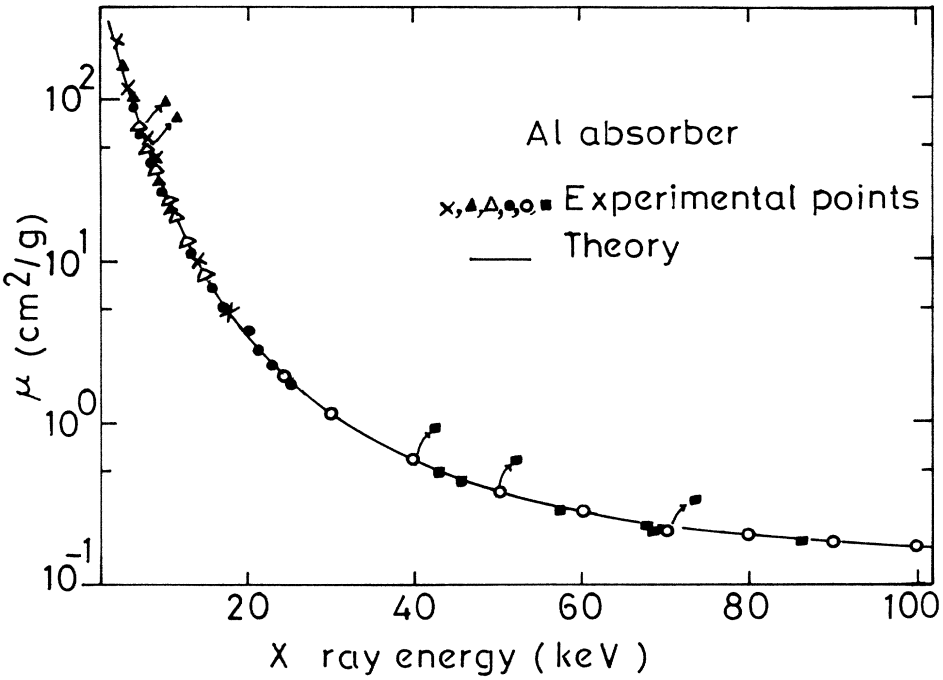

FIG. 4. Comparison of the experimental results for x-ray attenuation coefficients in aluminum. Experimental points: △, present results; ●, Millar and Greening (Ref. 19); ○, McCrary *et al.* (Ref. 22); ■, Wiedenbeck (Ref. 21); ▲, Hughes *et al.* (Ref. 18); ×, Parthasarathy and Hansen (Ref. 23). Theory (solid line): Storm and Israel (Ref. 4). The five points shown with arrows have been displaced from their original positions which lie on the theoretical curve, for the sake of clarity.

was also found to be negligible. The combined error due to uncertainties and nonuniformities in absorber thickness was found to be of the order of 0.1%. Therefore, the predominant error in the final results is due to statistics.

IV. RESULTS AND DISCUSSION

The results of the present measurements are summarized in Table II. The theoretical values given in the table for comparison have been obtained using the analytical expressions given by Montenegro *et al.*,[8]

$$\ln[\mu(\mathrm{cm}^2/\mathrm{g})] = 9.325\,574 - 2.073\,272(\ln E) - 0.368\,260\,3(\ln E)^2 + 0.052\,954\,73(\ln E)^3 \cdots , \quad (5)$$

where E is the x-ray energy in keV.

It is seen that there is very good agreement between the present experimental results and the theoretical values.

To the author's best knowledge, the measurements in the case of the tantalum and lead L lines have been carried out for the first time. For the copper $K\beta$ line, there has been one earlier work, that of Parthasarathy *et al.*[23] Their value (41.88±0.89) is far away from the theoretical value, whereas our value is in better agreement with theory. For Cu $K\alpha$, there have been several earlier measurements.[12,14–19,23] The results of these earlier experiments are compared with the present value in Table III. It can be seen that with the exception of Ref. 23, the results of all others agree with our results to within the experimental errors quoted for the various measurements.

It would be worthwhile to have a comparison between experiment and theory in the x-ray region between 4–100 keV for aluminum. Such a comparison has been given in Fig. 4. The solid curve is the theoretical curve obtained by using the compilation of Storm and Israel.[4] Throughout the energy regime considered, the agreement between theory and experiment is excellent.

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