

X-RAY SCATTERING COEFFICIENT AS A FUNCTION  
OF WAVE-LENGTH AND ATOMIC NUMBER

BY ERROL N. COADE

RYERSON PHYSICAL LABORATORY, UNIVERSITY OF CHICAGO

## ABSTRACT

The mass scattering coefficients for Au, Sn, Ag, Fe, and C were compared with those of Al for wave-lengths between  $\lambda=0.48\text{\AA}$  and  $\lambda=1.09\text{\AA}$  by collecting the scattered radiation in an ionization chamber surrounding the scatterer on one side. The primary beam consisted of characteristic fluorescence radiation excited in radiators of Sn, Ag, Mo, and Se by a water-cooled tungsten tube. The ratios obtained are shown in the table.

With Hewlett's measurement of the absolute value of the mass scattering coefficient of carbon these ratios can be transformed into absolute scattering coefficients.

## INTRODUCTION

WHEN x-rays pass through an absorbing screen part of the energy of the beam is spent in ejecting photoelectrons and part is scattered. If  $\mu$  is the total absorption we may write

$$\mu = \tau + \sigma$$

where  $\tau$  is the true absorption due to the ejection of electrons, and  $\sigma$  the absorption due to scattering. The fraction of the energy scattered per gram of the scattering substance is  $\sigma/\rho$ , the mass scattering coefficient. The experiment to be described was undertaken to measure  $\sigma/\rho$  directly, and to aid in determining the value of the true absorption from the known values of the total absorption. Another purpose was to find reliable values of  $\sigma/\rho$  to check current theories of the scattering by complex atoms.

Direct measurements of the mass scattering coefficient of x-rays have been made by Barkla and Dunlop, Hewlett, Mertz and others. Barkla and Dunlop<sup>1</sup> observed the scattering at  $90^\circ$  of filtered white radiation from an x-ray tube striking scatterers of different materials. It may be pointed out that these experimenters did not measure the true scattering coefficient because all their measurements were made at right angles to the primary beam. This would be adequate if the angular distribution of scattering were the same for all elements; but such is not the case. We know that as heavier atoms are used the angular distribution changes, with an increasing preponderance of scattering taking place in the forward direction. This scattering in excess of that called for on Thomson's theory was at that time considered to be extra-radiation, not connected with the scattering process, and was purposely excluded from measurement. In their experiments the purity of the primary radiation left much to be desired, since it consisted of direct radiation from an x-ray tube filtered through absorbing screens. This was

<sup>1</sup> Barkla and Dunlop, *Phil. Mag.* **31**, 222 (1916).

used because with fluorescence radiation the intensity of the scattered beam was so small that it could not be measured accurately. Barkla and Sale<sup>2</sup> repeated the experiment with modifications.

For the same reason Hewlett<sup>3</sup> used direct radiation for his primary beam. This radiation was, however, from a molybdenum target, and was filtered through a zirconium screen, thus giving a large proportion of homogeneous rays. By moving his ionization chamber to measure the intensity of scattering at all azimuths he was able to integrate the intensity distribution and get the true scattering coefficient. His method, however, required so many observations that its application over a wide range of elements and wave-lengths would be very tedious.

It was undoubtedly for this reason that Mertz<sup>4</sup> adopted a large ionization chamber surrounding the scattering block, which would receive the scattering for all azimuths. His measurements, however, were confined to elements of low atomic numbers with Na the highest. He likewise used white radiation from an x-ray tube filtered through Al and Cu. The effective wave-length was varied by changing the tube potential. Mertz used solid scattering blocks and had troublesome corrections to make for the absorption of the blocks. His ionization chamber was filled with air and he had difficulty in obtaining sufficient intensity to extend his measurements to higher atomic numbers and longer wave-lengths.

#### APPARATUS

In the present investigation a modification of the chamber used by Mertz was employed to measure simultaneously the radiation scattered at all azimuths. Improvement was made in the quality of the x-ray beam by using fluorescence radiation excited in blocks of Se, Mo, Ag, and Sn by direct radiation from an x-ray tube. The scattering blocks were of Al, C, Fe, Ag and Sn. Suitable filters placed in the primary or secondary beam prevented fluorescence rays excited in the scatterer from entering the ionization chamber.

The source of x-rays was a water-cooled Siemens tube of the Coolidge type with a tungsten target surrounded by a copper screen. Current was supplied to the tube from a transformer, whose secondary current was rectified by a full-wave kenotron rectifier, using a balanced circuit. The tube potential was from 35 to 50 peak k.v. with a current of 35 ma.

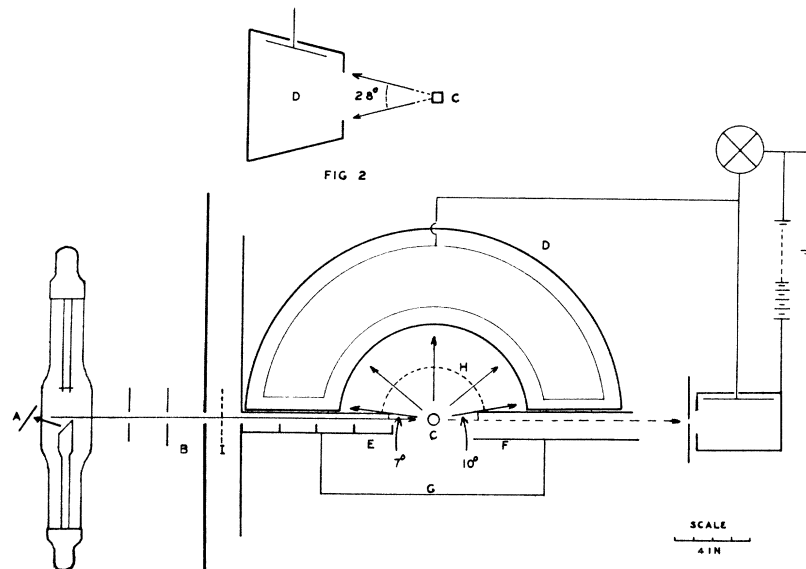
The experimental arrangement is shown in Fig. 1. The radiators, *A*, were placed three cm from the x-ray tube and directly in front of a system of collimating screens, *B*, with openings one-half inch square. The beam of fluorescence radiation, which we will call the primary beam, passed through these openings and struck the scattering blocks at *C*. Since no direct radiation from the tube was allowed to reach the scatterer the beam consisted almost entirely of fluorescence *K*-rays.

<sup>2</sup> Barkla and Sale, *Phil. Mag.* **45**, 743 (1923).

<sup>3</sup> Hewlett, *Phys. Rev.* **20**, 688 (1922).

<sup>4</sup> Mertz, *Phys. Rev.* **28**, 891 (1926).

The ionization chamber, *D*, shown also in Fig. 2, was so shaped that it would receive the x-rays scattered between two planes meeting along the path of the primary beam at an angle of  $28^\circ$ . The chamber was of the same depth throughout, so that the path of all the scattered x-rays through it would be the same. The extreme rays entering the chamber from the center of the block made angles of  $10^\circ$  and  $173^\circ$  respectively, with the forward direction of the primary beam.



Figs. 1, 2.

The window of the ionization chamber was covered by celluloid. A protecting ledge about the window prevented x-rays from striking the walls or the electrode, which consisted of an aluminum plate, the same shape as the top of the chamber, and mounted in the upper portion of the chamber. The entire outside of the chamber and all the electrometer connections were covered with  $1/32''$  lead. Lead screens, *E* and *F*, were used to reduce the effect of air scattering from the path of the primary beam. A lead screen *G*, enclosing the scattering block and the window of the ionization chamber was found useful in excluding stray radiation. Absorbing screens were placed at *H* and *I* when required. The chamber was filled with argon at atmospheric pressure and was connected to a Compton electrometer, the sensitivity of which was about 10,000 mm per volt.

The scattering blocks were then mounted on supports of silk thread attached to wire frames and were so placed in the path of the x-ray beam that radiation from every part of the first slit reached every part of the scattering block.

#### FILTERS

Radiation of wave-length other than that desired was prevented from

entering the ionization chamber by filters of aluminum, silver, or tin placed in the primary or secondary beam or both. In addition, the potential of the tube was altered from 35 peak k.v. for Mo and Se to 50 peak k.v. for Ag and Sn. For scattering blocks of carbon and aluminum the *K*-radiation is so soft that it is absorbed by the air before reaching the ionization chamber. Consequently no filter was required. For the iron scatterer a filter of aluminum 0.2 mm in thickness was used to remove 99 percent of the *K*-radiation. When the scatterer was silver no filter was required for Mo radiation, but for Ag radiation filters of silver, each absorbing 50 percent of the *K*-rays, were placed in both the primary and secondary beams. The same filters were used for the scattering of Ag radiation by tin. When tin was used to scatter Sn rays a filter of tin was placed in the primary beam to absorb 50 percent of the characteristic radiation. This presumably absorbed more of the short wave-lengths present and prevented the excitation of fluorescence Sn rays. When Se rays were scattered by tin no filter was used, since the potential, 35 peak k.v., was too low to excite the fluorescence radiation. When gold was used to scatter Ag or Sn rays, an aluminum filter 1.2 mm thick was placed in the secondary beam to absorb the *L*-radiation.

The gold foil used was mounted on a celluloid base and was compared with an aluminum scattering block, likewise mounted on celluloid. In correcting for the scattering of the celluloid an amount was deducted equal to one-half of the scattering from a celluloid block of the same dimensions. For this and for all the other scattering blocks corrections were made for air scattering and for the natural leak of the electrometer system. Due to the length of air path in front of the chamber and to the size of the chamber itself, these corrections were appreciable, and their magnitude for longer wave-lengths and higher atomic numbers than those used made measurements by this method impracticable.

#### MEASUREMENT

The measurement of the mass scattering coefficient was made as follows: Let  $I_0$  be the intensity when no scatterer is in the path of the primary beam,  $I_1$  be the intensity when an aluminum block is in the path of the beam,  $I_2$  be the intensity when an iron (or other) block is in the path,  $m_1$  be the mass of the aluminum scatterer and  $m_2$  be the mass of the iron (or other) scatterer. Then the ratio of the mass scattering coefficients of the two materials is

$$\frac{(\sigma/\rho)_{Fe}}{(\sigma/\rho)_{Al}} = \frac{m_1}{m_2} \times \frac{I_2 - I_0}{I_1 - I_0} .$$

The resulting ratios are shown in Table I and are plotted in Fig. 3. Data obtained by Barkla and Dunlop<sup>1</sup> are included for comparison.

The purity of the primary radiation was tested roughly by absorption methods and the beam was found to be approximately monochromatic. No attempt, however, was made to measure the wave-lengths accurately, because it was felt that better results could be obtained from published

TABLE I. Ratio of mass scattering coefficients of elements to that of aluminum for different wave-lengths

Scatterer	Radiator			
	Sn	Ag	Mo	Se
Au	5.49	6.75		
Sn	2.33	2.82	3.44	
Ag		2.65	3.51	
Fe	1.41	1.65	2.09	
C	1.07	0.95	0.87	0.79
Effective Wave-length (calc.)	0.48A	0.55	0.70	1.09

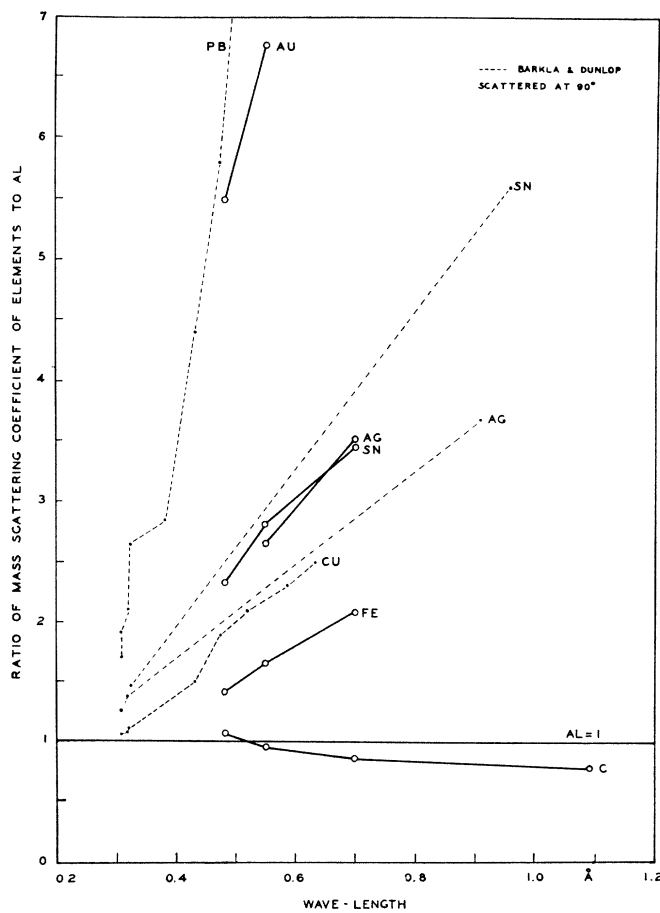


Fig. 3.

values for x-ray spectrum lines. Accordingly the wave-lengths of the  $K_{\alpha}$  and  $K_{\beta}$  lines of each element were weighted according to the relative

intensities of each line,<sup>5</sup> and the average obtained. The weights are contained in the following table:

TABLE II.

Atomic No.	Element	Intensity ratio
34	Se	6.0
42	Mo	5.5
47	Ag	4.7
50	Sn	4.7

## ABSOLUTE MASS SCATTERING COEFFICIENTS

The absolute values of the mass scattering coefficient can be deduced from Hewlett's measurements on carbon. He found<sup>3</sup> that  $\sigma/\rho = 0.200$  for  $\lambda = 0.7\text{\AA}$ . The corresponding value of  $\mu/\rho$  for the same wave-length was found also by Hewlett<sup>6</sup> to be  $\mu/\rho = 0.532$ . Substituting in

$$\frac{\tau}{\rho} = \frac{\mu}{\rho} - \frac{\sigma}{\rho}$$

one obtains  $\tau/\rho = 0.332$

But  $\tau$  is known to be very nearly proportional to  $\lambda^3$  i.e.

$$\frac{\tau}{\rho} = K\lambda^3.$$

Therefore, for  $\lambda = 0.7\text{\AA}$ ,  $K = 0.968$  whence  $\tau/\rho = 0.968\lambda^3$

From the equation

$$\frac{\sigma}{\rho} = \frac{\mu}{\rho} - \frac{\tau}{\rho}$$

We obtain the value of  $\sigma/\rho$  for carbon for the other wave-lengths as given in the following table:

TABLE III. *Mass scattering coefficients for carbon.*

Element	$\lambda$	$\sigma/\rho$ (calculated)
Sn	0.48\AA	0.183
Ag	0.55	0.186
Mo	0.70	0.200
Se	1.09	0.330

With these values for carbon in Table I the absolute values of the mass scattering coefficients for the other elements were calculated and are shown in Fig. 4. Data obtained by Mertz for carbon are shown by the broken line for comparison.

<sup>5</sup> Siegbahn, Spectroscopy of X-rays, p. 96. These data are for the ratio of lines excited by cathode rays. That the ratio is the same for fluorescent lines has been shown in the case of Ag K-rays by A. H. Compton, Proc. Nat. Acad. Sci. **14**, 549 (1928).

<sup>6</sup> Hewlett, Phys. Rev. **17**, 284 (1921).

The writer is indebted to Professor A. H. Compton for suggesting this experiment and for invaluable advice during the course of the investigation.

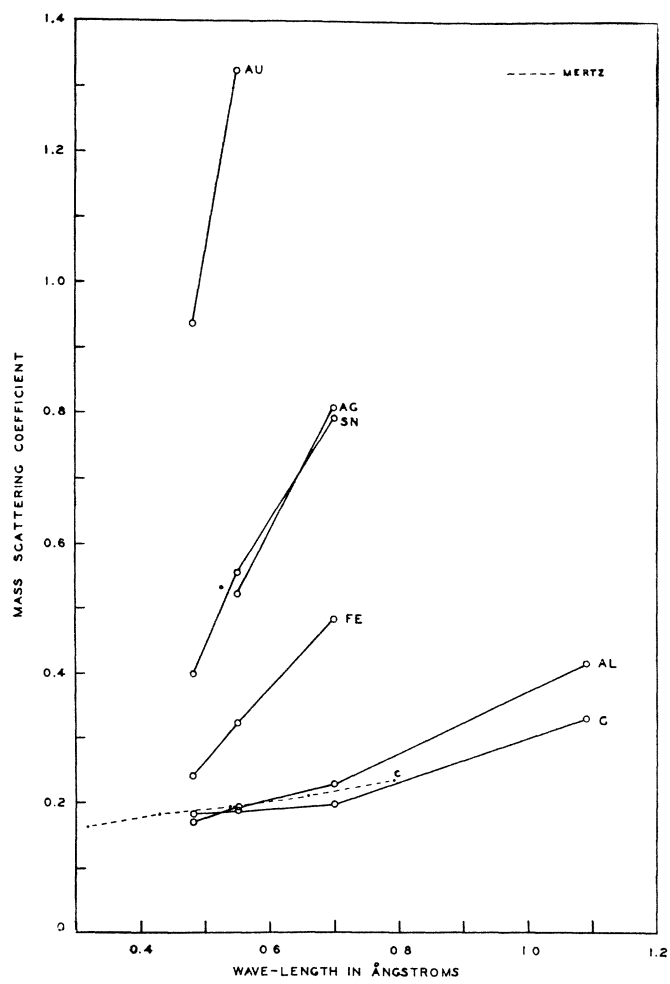


Fig. 4.