THE WAVE-LENGTHS OF SECONDARY X-RAYS (*Second note*)

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In a previous note[1] the authors have described experiments on the wave-lengths of secondary X-rays produced in secondary radiators, consisting of potassium iodide, barium chloride, lanthanum oxide, praseodymium carbonate and neodymium carbonate. The researches showed that, within the errors of experiment, the wave-lengths of the secondary fluorescent X-rays have the same values as those of the characteristic K series lines of the X-ray spectra when potassium, barium, lanthanum praseodymium and neodymium, respectively, are used in the targets of the X-ray tube. In other words, the lines in the characteristic spectrum of a chemical element have the same wave-lengths, whether they are excited by the bombardment of electrons or by primary X-rays. It appeared also that the relative intensities of the lines of the K series were substantially the same in the two cases. Further, the experiments indicated that a large amount of the secondary radiation (scattered rays) has the same wave-lengths as the primary rays in the K series of X-rays characteristic of the tungsten target. We obtained no evidence of radiation comparable in intensity with this scattered radiation and having wave-lengths .024 ångström longer than the primary wave-lengths, as an interesting theory of Prof. A. H. Compton's[2] demands.

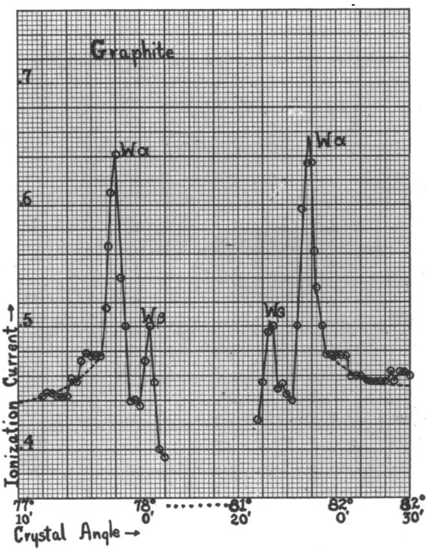

FIGURE 1

In our experiments we employed the X-rays from a tungsten target as the primary, exciting X-rays. Professor Compton[2] has published accounts of important experiments in which he used the rays from a molybdenum target. His experiments indicate the presence of scattered radiation having wave-lengths averaging .024 ångström longer than the primary rays, when carbon was used as a secondary radiator. The radiation was analyzed by means of an ionization spectrometer. More recently, P. A. Ross[3] has published the results of experiments by the photographic method and with a molybdenum target, which appear to confirm the wave-length shift observed by Compton. The shifted wave-lengths, however, occupy a band in the spectrum that is broad as compared with the primary.

We have repeated our experiments using as secondary radiators chemical elements of lower atomic weight than those mentioned above, namely, carbon, aluminium, sulphur and copper. The primary, exciting radiation was, as before, the X-rays from a Coolidge tube with a tungsten target operated at a constant voltage of eighty to ninety thousand volts, and including, therefore, the K series lines of tungsten. The tungsten K lines have wave-lengths in the neighborhood of .2 ångström, whereas those of molybdenum lie in the neighborhood of .7 ångström.

The exact arrangement of the apparatus is represented in figure 1 of the previous note. We have made four experiments with graphite as the secondary radiator. The curve in figure 1 of this note represents the results of one of these experiments. The abscissas of the two curves give the angular positions of the crystal corresponding to reflections of X-rays on the two sides of the zero line of the spectrometer, the ordinates are the corresponding ionization currents. The tall peaks represent the α and β lines in the K series of tungsten and correspond to the wave-lengths of these tungsten lines, the wave-lengths being calculated by the Bragg formula using half the angular distance between corresponding peaks. The curves indicate a large amount of scattered radiation having precisely the wave-lengths of the primary radiation exciting it.

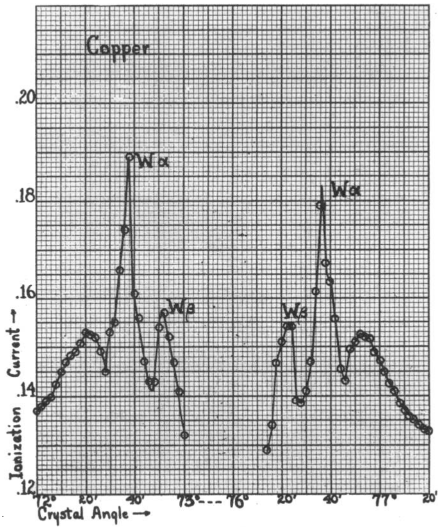

FIGURE 2

The secondary rays come from the radiator at right angles to the primary rays and Compton's theory demands that in this case the shift in the scattered radiation should amount to .024 ångström and should be independent of the wave-lengths of the primary, exciting rays. This wave-length shift of .024 corresponds to between thirteen and fourteen minutes of arc on the scale giving the position of our calcite crystal. It appears from the curve that there is no especially large amount of radiation corresponding to points thirteen or fourteen minutes away from the α peaks themselves. The latter correspond with the wave-lengths of the primary tungsten spectrum to within the errors of measurement. In other words, in the case of tungsten primary radiation there is no evidence for scattered rays, having wave-lengths exactly .024 ångström longer than the primary rays, and with an intensity at all comparable with the scattered rays of precisely the same wave-lengths as the primary.

In this particular curve there are small irregularities thirteen or fourteen minutes from the α peaks. We have chosen this curve for representation because it is the only carbon curve which does show such irregularities. If we took an average of our four experiments with carbon, the curve would run about as represented by the dotted line, which also indicates no especially strong radiation thirteen or fourteen minutes from the α peaks.

Our experiments with aluminium and sulphur have lead to the same results. We found markedly intense radiation at wave-lengths within experimental errors, equal to those of the α and β lines in the K series of the tungsten target but no evidence of any especially intense lines having wave-lengths 0.24 ångström longer.

The curves in figure 2 represent secondary radiation from a plate of copper. These curves also have tall peaks that correspond to wave-lengths equal to those of the α and β lines in the K series of the tungsten target. In addition to these, there is evidence of an excess of radiation represented by the two humps on the outside of the X-peaks at a distance of seventeen or eighteen minutes from the X-peaks. It is difficult to estimate just how much radiation these humps indicate for part of them at least may be due to the form of the continuous spectrum radiation curve. The continuous spectrum radiation curve always has a maximum, the position of which depends upon the voltage applied to the tube and the amount of matter that the X-rays have passed through, etc. The distance of the humps on the copper curve from the α-peaks is somewhat greater than the maximum distance demanded by Compton's theory.

The following table contains the wave-lengths corresponding to the peaks on our ionization curves, the values being calculated from the Bragg formula.

WAVE-LENGTHS OF SCATTERED X-RAYS (In ångströms)

SCATTERING SUBSTANCE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	ALUMINIUM
α Lines	.2100	.2098	.2098	.2104	.2098
β Lines	.1841	.1858	.1851	.1850	.1845
SCATTERING SUBSTANCE	SULPHUR	SULPHUR	COPPER	AVERAGE VALUES	
α Lines	.2105	.2096	.2098	α .2100	
β Lines	.1878	.1850	.1854	β .1850	
Primary Rays Direct from Target	α_2 = .2134, α_1 = .2086, β = .1841				

It appears that the wave-lengths of the rays scattered from the $K\alpha$ doublet of the tungsten target lie between that of the strong α_1 line and that of the weaker α_2 line and nearer the former. Further, the values of the wave-lengths of the rays scattered from the β group are on the average a fraction of one per cent larger than that of the primary X-rays. This difference does not appear to be greater than experimental errors in this case, for the β peaks lie on portions of the general radiation curves that are rapidly rising, and we would expect from this a slight apparent shift toward longer wave-lengths.

Undoubtedly among the secondary X-rays there is a certain amount of radiation having longer wave-lengths than the primary, exciting rays. Our experiments with copper, however, are the only ones in which we have found evidence of radiation with wave-lengths longer than the primary by a definite amount.

The transfer of energy and momentum from a quantum of radiant energy to a single, free electron forms the basis of Compton's theory of scattered radiation. Another line of thought indicates that there must be tertiary rays having wave-lengths longer than the primary rays by a certain amount. The fundamental idea of this is that the photoelectrons produced by the primary rays, when they strike neighboring atoms, must produce radiation just as the electrons in the X-ray tube produce it, when they strike the atoms of the target. Mr. Hu[4] showed in his doctor's thesis that the energy of the photoelectrons due to X-rays was a few percent less than the $h\nu$ value of the primary radiation. De Broglie[5] has published accounts of important investigations, which show that the difference between the energy of the photoelectrons and the $h\nu$ value of the incident radiation equals the energy required to lift an electron completely out of the atom. This latter energy equals the $h\nu$ value of the critical absorption frequency of the chemical element from which the photoelectrons come. When electrons strike ordinary atoms they produce continuous spectrum radiation having a short wave-length limit, the $h\nu$ value of which equals their kinetic energy. We would, therefore, expect the photoelectrons due to X-radiation to produce a tertiary radiation of lower frequency and, therefore, of longer wave-length than the primary. The short wave-length limit of this tertiary radiation ought to be a definite amount longer than the wave-length of the primary rays, this amount depending upon the chemical element used as a secondary radiator.

If ν_1 and ν_2 represent the frequency of the primary radiation and the critical absorption frequency of the secondary radiator, respectively, then the frequency, ν, of the limit of the tertiary radiation may be calculated from the equation.

$$h\nu = h\nu_1 - h\nu_2.$$

The frequency shift of the limit of the tertiary radiation from the primary is

$$\nu_1 - \nu = \nu_2.$$

For any particular chemical element, used as a secondary radiator, ν_2 is constant and the frequency shift for such an element is independent of the wave-lengths of the primary rays. In Compton's theory the wave-length shift turns out to be independent of the primary wave-lengths.

Calculating the wave-length of the limit of the tertiary radiation in terms of the wave-lengths λ_1 and λ_2 we have

$$\lambda = \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1},$$

and for the wave-length shift

$$\lambda - \lambda_1 = \frac{\lambda_1^2}{\lambda_2-\lambda_1}.$$

If the critical absorption wave-length, λ_2, is large compared with the primary wave-length, λ_1, the wave-length shift becomes approximately proportional to the square of the primary wave-length. In our experiments with sulphur and aluminium $\lambda_2 = 5.0$ and 7.9, respectively, and $\lambda_1 = .21$. Hence the wave-length shifts amount to only about .009 and .006, respectively, and the limits of the tertiary spectra lie so close to the α and β lines that they would not be appreciable on our curves. In the experiment with carbon the limit of the tertiary spectrum would lie still closer to lines in the primary radiation.

If the secondary radiator consists of copper the limit of the tertiary radiation lies some distance from the lines in the primary rays. For copper $\lambda_2 = 1.38$ and the tertiary radiation due to the photoelectrons ought to have a short wave-length limit .037 ångström longer than the wave-length of the primary K line. This difference in wave-length corresponds to about 20 minutes of arc in the position of the calcite crystal in our experiments. Hence, we would expect to find some radiation of wave-lengths roughly corresponding to the humps actually observed on our copper curves.

Applying this theory to the experiments by Compton and those by Ross, we find the following estimate of the shift in the wave-length of the tertiary radiation. The K critical absorption wave-length of carbon has been estimated from ionization potentials and found to be in the neighborhood of 42 ångström (Foote and Mohler). Calculating from this the shift in wave-length if we use the Kα line of molybdenum as primary radiation, we find that it should be of the order of magnitude of .012 ångström. According to our theory, therefore, there ought to be tertiary radiation beginning at a wave-length something like .012 ångström longer than the Kα line of molybdenum, and having an average wave-length somewhat longer still. Just how much longer we do not know for the position of the maximum of the general radiation depends upon a great variety of experimental conditions. The position of the maximum for instance ought to depend somewhat on the angle of incidence of the primary X-rays. Possibly the radiation observed by Compton and Ross may be the peak of this continuous spectrum radiation due to the bombardment of the photoelectrons against neighboring atoms in the secondary radiator. This theory would explain for instance the fact that the observed radiation is a band much broader than the lines of the primary rays.

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[1] These PROCEEDINGS, Dec. 1923.

[2] *Bull. Natl. Res. Council,* Oct. 1922, p. 16: *Physic. Rev.,* May 1923, p. 483, and June 1923, p. 715.

[3] These PROCEEDINGS, July 1923, p. 246.

[4] *Physic. Rev.,* June 1918, p. 505.

[5] *Comptes Rendus, Paris,* Jan. 31: March 29: Sept. 26, 1921; *J. Physique,* Sept. 1921.

SYMBIOSIS BETWEEN TERMITES AND THEIR INTESTINAL PROTOZOA[1]

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A correlation between the presence of intestinal protozoa in termites and a wood-feeding habit was postulated by Imms,[2] and this, if true, as Imms pointed out, indicates a possible symbiotic relationship between termites and their intestinal protozoa. After making several microchemical tests on the protozoa, Buscalioni and Comes[3] concluded that the protozoa digest the wood particles which they take into their bodies; and from this conclusion, without stopping to consider whether or not the protozoa can digest wood, these authors claim that they have established symbiosis between termites and their intestinal protozoa. Other investigators, notably Grassi[4,5] and Kofoid,[6] though devoting most of their time to systematics and morphology, have usually regarded the protozoa either as commensals or parasites. Recent investigations by the writer[7,8], together with hitherto unpublished data, are briefly summarized in this paper.

Examination of Museum Material.—Careful examination of the intestinal contents of five workers of each species of termites in the U. S. National Museum revealed that wherever protozoa were present wood was also present and, *mutatis mutandis,* protozoa were present only when wood was present; thus confirming Imms' postulatum. Four families of termites are known. Among the 18 genera and 64 species examined from the family Termitidae, protozoa and wood were present in only 1 of the 21 species of the genus *Nasutitermes* and 2 of the 8 species of the genus *Mirotermes;* but protozoa and wood were present in 18 genera and 76 species,