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ON TERTIARY X-RADIATION, ETC.

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Communicated December 3, 1923

In two notes[1] in these PROCEEDINGS for December 1923 we have described experiments on secondary X-radiation produced by primary X-rays from a tungsten target falling on secondary radiators consisting of various chemical elements. Measurements with an accurate spectrometer showed that within the limits of error (about .1%) the scattered radiation had the same wave-lengths as the primary X-rays, and that the fluorescent radiation had the same wave-lengths as the line spectra of the chemical elements obtained when they were used as targets. Further, evidence appeared of radiation in the case of a copper secondary radiation that may be interpreted as tertiary radiation due to the bombardment of the copper atoms by photo-electrons ejected from them by the primary rays. This tertiary radiation occupies a band in the spectrum that is broader than the lines in the primary radiation. The short wave-length limit of a tertiary radiation band may be calculated from the formula

$$h\nu = h\nu_1 + h\nu_2 \qquad (1)$$

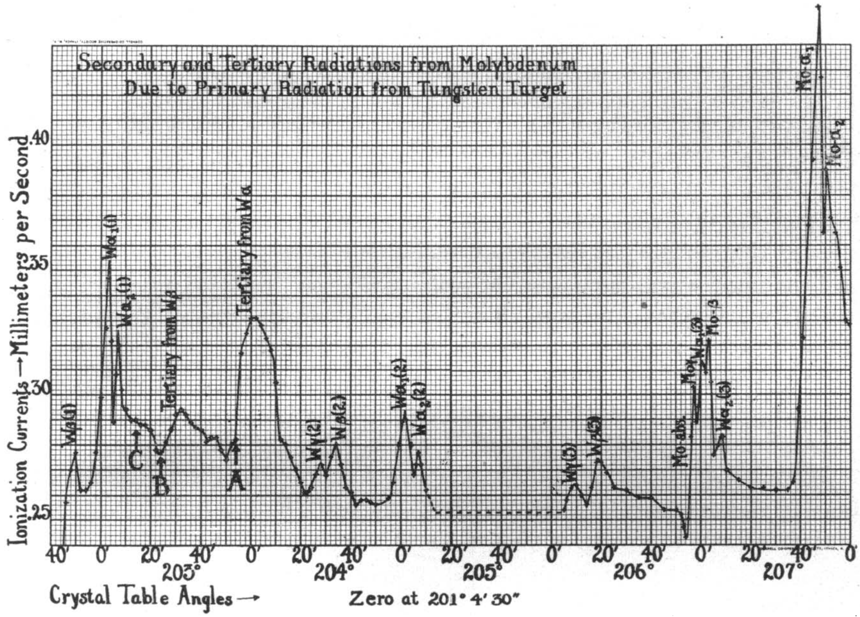
where ν, ν_1 and ν_2 are the frequencies of the primary, the limit of the tertiary radiation and the critical absorption of the secondary radiator, respectively. From this we get the following equation for the difference between the short wave-length limit of the tertiary and the wave-length of the primary rays,

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

The formula indicates that the wave-length shift, $\lambda_1 - \lambda$, increases if the critical absorption wave-length, λ_2, of the secondary radiator decreases. The critical absorption wave-length of a chemical element grows smaller as the atomic number of the element increases. Hence, by taking a secondary radiator consisting of a chemical element of higher atomic number than copper (N = 29), the wave-lengths of the tertiary radiation ought to shift towards a larger value.

The object of the present note is to describe experiments in which we have used molybdenum (N = 42) and silver (N = 49) as secondary radiators, the primary rays coming as before, from a tungsten target. Figure 1 in the first of the two notes above referred to illustrates the arrangement of the apparatus, the only change made being the substitution of plates of metallic molybdenum and silver as secondary radiators.

The curves in the figure of this note represent the spectrum of the radiation from a molybdenum plate due to primary radiation from the tungsten target of the X-ray tube. The curves give the ionization currents for



different settings of the crystal of the spectrometer on one side of the zero of the instrument only. The corresponding data for radiation on the other side of the zero were obtained and from them the exact zero for the setting of the crystal table was estimated to be at 201°4′30″. The three peaks at the extreme left of the curve in the figure correspond to the β, α_1, and α_2 lines in the K series of tungsten, as represented in the scattered radiation from the molybdenum plate. We wish to call attention especially to the fact that the resolving power of the spectrometer sufficed to separate the α_1 and α_2 lines from each other.

Further along in the spectrum, at an angle of about 204°50′, the second order spectrum of these same lines begins. Here the tungsten γ line, as well as the β, α_1 and α_2, appear separately. Further along still, the third order spectrum of the γ and β lines appears at angles of about 206°10′ and 206°20′, respectively. The peaks corresponding to the third order reflections of the α_1 and α_2 lines fall close to and are intermingled with the γ and the β lines of the fluorescent K series spectrum of the molybdenum plate. All four of these lines appear separated from each other and the fact that they lie so close together furnishes an excellent means of comparing the wave-lengths of the molybdenum fluorescent spectrum with those of the scattered radiation corresponding with the tungsten spectrum. Much of the secondary radiation is produced within the substance of the molybdenum plate and before these rays reach the spectrometer they must pass through some molybdenum. The critical absorption of the molybdenum, the wave-length of which lies very close to the limit of the molybdenum K series spectrum, is shown on the curve as an abrupt rise at 206°56′. The two peaks at the extreme right of the curve represent the α_1 and α_2 lines in the fluorescent K series of molybdenum.

TABLE I

SECONDARY AND TERTIARY RADIATION FROM MOLYBDENUM DUE TO PRIMARY RADIATION FROM TUNGSTEN

Wave-Lengths Are Given in Ångströms. Zero of Crystal Table Angle = 201°4′30″

CRYSTAL TABLE READING	ANGLE, θ, OF INCIDENCE	ORDER, n, OF SPECTRUM	WAVE-LENGTH $n\lambda = 2d\sin\theta$	WAVE-LENGTH KNOWN OR CALCULATED	CHARACTER OF RADIATION
202°49′30″	1°45′00″	1	.1849	.1842	Tungsten Kβ
203° 2′55″	1°58′25″	1	.2086	.2086	Tungsten Kα_1
203° 6′40″	2° 2′10″	1	.2148	.2134	Tungsten Kα_2
203°10′22″	......	1	...	...	Tertiary from L Electrons
203°24′00″	2°19′30″	1	.260	.262	Tertiary f. Wβ
203°54′00″	2°49′30″	1	.311	.315	Tertiary f. Wα
204°28′00″	3°23′30″	2	.1792	.1790	Tungsten Kγ
204°33′50″	3°29′20″	2	.1843	.1842	Tungsten Kβ
205° 1′30″	3°57′00″	2	.2086	.2086	Tungsten Kα_1
205° 7′00″	4° 2′30″	2	.2135	.2134	Tungsten Kα_2
206° 9′20″	5° 4′50″	3	.1789	.1790	Tungsten Kγ
206°19′00″	5°14′30″	3	.1844	.1842	Tungsten Kβ
206°55′50″	5°51′20″	1	.6180	.6184	Mo. Absorption
206°57′00″	5°52′30″	1	.6199	.6197	Molybdenum Kγ
207°00′15″	5°55′45″	3	.2085	.2086	Tungsten Kα_1
207° 3′00″	5°58′30″	1	.6307	.6311	Molybdenum Kβ
207° 8′45″	6° 4′15″	3	.2135	.2134	Tungsten Kα_2
207°47′10″	6°42′40″	1	.7078	.7078	Molybdenum Kα_1
207°50′00″	6°45′30″	1	.7126	.7121	Molybdenum Kα_2

As indicated in table I, the wave-lengths of the X-rays corresponding to these various peaks agree very closely with the measured and recorded wave-lengths of the K series lines of tungsten and of molybdenum, so that the data furnish additional evidence of the general correctness of the theory that scattered radiation has, essentially, the same wave-lengths as the primary and that the wave-lengths of the fluorescent lines produced in a chemical element by primary X-rays are the same as those produced by the bombardment of electrons.

In addition to the peaks corresponding to the scattered and fluorescent radiation, several humps appear on the curve at A, B and C, respectively. These humps correspond to wave-lengths that agree very well with the wave-lengths of the tertiary radiation due to the bombardment of the atoms by the electrons emitted by the primary radiation. If we substitute in equation (2) for λ the wave-length of the α_1 line in the K series of tungsten, namely .2086, and for λ_2 the critical absorption wave-length in the K series of molybdenum, namely .6184, we find that the tertiary radiation due to the photo-electrons emitted by the tungsten α lines should have a short wave-length limit, equal to .315. Calculating from this the angle at which the corresponding rise in the curve should begin, we find that it ought to start at the point marked A in the figure. The hump beginning at this point, therefore, and lying to the right of it, represents tertiary radiation due to the electrons from the K level in molybdenum atoms that are ejected by the X-rays belonging to the primary α lines in the K series of tungsten. A similar calculation for the electrons emitted from the K levels of molybdenum by the tungsten β line rays shows that the hump corresponding to the tertiary radiation in this case should begin at the point marked B in the diagram. According to the above calculations, the point marked A should lie 1° to the right of the peak representing the α_1 line of tungsten, and the point marked B should lie 30′ to the right of the same peak. It must be remembered, however, that in estimating the positions of the points A and B, a certain correction has to be made for the angular breadth of the incident beam of X-rays. This correction amounts to half the breadth of a peak corresponding to a single line. What amounts to the same thing, however, is that the point A should lie 1° to the right of the point on the curve where the tungsten α_1 peak begins to rise, and the point marked B should lie 30′ to the right of the same point. Since the short wave-length limits of the two humps marked A and B actually fall so close to their theoretical positions, there can be no doubt but that the humps represent the tertiary radiation due to the electrons ejected from the K levels of the molybdenum atoms by the primary α and β radiation of tungsten.

There is evidence at the point C on the curve of some excess radiation. This may be interpreted as tertiary radiation due to the ejection of electrons from the L levels of the molybdenum atoms by the primary Kα X-rays. Calculation from formula (2) shows that the short wave-length limit of the tertiary radiation in this case should lie only about 5′ to the right of that of the primary rays falling on the plate. The breadth of a hump representing tertiary radiation, however, being much greater than the breadth of a peak representing a primary line, part of the tertiary radiation shows itself beyond and to the right of the α peaks.

Table I contains the numerical data in some detail. Column 1 contains the actual readings on the spectrometer scale of the various characteristics represented on the curve. Column 2 contains the angles of incidence, θ, corresponding to the readings in Column 1. Column 3 contains the order of the spectrum and column 4, the wave-lengths, expressed in ångströms, calculated from the ordinary Bragg equation. In computing the short wave-length limits of the tertiary radiation from tungsten α and tungsten β lines, the correction for the breadth of the incident beam has been made. Column 5 contains the wave-lengths of the tungsten and molybdenum K series lines that have been measured in our laboratory and, in addition, the short wave-length limits, λ_1, of the tertiary radiation due to the tungsten α and tungsten β lines, as calculated from equation (2). The data show a *very* close agreement between observed and previously recorded wave-lengths of tungsten and molybdenum K series lines and a good agreement (less than $^1/_2\%$) between the observed and calculated values of the wave-length limits of the tertiary spectra.

In this experiment the secondary beam emergent from the molybdenum radiator at an angle of 90° from the primary beam was analyzed. At angles of 45° and 135° the short wave-length limits of the tertiary radiation humps are found experimentally to have precisely the same angular displacements from the point where the tungsten α_1 peak begins to rise as at 90°. Depending upon such factors as filtration, however, the shapes and angular positions of the maxima of the humps differ greatly. The highest points on the humps move towards larger angles (and wave-lengths) with increase in the angle between primary and secondary beams. Comparative curves will be published later.

An experiment has been performed with silver as a secondary radiator similar to that above described for molybdenum. The curve representing the data shows (*a*) peaks corresponding to the tungsten line spectrum reflected in the first, second and third orders, respectively, of the scattered radiation, (*b*) other peaks representing the fluorescent K series lines of silver, and (*c*) broad humps corresponding to the tertiary radiation produced by the photo-electrons ejected from the silver atoms by the primary rays from the tungsten target. The peaks representing the β and γ lines in the fluorescent K series of silver lie between the second and third order spectra of the tungsten lines, and those corresponding to the α_1 and α_2 fluorescent lines of silver lie between the β and γ peaks and the α_1 and α_2 peaks in the third order spectrum of tungsten. In other words, the fluorescent K series silver lines have shorter wave-lengths than those of molybdenum. This, of course, was to be expected, for silver has a higher atomic number (47) than molybdenum (42). Further, the humps corre-