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XVII. *Penetrating Power of the X Radiation from a Coolidge Tube.* By Sir E. RUTHERFORD, F.R.S., Professor of Physics, University of Manchester*.

THE present paper contains an account of some experiments made to determine the maximum penetrating power of the X rays excited by high voltages in a Coolidge tube, using lead as the absorbing material. Owing to the lack of time at my disposal, the experiments, made a year ago, are incomplete; but they may prove of interest in indicating the penetrating power of the X radiation that can be obtained from this source under practicable conditions, and in throwing light indirectly on the probable frequency of the very penetrating gamma radiation from radioactive bodies.

In these experiments, the absorption of the X radiation by lead has been examined over a very much wider range of intensity and of thickness of absorber than in the original experiments of Rutherford, Barnes, and Richardson †.

To excite the radiation, a large induction-coil of 20-inch spark was used, actuated by a mercury motor-break in an atmosphere of coal-gas. The heating current through the tungsten spiral was adjusted to give a radiation of maximum intensity at the voltage required, which was fixed by an alternative spark-gap between points. The radiation was found to be most constant when a fairly rapid stream of sparks passed between the points during the measurements. The well-insulated Coolidge tube was placed inside a large lead box, and the X rays, issuing through a rectangular opening in

* Communicated by the Author.

† R.. B., and R., *Phil. Mag.* xxx. p. 339 (1915).

the box, passed into the measuring vessel which was placed close to the opening. The ionization current was measured by means of lead electroscopes of the self-contained type used for gamma rays. Three of these electroscopes, of cubical form, respectively 11 cm., 10 cm., and 12 cm. side, were employed in the course of the experiments. For determining the initial absorption, the lead face of the electroscope was cut away, and replaced by thin aluminium-foil. For greater thicknesses of absorber, a lead electroscope with sides 3 mm. thick was used; while for still greater thicknesses, a lead electroscope 8 mm. thick was used in some experiments. In order to avoid disturbances due to stray radiations, the windows of the electroscopes were of thick plate-glass, and still further protected by lead extensions. Such precautions are essential when, as in the present experiments, the intensity of the end radiation under measurement was in some cases less than one millionth of its initial value.

In order to make experiments over such a wide range, the heating current through the tungsten spiral was adjusted to give a convenient rate of leak in the electroscope in each experiment.

The voltage corresponding to the alternative spark-gap was determined by comparison with the sparking potential between two large brass spheres 20 cm. in diameter.

The absorbing lead plates, which were of much greater area than the face of the electroscope, were placed close to the electroscope. In such a case, the greater part of the radiation scattered in the absorber in a forward direction enters the electroscope. The average absorption coefficients μ for different thicknesses of the absorber were determined in the usual way. The results for different voltages are given in the following table:—

Max. Voltage.	Range of thickness in lead, mm.	Absorption Coefficient, μ cm. $^{-1}$	Mass Abs. Coef. μ/ρ .	Max. Voltage.	Range of thickness in lead, mm.	Absorption Coefficient, μ cm. $^{-1}$	Mass Abs. Coef. μ/ρ .
79,000	1.8—2.5	27	2.37	183,000	0.7—1.3	26	2.28
	2.5—3.1	26	2.28		1.3—2.0	24	2.11
92,000	1.8—2.5	25	2.19		2.4—4.0	20.5	1.80
	2.5—3.4	24	2.11		4.0—4.6	18	1.58
105,000	3.1—3.7	24	2.11	196,000	4.6—5.3	15	1.32
	2.7—3.3	23	2.02		5.3—6.4	13	1.14
	3.3—3.9	22	1.93		6.4—7.0	12	1.05
118,000	3.9—4.6	22	1.93		4.3—5.5	13	1.14
	2.7—3.3	22	1.93		5.5—6.4	12	1.05
144,000	3.3—3.9	22	1.93		6.4—7.8	11	.96
	2.7—3.3	22	1.93		7.8—9.2	10	.88
170,000	3.4—4.6	22	1.93		8.8—10.0	8.5	.75
	3.1—3.7	18	1.58				
	3.7—4.3	17	1.49				
	4.3—5.5	15	1.32				

It will be seen from the above table that the thickness of lead through which the radiation was measurable increased with the voltage applied. This is a result not only of the increase of the penetrating power of the radiation, but also of the large increase with voltage of the intensity of the radiation. With a voltage of 196,000, the radiation was detected and measured through 10 mm. of lead. In this case, the intensity of the radiation after passing through this thickness of lead was considerably less than one millionth of its initial value. No doubt by the use of still more powerful rays and more sensitive methods of measurement, the radiation could be detected through a still greater thickness. The maximum voltage applied (196,000 volts) was about the limit of capacity of the induction-coil under the working conditions. In addition, I should adjudge this voltage to be about the limit of safety for the bulb itself, so that no attempt was made to examine the penetrating power of the radiation for still higher voltages.

Certain interesting points arise in considering the results given in the table:—

(1) There is not much change in the value of μ for the end radiations between 79,000 and 144,000 volts, and no observable change in μ between 105,000 and 144,000 volts.

(2) Between 105,000 and 144,000 volts the radiation is absorbed nearly exponentially with a value of $\mu=22$. Above 144,000 volts the absorption is no longer exponential, but the value of μ decreases progressively with increase of thickness of absorber. This is best shown by the results for 183,000 volts, in which the value of μ decreases from 26 to 12 as the thickness of absorber is increased from .7 to 7.0 mm.

These results, which are at first sight peculiar and unexpected, can be very readily explained by taking into account the absorption of rays of different frequency by lead. In a recent paper*, Hull and Miss Rice have carefully examined the absorption coefficient of lead for X rays of different wave-lengths, obtained by reflexion from a rock-salt crystal. For wave-lengths greater than 0.149 Å.U., the absorption in lead obeys the law $\mu/\rho=430\lambda^3+0.12$, where λ is the wave-length in Ångström units and 0.12 is the assumed mass-scattering coefficient, σ/ρ . The value of μ/ρ suddenly increases for values of λ below 0.149 Å.U. owing to the presence of a characteristic absorption-band in lead. The presence of this sharp absorption-band has been shown also photographically by Hull and Miss Rice and by

* Hull and Miss Rice, *Phys. Rev.* viii. p. 326 (1916).

De Broglie. By plotting the logarithm of λ (fig. 1) against the logarithm μ/ρ for lead, Hull has shown that the curve is nearly a straight line AB. At B, where $\sigma = 0.149 \text{ \AA.U.}$, the absorption suddenly increases, shown by the nearly horizontal line BC. Assuming that the law of absorption after passing

Fig. 1.

through the absorption-band is similar to that observed before, the line CDE should represent the new portion of the curve. The circles represent values actually found by Hull and Miss Rice. Taking the quantum relation, $\lambda = 0.149 \text{ \AA.U.}$ corresponds to 83,000 volts, and the minimum corresponding value of μ/ρ for lead found by Hull was 1.50, *i. e.* $\mu = 17.5$. From the dotted portion of the curve the radiation emitted between $\lambda = 0.149 \text{ \AA.U.}$ and $\lambda = 0.098 \text{ \AA.U.}$, *i. e.* between 83,000 and 125,000 volts, should be more absorbed than that emitted for voltages slightly less than 83,000. We should thus expect the value of μ for the end radiation to be sensibly constant for the above range of voltages. Actually we find μ nearly constant between 92,000 and 144,000 volts. This difference is not important, and is to be anticipated from the nature of the measurements. A radiation more penetrating

than $\mu=22$ must be present in some quantity before its presence can be detected by absorption methods. The minimum value found by Hull, $\mu=17.5$, is somewhat less than the value, $\mu=22$, found in these experiments, but the difference is no doubt to be ascribed to the difficulties of accurate measurement of μ in both cases.

From the dotted portion of the curve, the minimum value of μ for lead at 196,000 volts ($\lambda=0.63$ Å.U.) should be about 5. The observed value is 8.5. Taking into account that the minimum value of μ for 196,000 volts must be somewhat less in any case than 8.5, and that the actual curve of absorption is probably somewhat steeper than the dotted portion of the curve, there is not a marked divergence between the observed and the calculated results. Taking these factors into consideration, the absorption measurements are not in themselves inconsistent with the view that the maximum frequency of the radiation from a Coolidge tube is given by the quantum relation, $E=h\nu$, over the range of voltage examined. Hull and others have already shown by crystal methods that this relation certainly holds up to 100,000 volts and probably up to 150,000 volts.

The peculiarities of the absorption by lead of X rays of different frequencies affords a simple explanation of the results obtained by Rutherford, Barnes, and Richardson*. In their experiments the absorption of the end rays by aluminium was found unchanged between 142,000 and 175,000 volts after the rays had passed through 2.49 mm. of lead as absorber. A reference to the table shows that under these conditions the issuing radiation consisted mainly of the characteristic radiation of lead with a value of $\mu=22$, and no observable change in the absorption by aluminium is to be expected under the experimental conditions.

Absorption by Aluminium.

A few isolated and approximate measurements were made of the absorption of the rays by aluminium under different conditions. In order to avoid complications due to the characteristic radiations of heavy elements like lead, the greater part of the radiation was first absorbed by its passage through an element of low atomic weight like iron. Under such conditions, the absorption results should not be seriously influenced for frequencies much higher than that of the K radiation of iron. The following results were

* *Loc. cit.*

obtained for the absorption by aluminium of the end radiation after passing through iron:—

Volts.	μ .	μ/ρ .
92,000	·38	·14
144,000	·30	·11
183,000	·23	·085

The corresponding values of μ were found to be higher if lead were used as initial absorber instead of iron.

The absorption was measured by placing the aluminium plates close to the electroscope between the latter and the iron plate. Under such conditions the greater part of the forward scattered radiation enters the electroscope, and consequently the absorption coefficient as measured is intermediate between μ and $\mu + \sigma$ (where μ is the true absorption coefficient and σ the scattering coefficient), and probably closer to the former. The value of μ as given by Hull and Miss Rice corresponds to $\mu + \sigma$ in the above notation.

In a recent paper, S. J. Allen and Alexander* have examined the absorption of X rays from a Coolidge tube when different metals are used as filters for the rays. With a tin filter, they found that the absorption coefficient in aluminium for the issuing rays was lower than for any other metal. The value, $\mu/\rho = 0.12$, for aluminium was observed with a steady voltage of about 120,000 volts; with an iron filter $\mu/\rho = 0.134$ under the same conditions. These numbers are in good agreement with those found by the writer.

Application to the wave-lengths of gamma rays.

The observations on the absorption of X rays in aluminium and lead throw important light on the difficult question of the probable wave-lengths of the penetrating gamma rays from radioactive substances. For convenience, the approximate results so far obtained are collected in the following table. The minimum wave-length is deduced from the voltage or *vice versa* on the assumption that the quantum relation, $E = h\nu$, holds.

The rows with an asterisk give values of μ/ρ obtained by Hull and Miss Rice (*loc. cit.*). In their case, the values of μ/ρ include the effect of scattering as well as absorption, and are consequently not strictly comparable with the values found by the author for aluminium, in which the correction for scattering is less important. The values of μ/ρ for the

* Allen and Alexander, Phys. Rev. ix. p. 198 (1917).

penetrating gamma rays from radium C are those given in a recent paper by Ishino *, where the coefficients of absorption and scattering were separately determined. The values of the mass-scattering coefficients, σ/ρ , for the gamma rays were found by him to be .045 for aluminium and .034 for lead—values much smaller than those previously found for ordinary X rays.

Voltages (volts).	Wave-length in Å.U. λ.	Mass Absorption Coefficient μ/ρ	
		in Aluminium.	in Lead.
*84,000	0.147	0.154	1.50
92,000	0.135	0.14	
*102,000	0.122		3.00
144,000	.086	0.11	
183,000	.068	.085	1.05
196,000	.063		0.75
Gamma rays from radium C	} ?	.026	.042

It will be observed from the table that the value of μ/ρ in aluminium decreases very slowly between 84,000 and 196,000 volts, even at a slower rate than the first power of the wave-length; while for longer waves it is well known that the value of μ varies approximately as the cube of the wave-length. As we should expect, the variation in μ/ρ with wave-length is much more rapid for lead than for aluminium over the same range. It will be noted that, while the value of μ/ρ for aluminium for X rays generated at 183,000 volts is only 3 times the value for the gamma rays, the corresponding ratio in the case of lead is more than 20. The general results suggest that when the value of μ/ρ becomes of the same order of magnitude as that of σ/ρ , the former coefficient varies slowly with the wave-length, the latter probably remaining constant. In addition, it appears not unlikely that there is a definite connexion between absorption and scattering, and that, for very short waves, the absorption like the scattering may ultimately reach a minimum value independent of wave-length. From some points of view such a connexion between these two quantities is not improbable, but unfortunately no waves of sufficiently short wave-length are available to test the relation experimentally.

The two shortest wave-lengths of the gamma rays observed

* Ishino, Phil. Mag. xxxiii. p. 129, January 1917.

in the experiments of Rutherford and Andrade* were $\cdot072$ and $\cdot099$ Å.U., corresponding on the quantum relation to waves excited by 174,000 and 125,000 volts. The values of μ/ρ for aluminium corresponding to X rays excited at these voltages are about $\cdot09$ and $\cdot12$ respectively, while the observed value of μ/ρ for the penetrating gamma rays from radium C is much less, viz. $\cdot026$. Since undoubtedly for such high frequencies, μ/ρ varies very slowly with frequency, it is clear that the wave-length of the more penetrating radiation is considerably smaller than that of the shortest waves observed by Rutherford and Andrade. In other words, the wave-length of the main gamma rays is much shorter than was previously supposed. This conclusion is still more strongly confirmed by the observations on the absorption of the radiation by lead. For a voltage of 196,000 volts, corresponding to a still shorter wave-length than the shortest observed by Rutherford and Andrade, the observed value of μ/ρ in lead was $0\cdot75$, while the value of μ/ρ found by Ishino for the penetrating gamma rays was $\cdot042$ —a ratio of nearly 20 times. Even allowing that the true value of μ/ρ for waves generated at 196,000 volts is somewhat smaller than the value observed, the largeness of the ratio shows that the gamma rays must be much shorter than those generated at 200,000 volts, *i. e.* much shorter than $\lambda = \cdot062$ Å.U.

In our present ignorance of the law of variation of μ/ρ with frequency in this region of the spectrum, it is only possible to estimate the actual wave-length of the most penetrating gamma rays. It is clear, however, that the waves are at least three times and may be ten times shorter than those which correspond to 200,000 volts, *i. e.* they correspond to waves generated by voltages between 600,000 and 2,000,000 volts, and thus lie between $\cdot02$ and $\cdot007$ Å.U. It is thus clear that the gamma rays from radium C consist mainly of waves of about $\frac{1}{100}$ the wave-length of the soft gamma rays from radium B, and are of considerably shorter wave-length than any so far observed in an X-ray tube, with the highest voltages at our disposal.

Another very interesting and important point arises from this discussion. It is well known that the β rays from radium B and radium C when examined in a magnetic field give a veritable spectrum of bright lines corresponding to definite groups of β rays, each group consisting of electrons expelled with a characteristic and definite velocity. The

* Rutherford and Andrade, *Phil. Mag.* xxviii. p. 263 (1914).

energy of motion of each of these groups of electrons have been measured by Rutherford and Robinson*, and the more intense groups (labelled with letters in the original paper) are given in the following table:—

β rays from Radium B.				β rays from Radium C.			
Group.	Intensity.	Energy $\div 10^{13}e$.	Voltage(volts).	Group.	Intensity.	Energy $\div 10^{13}e$.	Voltage(volts).
A	s.	3.332	333,200	A	m.f.	21.02	2,102,000
B	v.s.	2.610	261,000	B	m.f.	17.51	1,751,000
C	v.s.	2.039	203,900	C	m.	16.71	1,671,000
D	v.s.	1.519	151,900	D	m.	14.09	1,409,000
E	s.	.503	50,300	E	m.s.	13.28	1,328,000
F	v.s.	.376	37,600	F	m.	11.49	1,149,000
				G	m.s.	10.31	1,031,000
				H	m.s.	5.94	594,000
				K	s.	5.16	516,000
				L	m.	2.96	296,000
				M	m.	2.59	259,000
				N	m.	1.81	181,000

The column headed "voltage" gives the potential difference in volts between which the electron must move to acquire the observed energy.

Apart from the low-velocity groups L, M, N, the β rays from radium C consist mainly of groups lying between 500,000 and 2,000,000 volts. This is about the same range of voltage as we estimated to excite the penetrating gamma rays from consideration of the absorption of X rays and gamma rays by aluminium and lead. It would thus appear probable that the observed groups of β rays are due to the conversion of the energy, $E=h\nu$, of a wave of frequency ν into electronic form, and that consequently the energy of the β -ray groups may be utilized by the quantum relation to determine the wave-lengths of the penetrating gamma rays.

Such a conclusion is borne out by consideration of the groups of rays from radium B.

H. Richardson† has determined the absorption of these rays by lead, and concluded that they could be analysed approximately into three component groups for which the absorption coefficients, μ , in lead were 45, 6, and 1.5 cm^{-1} respectively. From the observations with a Coolidge tube, the value, $\mu=6$, should correspond to waves excited at about

* Rutherford and Robinson, *Phil. Mag.* xxvi. p. 717 (1913).

† Richardson, *Proc. Roy. Soc.* xci. p. 396.

200,000 volts, and it is to be noted in the table that three strong groups, B, C, and D, of β rays from radium B correspond to voltages between 261,000 and 152,000 volts, an average of about 200,000 volts. The value of $\mu=1.5$ may correspond to group A or a still swifter group, of voltage about 500,000 volts, observed in the spectrum of β rays excited in lead by the gamma rays from radium B and radium C together*.

The results as a whole suggest that the groups of β rays are due to the transformation of the gamma rays in *single* and not *multiple* quanta, according to the relation $E=h\nu$. The multiple relations observed between the energy of some of the groups of β rays† must on this view indicate approximate multiple relations between the frequencies of the gamma rays.

With the assistance of Mr. J. West, B.Sc., I have made some experiments to see whether it is possible to detect by the crystal method the presence of waves shorter than those observed in the experiments of Rutherford and Andrade (*loc. cit.*). A narrow pencil of gamma rays and strong sources were employed, but no certain evidence of the existence of such waves was obtained. This may be due either to the overlapping of the numerous lines that should be present, or to the failure of the crystal to resolve waves whose length is very small compared with the grating space.

If the single quantum relation should prove to hold generally for the conversion of γ rays into β rays, the magnetic spectrum of β rays should afford a reliable method of extending the investigation of X-ray spectra into the region of very short waves where the crystal method either breaks down or is practically ineffective, and thus places in our hands a new and powerful method of analysing waves of the highest obtainable frequency. The complexity of the β -ray spectrum for radium B and radium C indicates that the spectrum of the gamma rays, and presumably the very high-frequency spectra of heavy elements in general, are as complicated as the ordinary light spectra of such elements.

University of Manchester.
May 12, 1917.

* Rutherford, Robinson, and Rawlinson, *Phil. Mag.* xxviii. p. 285 (1914).

† Rutherford, *Phil. Mag.* xxviii. p. 305 (1914)