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Measurements on X-Ray Production and Absorption in the Range 0.7 to 2.5 Mv

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In the voltage range from 0.7 to 2.5 Mv, the intensity and the total mass absorption coefficient of the heterogeneous radiation produced in a thick gold target have been measured as a function of tube voltage, angle with respect to the electron beam, and thickness and material of the filter. Curves giving the dependence of absorption coefficient on voltage are presented for lead, tin, copper, aluminum, carbon, and water as absorbers. A method is described for calculating the absorption coefficient of the heterogeneous radiation produced at a given tube voltage and subjected to a given amount of filtration, utilizing accepted values for the absorption coefficient of homogeneous radiation. Measured and calculated values of the absorption coefficients for heterogeneous radiation are in good agreement. Curves giving the dependence of intensity on angle are in qualitative agreement with approximate theory. Curves giving the dependence of absorption coefficient on angle and the dependence of intensity in the forward direction on voltage are presented. A method for calculating the efficiency of x-ray production from these data is described and used to obtain results in satisfactory agreement with theory in the voltage range from 0.90 to 2.35 Mv.

I. INTRODUCTION

THIS research is concerned with the intensity and quality of the continuous radiation produced at a thick target of high atomic number by bombardment with high energy electrons, and with the absorption of this radiation by various materials.[1] Such information has application in high voltage x-ray research and therapy, and makes possible a limited comparison with existing theory.

Most previous precision measurements of absorption coefficients have been made with *homogeneous* radiation either at low voltage where homogeneous x-rays are obtainable by crystal reflection, or at high voltage as the homogeneous gamma-rays from radioactive materials. Such measurements have been made in various materials[2] up to 0.5 Mv with a probable error of one percent, up to 2.5 Mv with a probable error[3] of four percent, and in a few elements at isolated higher voltages[4] with less accuracy. Experiment and theory concerning the absorption of homogeneous radiation are in satisfactory agreement throughout the voltage range involved.

Measurements of the intensity and quality of the *heterogeneous* radiation produced at a thick target have been made up to 0.5 Mv, and to a limited extent up to 1.0 Mv. In the low voltage

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[1] Rough preliminary results were presented earlier: L. C. Van Atta and D. L. Northrup, Am. J. Roent. and Rad. Therapy **51**, 633 (1939); present authors, Phys. Rev. **59**, 688A (1941).
[2] J. Read and C. C. Lauritsen, Phys. Rev. **45**, 433 (1934).
[3] C. Y. Chao, Phys. Rev. **36**, 1519 (1930); G. T. P. Tarrant, Proc. Roy. Soc. **128A**, 345 (1930).
[4] L. A. Delsasso, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **51**, 391 (1937).

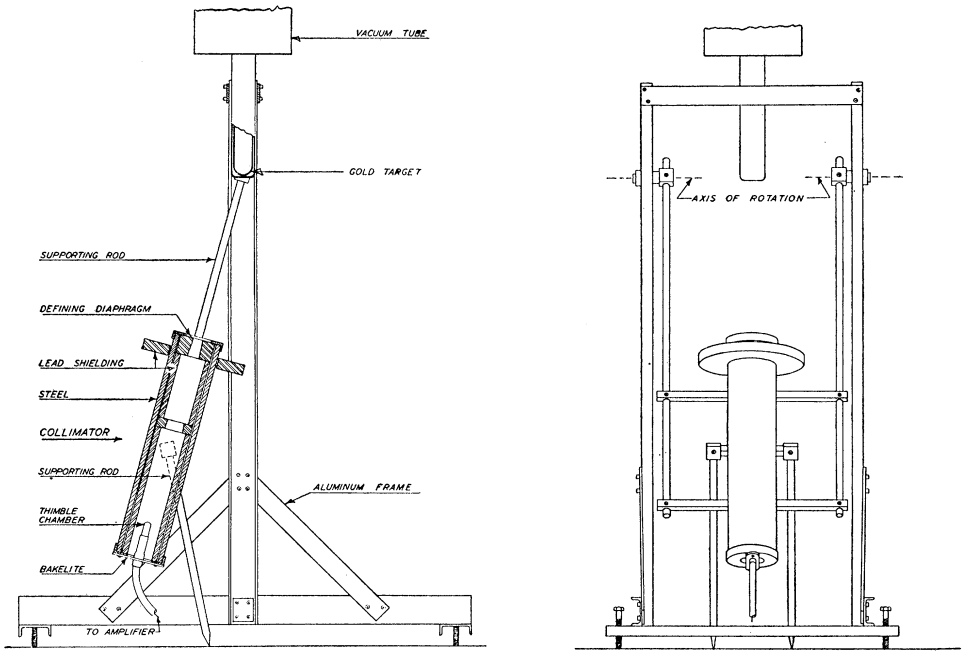

FIG. 1. General view of the x-ray target, collimator, and thimble chamber, and the structural frame supporting the collimator.

range the efficiency of production of x-rays, the angular distribution of the radiation from thin targets, and the absorption coefficients in various materials have been measured with considerable precision. In the region between 0.5 and 1.0 Mv, where characteristic radiation no longer plays an important part, much remains to be done. The variation of the intensity of heavily-filtered radiation with angle has been determined at 0.5 Mv.[5] The dependence of intensity on thickness in various absorbers has been measured for the heterogeneous radiation produced at voltages up to 1.0 Mv.[6]

II. APPARATUS

The general scheme is to make intensity measurements in a severely collimated x-ray beam with an air-equivalent thimble chamber. The collimation serves to define the angle with respect to the direction of the original electron beam, to exclude x-rays scattered in the absorber, and to exclude the background of x-rays scattered from various parts of the room. By varying the direction of the axis of the collimator with the x-ray target as a center, the intensity or the absorption coefficient of the radiation can be measured as a function of angle. Figure 1 shows the x-ray target, the collimator, the thimble chamber, and the aluminum structural frame which supports the collimator.

The collimator was subjected to two performance tests. Absorption measurements in lead for thicknesses up to 10 cm were made with 2.5- and 1.3-cm diameter defining diaphragms. The resulting curves (I/I_0 *versus* absorber thickness) were identical, showing that the 2.5-cm diameter diaphragm provided sufficient collimation. As the thickness of lead absorber was further increased to 15 cm the x-ray intensity at the thimble chamber continued to decrease exponentially, which indicated that the background radiation inside the collimator was negligible.

The thimble chamber was adopted for the measurement of x-ray intensity on the basis of considerable previous experimental[7] and theo-

[5] K. E. Corrigan and B. Cassen, Am. J. Roent. and Rad. Therapy **37**, 811 (1937).

[6] R. Phillips and G. S. Innes, Brit. J. Radiol. **11**, 498 (1938); J. C. Hudson, Radiol. **32**, 530 (1939). Also Folsom, Stone, Rose, Bouwers, and Hermann and Jaeger.

[7] O. Glasser and L. Rovner, Am. J. Roent. and Rad. Therapy **36**, 94 (1936); L. S. Taylor, G. Singer, and A. L. Charlton, Am. J. Roent. and Rad. Therapy **41**, 256 (1939); and others.

retical[8,9] work. This work has shown that the thimble chamber is the only practicable method for measuring radiation above 0.4 Mv, that measurements made by different observers with chambers of different geometries and different "air-equivalent" wall materials are accurately comparable, and that the corrections for wall effect necessary to reduce reading to roentgens, according to the accepted definition, are small and calculable.[8] An "air-equivalent" wall material is one in which the x-ray beam has the same equilibrium complement of electrons as it has in air. Theoretically the wall thickness should be at least as great as the range of secondary electrons in the material[9] if the chamber is to be used in a collimated beam, but experimentally the wall thickness can be somewhat less than this. In the case of carbon which is the element most nearly air-equivalent, the correction factor to obtain equivalent roentgens from the actual readings is 1.023 in the case of gamma-rays from radium in equilibrium with its decay products, and is 1.027 in the case of the total radiation at 0.6 Mv. Thus the x-ray intensity measured by a carbon-wall thimble chamber in the energy region from 0.6 to 2.5 Mv may be written $r=1.025(I/V)$ roentgens per min. where I=ionization current (stat-coulombs per min.) and V=volume of chamber (cc).

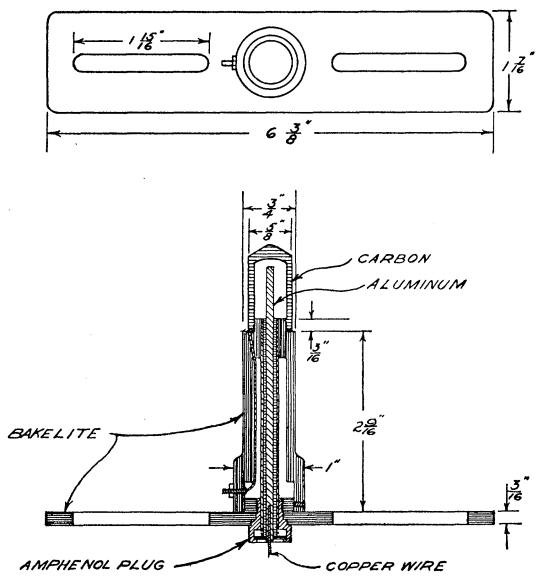

FIG. 2. Detailed view of the carbon-walled thimble chamber with its mounting strap.

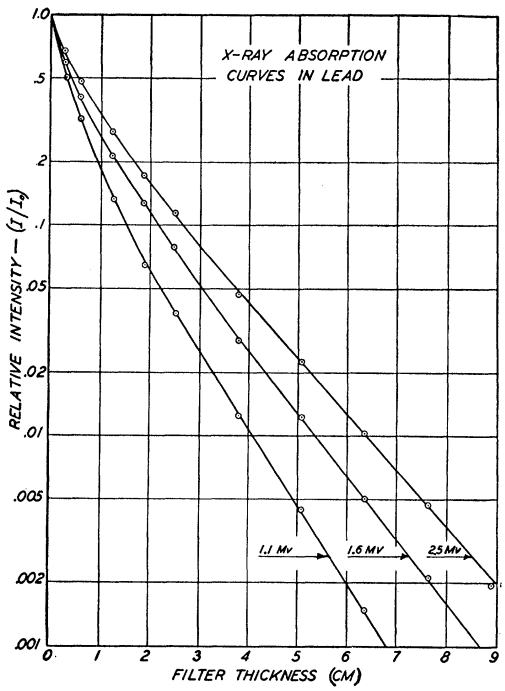

FIG. 3. Absorption curves in lead for the radiation produced at various voltages.

The thimble chamber used in these experiments is shown in cross section in Fig. 2, with a mounting strap for fastening the chamber to the lower end of the collimator. The volume of the chamber is 1.94 cc and the wall thickness is 2.4 mm on the sides. High voltage is applied to the carbon thimble by means of a wire leading to the side binding post. Ionization current is collected on the central aluminum wire and conducted to an amplifier. An aluminum tube connecting to the cable shield acts as a guard ring to reduce the effective leakage current. Saturation voltage for high x-ray intensities proved to be 270 v. This thimble chamber was subjected to several performance tests which proved it to be entirely satisfactory for the measurements involved.

The ionization produced in the carbon thimble chamber was measured with a current amplifier rather than by a condenser discharge method, in order to have a continuous reading of x-ray intensity and to avoid the necessity of maintaining constant conditions. The sensitivity ratios for the various ranges were measured with a constant

[8] G. C. Laurence, Can. J. Research **15A**, 67 (1937).
[9] L. H. Gray, Proc. Roy. Soc. **156A**, 578 (1936).

x-ray beam under actual conditions of use and were found to agree within the accuracy of reading with the ratios calculated from the input resistor values.

The construction of the target is indicated in Fig. 1. It is evident that much greater absorption must be expected in the neighborhood of 90° and that this effect must be considered in connection with angular distribution curves. Gold was chosen as the target material because it is the element of largest atomic number practicable for such use. The thickness used was required both for strength and for stopping the high speed electrons. An earlier target[1] of lead electroplated onto copper was not satisfactory because of a tendency of the lead to evaporate away from the target spot.

For the absorption coefficient measurements the absorber consisted of disks of the pure material 10 cm in diameter and each of such thickness as to reduce the intensity by 30 to 50 percent. In the case of water, distilled water of known temperature was used in a 15-cm diameter glass cylinder. The total thickness of absorber, in addition to a lead pre-filter, varied from 10 cm in the case of lead to 30 cm in the case of water.

III. MEASUREMENT OF ABSORPTION COEFFICIENTS

For the measurement of absorption coefficients, thimble chamber intensity readings in the collimated beam were taken as a function of thickness of absorber placed above the defining diaphragm. Comparable relative intensity readings were obtained by dividing each intensity reading by the corresponding electron current, averaging the results obtained with increasing and decreasing filter thickness, and dividing successive intensity values by the initial value. When such relative intensity (I/I_0) values are plotted against filter thickness on semi-logarithmic paper, the slope of the resulting curve provides a measure of the total mass absorption coefficient, $\mu_m = \ln (I_0/I)/\rho x$. Curvature in the initial part of these curves is an indication of a decreasing absorption coefficient because of the selective absorption of the softer components in the heterogeneous radiation. After sufficient filter has been used the wave-length distribution of the radiation in the beam becomes so narrow that the corresponding absorption coefficient is approximately constant. The resulting straight line portion of the logarithmic curve permits an accurate determination of the final constant value of absorption coefficient.

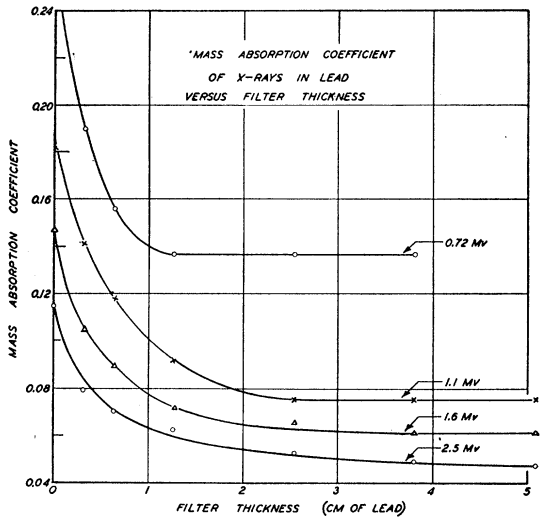

FIG. 4. Mass absorption coefficient in lead *versus* filter thickness for the radiation produced at various voltages.

Typical absorption curves are shown in Fig. 3, which gives the absorption in lead of the radiation produced at various voltages. It appears that the absorber thickness necessary for establishing the equilibrium condition increases with voltage, but that the final slope is constant over a wide range of absorption. This is more evident in Fig. 4, in which the mass absorption coefficient obtained from the slope of the logarithmic curves is plotted against filter thickness for the radiation produced at several voltages. From Fig. 4 we see that the initial absorption coefficient at each voltage is somewhat more than twice the final absorption coefficient and that the filter thickness necessary for obtaining the equilibrium condition is roughly proportional to the voltage.

In Fig. 5 is given the variation with voltage of the final value of absorption coefficient for several absorbing materials. The curves are drawn through the experimental points without regard to theory. In the case of absorbers other than lead a sufficient thickness of lead pre-filter was used to establish approximately the equilibrium condition.

The data presented in Fig. 5 represent the summary of approximately 1600 intensity readings on 83 absorption curves. For each absorption

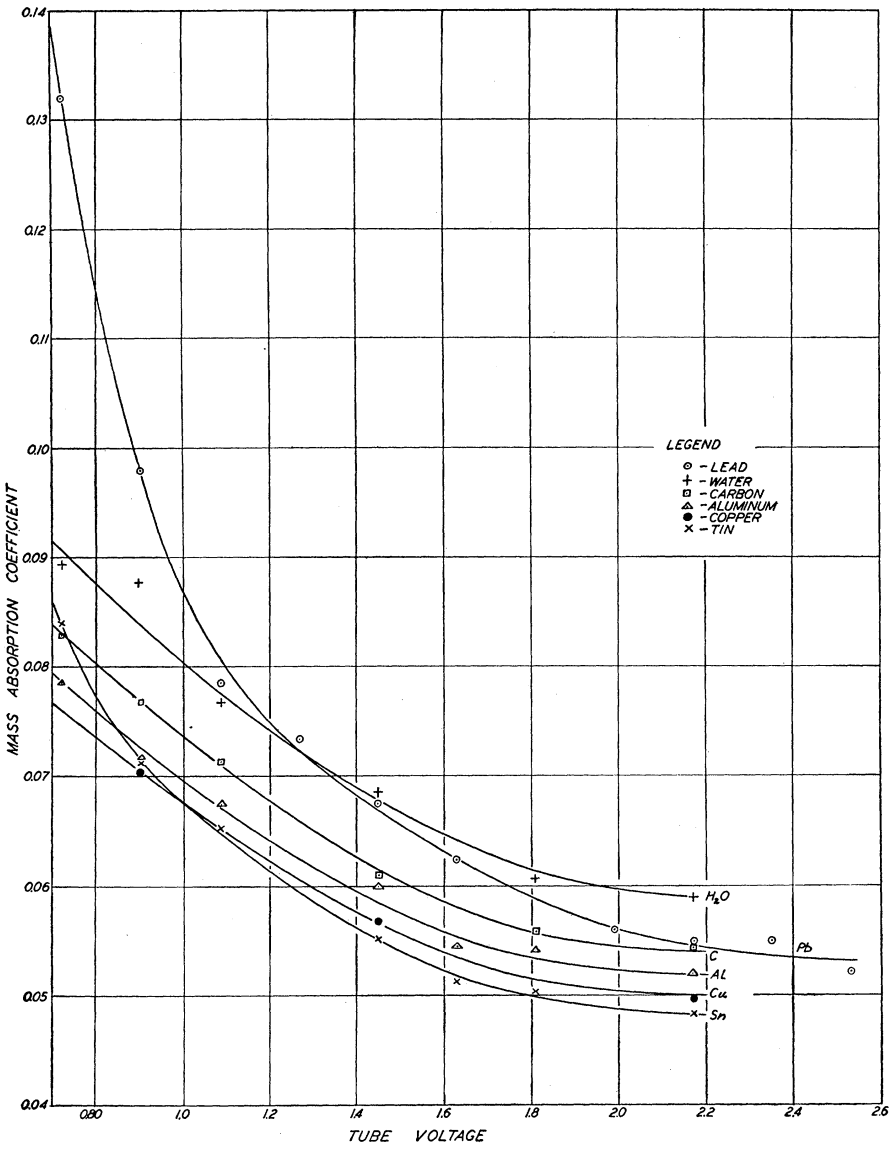

FIG. 5. Experimental values for the mass absorption coefficient in several materials of heavily filtered heterogeneous radiation plotted as a function of the tube voltage.

curve an estimated probable error in the slope can be obtained by considering the spread in the curves which might reasonably be used to represent the points. Such estimated probable errors for individual curves (i.e., for individual determinations of absorption coefficient) ranged from 0.3 percent to 4 percent with an average value of 1.2 percent.

It is evident from Fig. 5 that in four of the curves (H_2O, C, Al, and Cu) the same type of absorption is present, whereas in two of the curves (Pb and Sn) there is an additional absorption which becomes important at low voltage. In the higher part of the voltage range the order of increasing mass absorption coefficients (excepting Pb) is Sn, Cu, Al, C, and H_2O. These results are in agreement with theory in which the total absorption of energy from the x-ray beam is considered to be due to true absorption and scattering by free electrons (Compton absorption and

scattering),[10] absorption by bound electrons (photoelectric absorption),[11] and absorption due to the production of positron-electron pairs (pair production).[12]

Photoelectric absorption and pair production are appreciable in this voltage range only for lead and tin. Photoelectric absorption explains the steeper rise in the lead and tin curves of Fig. 5 at the low voltage end, and is appreciable throughout the entire voltage range in the case of lead.

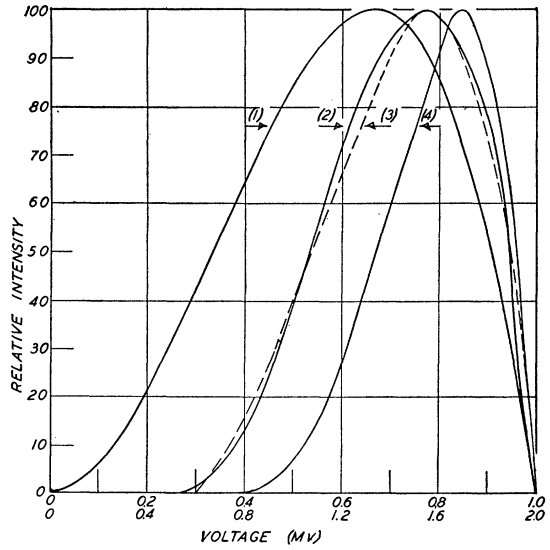

FIG. 6. Distribution in voltage of unfiltered (1) and filtered (2, 3, 4) radiation assuming Kramers' law and accepted values for lead absorption coefficients.

With the exception of lead, the absorption coefficient in the middle part of the voltage range is almost entirely due to Compton effect and therefore should be proportional to the number of electrons per gram of absorber, as is found experimentally to be the case. At the high voltage end, pair production[13] is responsible for about 12 percent of the absorption in lead and 7 percent in tin.

It appears therefore that the measured absorption coefficients for heterogeneous radiation are in general qualitative agreement with accepted theory for homogeneous radiation. In order to make a quantitative comparison, it is necessary to know the distribution in wavelength of the heterogeneous radiation. Kramers' theory[14] yields the relation

$$I_V = \text{constant} \cdot V^2(V_0 - V)$$

where V_0 = tube voltage. This relation was used to obtain curve (1) in Fig. 6 for the distribution in voltage of the unfiltered radiation produced either at 1.0 or 2.0 Mv. The change in the shape of this curve as the result of lead filtration can be calculated by using accepted values for the absorption coefficient of homogeneous radiation in lead at the different voltages. Curves (2) and (3) were obtained by assuming the thicknesses of lead pre-filter actually used at 1.0 and 2.0 Mv, respectively, in measuring the absorption coefficients of other materials. From these curves it appears that the distribution of the radiation after pre-filtering was very similar in the two cases. Curve (4) gives the distribution of the radiation produced at 2.0 Mv and filtered through 11.5 cm of lead. From curves (1), (3), and (4), together with accepted values for the absorption coefficient of homogeneous radiation in a given material, it is possible to calculate the absorption coefficient in that material of the heterogeneous radiation produced at 2.0 Mv and filtered through 0, 3.8, and 11.5 cm of lead. The results of these calculations for lead and aluminum absorbers are compared with the experimental values in Table I.

These calculations show the same effect of lead filter on heterogeneous radiation as was observed experimentally, i.e., that the initial high absorption coefficient *in lead* is reduced to roughly half-value and then becomes approximately constant

TABLE I. Calculated and measured values for the mass absorption coefficient in lead and aluminum of the heterogeneous radiation produced at 2.0 Mv after various amounts of lead filter.

Thickness of lead filter (cm)	Mass absorption coefficient (cm^2/g) Lead		Aluminum	
	Calculated	Measured	Calculated	Measured
0	0.090		0.059	
3.8	0.054	0.056	0.052	0.052
11.5	0.050		0.048	

[10] O. Klein and Y. Nishina, Zeits. f. Physik **52**, 853 (1929).

[11] H. R. Hulme, J. McDougall, R. A. Buckingham, and R. H. Fowler, Proc. Roy. Soc. **146A**, 83 (1934). M. T. Jones, Phys. Rev. **50**, 110 (1936).

[12] H. Bethe and W. Heitler, Proc. Roy. Soc. **146A**, 83 (1934).

[13] For the calculation of absorption by pair production, we are indebted to Dr. R. D. Evans, "Introduction to the Atomic Nucleus," M.I.T. course notes.

[14] H. A. Kramers, Phil. Mag. **46**, 863 (1923).

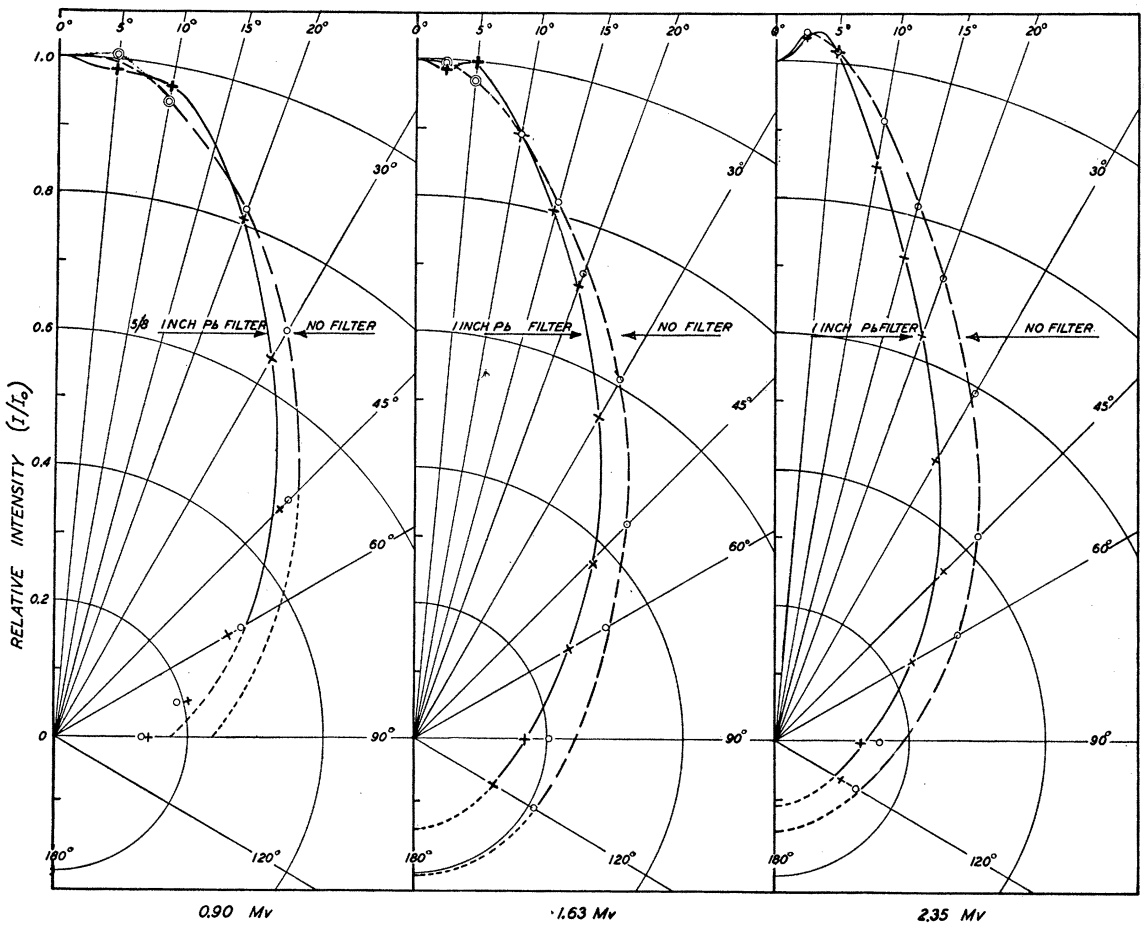

FIG. 7. Variation of intensity with angle for the unfiltered and filtered radiation at three values of tube voltage.

as the filter thickness is further increased. The absorption coefficient at small filter thicknesses could not be determined accurately because it changed so rapidly with added absorber. There was not sufficient intensity left after 11.5 cm of lead filter to permit an accurate measurement of the absorption coefficient of the resulting radiation. However, for lead thicknesses between 3.8 cm and 11.5 cm no appreciable change in absorption coefficient was observed. The calculated and measured values for both lead and aluminum absorbers after 3.8 cm of lead filter are in very satisfactory agreement. This agreement tends to confirm the values for the absorption coefficient of homogeneous radiation and to indicate that the distribution function given by Kramers' theory represents a reasonable approximation in spite of its theoretical limitations. Furthermore it tends to justify the method outlined above for calculating the absorption coefficient of the heterogeneous radiation in a severely collimated beam of x-rays produced at a given tube voltage and subjected to a given amount of filtration.

IV. MEASUREMENT OF ANGULAR DISTRIBUTION

To measure the x-ray intensity as a function of angle with respect to the forward direction of the electron beam, the collimator was pivoted in its support to swing about the x-ray target as a center. The thimble chamber in the collimated beam then provides an approximately true measure of the intensity as a function of angle. Having the collimated beam also permits insertion of absorbing material into the beam to obtain a measure of the quality of the radiation as a function of angle.

With the tube voltage held constant the collimator was set at various angles, and the intensity and electron current were recorded. The intensity readings were divided by the corresponding electron currents and by the specific intensity in the forward direction to obtain comparable relative intensity readings. This procedure was followed with no filter and with a heavy lead filter for three values of tube voltage.

The results of the angular intensity measure-

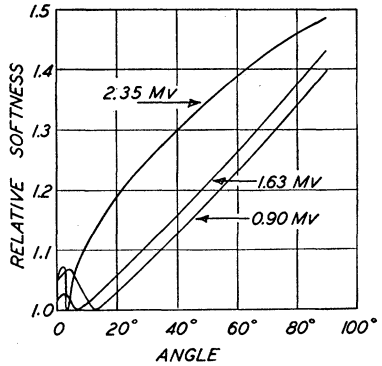

FIG. 8. Relative softness of the radiation produced at several voltages as a function of angle, where relative softness is defined as the ratio of unfiltered to filtered intensity.

ments are presented in Fig. 7. These curves show the strong predominance of the radiation in the forward direction. The intensity ratio between 0° and 90° varies from 4.2 for the unfiltered radiation at 0.90 Mv to 7.3 for the filtered radiation at 2.35 Mv. No attempt was made to pass these curves through the 90° experimental points because of the excessive absorption introduced by the target in that direction.

In Fig. 7, the unfiltered and filtered relative intensity values are compared for three values of tube voltage. This comparison shows that the radiation is considerably softer at larger angles. The softening of the unfiltered radiation with increasing angle is an effect which increases with voltage, as is shown by Fig. 8 in which the ratio of unfiltered to filtered relative intensities is plotted against angle for three values of tube voltage. The ratios have been adjusted to unity at the angle of hardest radiation, rather than at 0°. These curves of an arbitrarily defined quantity are presented primarily because of the way in which they emphasize the angle of maximum hardness of the radiation.

A detailed examination of the curves of Fig. 7 at small angles reveals an interesting fine structure. There is a maximum in the curves which becomes more pronounced and which moves in to smaller angles as the voltage is increased. This effect is so small at 0.90 and 1.63 Mv that the small angle points on these curves were taken with great care. The additional maximum at 0° on the 0.90- and 1.63-Mv curves can be obtained by combining two slightly overlapping angular distribution patterns of conventional shape, and is therefore assumed to be of no especial theoretical interest.

The angular positions of the intensity maximum at the several voltages are given in Table II with an estimated probable error of 0.5°. Examination of the curves shows that the maximum moves in to smaller angles as the voltage is increased, but for a given voltage the harder components of the radiation have their maxima at larger angles. If these curves are thought of as the combination of two slightly overlapping angular distribution patterns on opposite sides of the axis, resolving the lobes would increase appreciably the angle of the maximum.

The dependence of x-ray quality on angle for the heavily filtered radiation from a thick target was obtained by measuring the final value of the mass absorption coefficient in lead at a number of angles with a fixed tube voltage. The depend-

TABLE II. Angular position of the intensity maximum at several tube voltages.

Voltage	Positions of the intensity maximum			Positions of hardness maximum (Fig. 8)
	Unfiltered radiation	Filtered radiation	Sommerfeld theory	
0.90		9.0°	13°	13°
1.63	3.8°	4.5°	8°	7°
2.35	2.8°	3.3°	6°	3.7°

ence on angle of this absorption coefficient is given in Fig. 9 for the radiation produced at 1.09 and at 1.63 Mv. A pronounced dip in the curves at about 7° is followed by a regular rise as the angle is further increased. These curves illustrate the advantage of working in the forward direction rather than at 90° when penetrating radiation is required, and the additional advantage of working at a small angle from the forward direction if a small portal is used.

There is no available theory strictly applicable to the problem of calculating the angular distribution of the radiation produced in a thick target of high atomic number at high voltage. This is not surprising in view of the extreme difficulties imposed by these conditions. Sommerfeld's classical theory[15] is relativistic but assumes a thin target and complete stopping of the electron without change in direction. His wave mechanical theory[16] is non-relativistic and therefore not applicable. Later theories[12,17] are too complicated to justify calculation in that they are approximations for elements as heavy as gold. In spite of its limitations, therefore, Sommerfeld's classical theory has been used to calculate the positions of the intensity maximum in the angular distribution curves (last column, Table II). Actually the angular position of the hardest radiation (minimum in Fig. 8) is in better agreement with Sommerfeld's predicted angle than is the position of the intensity maximum. In general, theory predicts that the maximum will move toward smaller angles and will become more pronounced as the voltage is increased, but that for a given voltage the harder components of the radiation will have their maxima at larger angles. In these respects theory and experiment are in qualitative agreement.

V. EFFICIENCY OF X-RAY PRODUCTION

In all the measurements described previously the results have not depended on the absolute calibration of the thimble chamber, and not sensitively upon the variation of this calibration with x-ray quality. The results presented in Fig. 10, however, depend on the carbon thimble chamber for the absolute measurement of intensity in r-units. The x-ray intensity in the forward direction is plotted on double logarithmic paper as a function of voltage for the unfiltered radiation (except for the 2.3-mm lead equivalent thickness introduced by the target) and for radiation filtered through 2.5 cm of lead. The unfiltered radiation increases approximately as the third power of the tube voltage. The filtered radiation shows a more uniform increase as the 4.7 power of the voltage. This emphasizes the importance of having high voltage for producing radiation which is to be used through considerable absorbing material.

From a consideration of the x-ray intensity available at high voltage and the low value of the absorption coefficient after moderate filtration, it is evident that radiographical examination of very thick specimens, such as heavy steel castings, becomes feasible. If the target-to-specimen distance is made large, sufficient pre-filter is used, and stray radiation is carefully eliminated, good resolution should be obtained for thickness as great as 12 in. of steel.

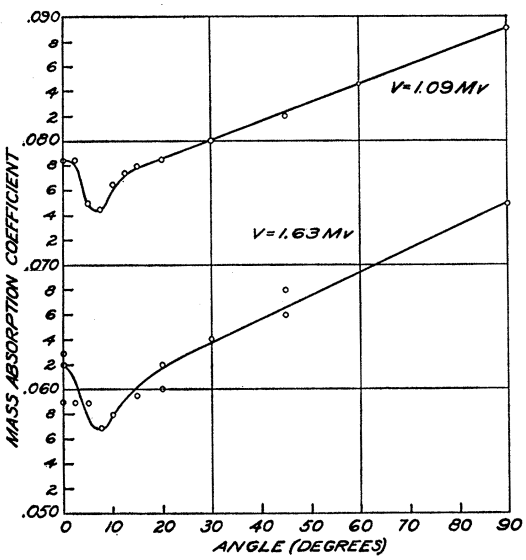

FIG. 9. Dependence on angle of the final value of the mass absorption coefficient in lead for the radiation produced at 1.09 and 1.63 Mv.

The efficiency of x-ray production may be defined as the ratio of the power radiated from the target as x-rays to the power received at the target as the result of electron bombardment. The power radiated as x-rays at a given tube voltage and beam current can be determined from a knowledge of the x-ray intensity (in roentgens) in all directions from the target, provided that the proper correction be made for true absorption in the target.

The rate at which energy passes through unit area at a distance r from the target and at an angle θ with respect to the forward direction of the beam is given in terms of the reading of an

[15] A. Sommerfeld, Physik. Zeits. **10**, 969 (1919).
[16] A. Sommerfeld, Ann. d. Physik **11**, 257 (1931).
[17] W. Heitler and F. Sauter, Nature **132**, 892 (1933); F. Sauter, Ann. d. Physik **20**, 404 (1934).

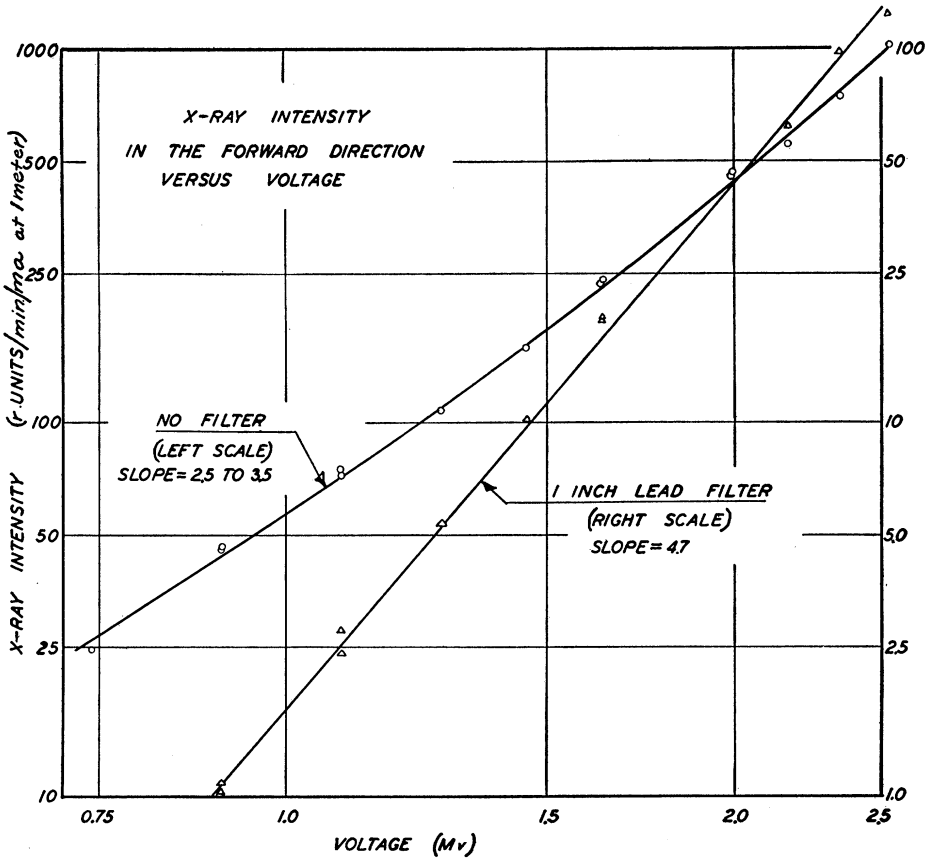

FIG. 10. Dependence of absolute intensity in the forward direction on voltage for unfiltered and filtered radiation.

air-wall thimble chamber at that point by

$$P_{r,\theta}=\int_r^\infty Idr=I_{r,\theta}/\mu \text{ roentgen cm/min.}$$

where μ is the linear coefficient for true absorption in air of the heterogeneous radiation incident upon the thimble chamber. If we accept a value of 45.5 ev per ion pair as the energy required for x-ray ionization in air,[19] we may write this expression in terms of a more conventional unit for radiation density

$$P_{r,\theta}=2.53\times10^{-10}I_{r,\theta}/\mu \text{ watt/cm}^2.$$

The total rate at which energy passes through a sphere of radius r is

$$P_r=1.59\times10^{-9}r^2\int_0^\pi (I_{r,\theta}/\mu)\sin\theta d\theta \text{ watt.}$$

If we introduce I_f, the x-ray intensity in the

TABLE III. Efficiency of x-ray production: a comparison of experiment with theory.

Voltage (Mv)	Experiment $I_f \int I_\theta \sin\theta d\theta$		μ	Target Correction Factor	η	Theory η
2.35	750	0.52	3.08×10^{-5}	1.22	10.4%	8.3%
1.63	240	0.61	3.30×10^{-5}	1.35	5.8	5.6
0.90	44	0.68	3.48×10^{-5}	2.00	3.0	3.4

[19] The generally accepted value of 32 ev per ion pair is apparently based on H. Geiger's early value of 33 ev obtained from alpha-particle ionization experiments (Proc. Roy. Soc. **82A**, 486 (1909)). The value of 45.5±1.0 ev obtained from the excellent work of J. F. Lehmann and T. H. Osgood on ionization in air by electrons in the energy range 200 to 1000 ev (Proc. Roy. Soc. **115A**, 609 (1927)) more properly applies to the case of x-ray ionization. We are indebted to Dr. M. S. Livingston, who brought these references to our attention as well as his own confirming calculation based on ionization by radium gamma-rays.

forward direction expressed in roentgens per min. and milliampere at one meter from the target and I_θ, the intensity at angle θ relative to that in the forward direction, and if we recognize the fact that the coefficient for true absorption in air does not depend appreciably on angle, we may write

$$P_1=1.59\times10^{-5}(I_f/\mu)\int_0^\pi I_\theta \sin\theta d\theta \text{ watt/ma.}$$

Then the efficiency of x-ray production is

$$\eta=1.59(I_f/\mu V)\int_0^\pi I_\theta \sin\theta d\theta \text{ percent}$$

where V is the tube drop in volts.

Experimental data already presented make it possible to calculate the efficiency at three voltages: 2.35, 1.63, and 0.90 Mv. Values of I_f are obtained from Fig. 10 and values of the integral are calculated from the dashed curves of Fig. 7. The values of μ, the linear coefficient for true absorption in air of the heterogeneous radiation incident upon the thimble chamber, were calculated as weighted averages from the corresponding coefficients for homogeneous radiation. From curves similar to those shown in Fig. 6 it is possible to obtain directly factors to correct for true absorption of x-ray power in the target. The ratio of the area under the Kramers' distribution to that under the reduced distribution gives the factor by which the power has been reduced in passage through the target. The correction is not serious except at the lowest voltage. Values of I_f, the integral, μ, the correction factor, and η are presented in Table III.

The theoretical values for the efficiency given in the last column were computed from curves calculated from Bethe and Heitler's theory by Arcimovic and Chramov.[20] In view of limitations in the theory when applied to targets of high atomic number, the agreement between theory and experiment throughout this voltage range may be considered quite satisfactory.

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[20] L. A. Arcimovic and V. A. Chramov, Comptes Rendus Acad. Sci. U.S.S.R., **18**, 415 (1938).

Errata: Quantization of Molecules, Inter- and Intramolecular Forces

[Phys. Rev. **63**, 309 (1943)]

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THE sentence on page 310, left column, lines 8–6 from the bottom should read: "In Fig. 1A, two Li^+ cores are placed at the internuclear distance 0.74A of H_2 ($n=$I)."

On page 311, left column, line 7 from the bottom should have $n=3$ instead of $n=$III.

Erratum: The Carbon Arc in Oxygen for the Spectrochemical Determination of Potassium

[Phys. Rev. **63**, 322 (1943)]

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THE last paragraph, beginning line 8 from the bottom, should read: "To the cathode is added 0.01 ml of serum, which amount in the human normally contains 33.0 gamma (micrograms) Na, 2.0 gamma K, 1.0 gamma Ca, 0.27 gamma Mg, and 1.3 gamma P. Also, 2.5 gamma Rb is added as the internal standard for K and 100 gamma Cd as the internal standard for all the other elements. The spectrum lines measured are Na 2680.3A, K 4044.1A, Ca 3006.9A, Mg 2783.0A, P 2535.6A, Rb 4201.8A, and Cd 2677.6A."