Absolute K-Ionization Cross Section of the Nickel Atom under Electron Bombardment at 70 kv

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Nickel sheets approximately 5×10^{-6} cm in thickness were bombarded with 70 kv electrons and the intensity of the resulting $K\alpha$ radiation was measured by a special air-filled ionization chamber connected to a calibrated quadrant electrometer. Isolation of the $K\alpha$ line was effected by Ross filters of cobalt and iron, supplemented by additional filters for evaluation of a correction for the continuous background radiation. After due consideration of the effects of electron scattering in the target and all relevant x-ray absorptions, it was concluded from the observed intensities that the cross section of the nickel atom for K ionization by 70 kv electrons is $(3.38\pm0.2)\times10^{-22}$ cm^2. From this result and Williams' equation for electron energy loss it is deduced that the efficiency of production of nickel K-radiation by electrons of 70 kev energy is 0.35 percent.

INTRODUCTION

When atoms are bombarded by electrons with energies in excess of the atomic K-ionization energy, there is a small but finite probability of K ionization. Observations[1] have told us something of the manner in which this probability varies with electron energy, but for only a few elements as targets. Theory[2] also has had something to say on this variation and, in general, has approved the observations. Concerning the *absolute magnitude* of this probability of K ionization through electron bombardment, we have but little precise information, either experimental or theoretical. Smith's paper contains data on helium and bombardment voltages up to 4500, but in the wide field of heavier elements and higher energies there is no experimental datum except that resulting from Clark's[3] work with silver targets at 70 kv.

The present work resembles that of Clark in that its object is to determine a K-ionization probability, or cross section, and its method is the measurement of the power of K x-ray emission. It differs in the employment of 28 Ni atoms as targets and in the abandonment of crystal reflection as the means of spectral isolation. The target material as mounted before the electron gun in our work was in the form of a sheet of nickel of surface density σ, prepared by evaporation of the metal in vacuum and condensation upon thin films of cellulose acetate which provided mechanical support without seriously contributing to the total x-ray emission. With such a target disposed for normal bombardment, the number of nickel atoms per cm^2 of target area is $\sigma N/A$ where N is the Avogadro number and A the atomic weight of nickel. The resulting number of K ionizations, being proportional to the atomic density and to the number n of bombarding electrons, may be written,

$$N_K=\Phi_K n\sigma N/A. \quad (1)$$

The evaluation of Φ_K was the object of this investigation.

The definition of Φ_K by Eq. (1) is not unique unless attended by a limitation on the types of paths permitted to the bombarding electrons within the target, for a long path naturally means numerous ions. We impose the requirement that the electrons of Eq. (1) shall pass through the target by the shortest possible path, i.e., along a straight line normal to the target faces. Thus defined, Φ_K, which has the dimensions of an area, may be thought of as the area per nickel atom (not per K electron) which must be hit to insure K ionization. Since real electrons do not and will not follow the required minimum path, we shall have to deduce the actual path, observe the number of ionizations and compute from these

[1] Webster, Clark, and Hansen, Phys. Rev. **37**, 115 (1931); P. T. Smith, Phys. Rev. **36**, 1293 (1930). Webster, Hansen, and Duveneck, Phys. Rev. **43**, 839 (1933).
[2] H. S. W. Massey, Proc. Roy. Soc. **A129**, 616 (1930); H. S. W. Massey and C. B. O. Mohr, *ibid.* **135**, 258; **136**, 289 (1932); **139**, 187 (1933). C. Møller, Zeits. f. Physik **70**, 786 (1931); C. Møller, Ann. d. Physik **14**, 531 (1932); H. Bethe, Ann. d. Physik **5**, 325 (1930).
[3] J. C. Clark, Phys. Rev. **48**, 30 (1935).

data the number N_K of ionizations which *would have occurred* had the ideal path been followed.

The method of this investigation was to determine σ by weighing and to infer N_K by a measurement of the ionization produced in a standard ionization chamber by the Ni $K\alpha$ radiation emerging from the target in consequence of the K ionizations. For purposes of measurement, the $K\alpha$ characteristic radiation was separated from other radiations, both characteristic and continuous, by five critically balanced filters of the kind first described by Ross.[4]

This battery of filters sufficed to isolate three spectral bands, of which one included the Ni $K\alpha$ wave-length and two furnished data on the continuous spectrum power at either side. An interpolation based upon the side-band powers yielded a value for the continuous spectrum power measured with the alpha-lines and made it possible to obtain the line power alone by subtraction of this background.

The ionizations included in N_K are supposed to have been produced exclusively by the direct action of the n electrons; in a real experiment a few ionizations from other causes must be expected. We have considered the production of K ionization by electrons rediffused into the nickel target by the backing film, and by absorption in the nickel of continuous x-radiation originating in the nickel itself, in the backing film and in the aluminum cup where the bombarding electrons finally came to rest. It was found possible to show that none of these processes would, under the conditions of our experiment, produce so many as 0.001 N_K K ionizations. Because of the smallness of this error, no attempt at a correction will be made in what follows.

X-RAY SOURCE

The fragile target was supported by a springy structure of 2 mil copper wire so designed as to yield to any strains which changes of temperature or pressure might impose upon the plastic film. This structure was housed in a field-free cylinder of brass, since experience had shown how short is the life of a thin target exposed to the principal accelerating field of an x-ray tube or to the violence of the discharges which are prone to occur when high potential is first applied to a newly evacuated tube. The accelerated electrons entered the shielded space through a hole $\frac{1}{16}$ inch in diameter located on the axis of the brass cylinder and were received after passing through the target in an aluminum cup 6 inches deep from which few of them could rediffuse to the target and none could escape without flowing through the attached microammeter. No sketch is furnished here since none of the x-ray tube dimensions was critical and the whole arrangement closely resembled the tube shown in a drawing by Harworth and Kirkpatrick.[5]

Though the total area of the target was about 30 cm^2, the focal spot itself covered less than a tenth of this area. By a well-controlled process of evaporation the thickness of metal was held to about 500A. The surface density σ, a quantity more important than the thickness, was determined with some precision by methods to be discussed below. The Cellophane window which permitted x-rays to pass from the target to the external measuring apparatus was located so as to transmit radiation emerging from the target face at a grazing angle between two and three degrees. No measurable radiation could be picked up at the ion chamber when the tube was operated with the target removed.

FILTERS

For determining the background at the short wave side of the Ni $K\alpha$ line a balanced Cu-Ni pair was used. A sheet of nickel was brought to a thickness of 0.0035 inch by jeweler's rolls and a copper sheet was adjusted to it by electroplating copper on and off until the filters transmitted equally to about 0.25 percent at 0.200, 0.600, 0.710, 0.800, and 1.538A and also for the fluorescent radiations from strontium and nickel with their predominating constituents at 0.875 and 1.656A respectively. None of these radiations lies within the Cu-Ni pass band; transmissions in this band were investigated by the use of Zn $K\alpha$ fluorescence radiation isolated by a Bragg spectrometer from the output of a strongly irradiated piece of zinc. Of the Zn $K\alpha$ radiation, which lies right in the middle of the Cu-Ni pass band, the copper filter transmitted 50.2 percent, while the

[4] P. A. Ross, J. Opt. Soc. Am. and Rev. Sci. Inst. **16**, 433 (1928).

[5] K. Harworth and P. Kirkpatrick, Phys. Rev. **62**, 334 (1942).

TABLE I. Filter characteristics.

Filter	Type	K-limit wave-length	Pass band trans-mission coef.	To isolate	Trans-mission coef. of pair
25 Mn	Evaporated	1.8916A	0.035	Long wave	$0.520 = T_1$
26 Fe	Electroplated	1.7394	0.555	background	
26 Fe	Electroplated	1.7394	0.068	Ni $K\alpha$	$0.571 = T_2$
27 Co	Electroplated	1.6040	0.639		
28 Ni	Metal sheet	1.4839	0.003	Short wave	$0.499 = T_3$
29 Cu	Metal sheet	1.3774	0.502	background	

corresponding transmission coefficient of the nickel filter was 0.3 percent. These filters, perhaps because of some impurity in the nickel, came into nice balance without the addition of any third material for K-jump correction.[6]

The background at the long wave side of the Ni $K\alpha$ line was determined by using a Fe-Mn pair. The iron member was prepared by electroplating on aluminum foil from an aqueous solution of ferrous ammonium sulfate, and its mate was formed by evaporation of manganese in vacuum upon aluminum foil. Like the Cu-Ni pair, the Fe-Mn filters were balanced at several wave-lengths, a special x-ray tube with targets of copper, nickel, iron, and chromium being used, in conjunction with a spectrometer, to provide the necessary monochromatic radiations. At 1.816A, within the pass band of this pair, the transmission coefficients of the iron and manganese filters were, respectively, 55.5 and 3.5 percent.

To isolate the Ni $K\alpha$ line and its neighboring continuous radiation from the thin target, a Co-Fe filter pair was required. This pair was procured by matching the iron filter described above with a cobalt filter produced by electroplating on aluminum foil from a cobaltous ammonium sulfate bath. Each of the successful electroplated filters was the end product of a series of only partially successful attempts[7] to obtain uniform, adherent coats of filter metal upon backing sheets of aluminum of proper thickness to compensate for the dissimilarity of the K jumps of the filters to be balanced. As finally adjusted, the cobalt filter passed 63.9 percent in the pass band (at 1.656A) and its iron companion passed 6.8 percent.

[6] P. Kirkpatrick, Rev. Sci. Inst. **10**, 186 (1939).

[7] Production of these and other filters was discussed in earlier papers. See P. Kirkpatrick, Rev. Sci. Inst. **15**, 223 (1944).

By the transmission coefficient, T, of a *pair* of filters is meant the difference between the transmission coefficients of the individual members of the pair for radiation whose wave-length is the mean wave-length of the pass band. The concept has a definite significance: The difference between the powers transmitted by the two filters from an incident spectrum *of any composition* needs only to be divided by the transmission coefficient of the pair to give the power which would be recorded by the same measuring equipment if it were possible to irradiate it solely with the full-strength pass-band component of the incident beam.

Table I summarizes the properties of the five filters.

RADIATION POWER MEASUREMENT

Emerging from the Cellophane window of the x-ray tube, the thin-target radiation passed through vertical and horizontal lead-jawed slits whose carefully measured widths and positions were such as to transmit to the ion chamber a diverging beam including a solid angle Ω of 2.638×10^{-4} steradian. The chamber itself, specially designed for absolute measurements, had the internal structure shown in Fig. 1. In this view, the axis of the chamber (and of the entering x-ray beam) is seen in a vertical position, though in use this axis was horizontal. The several electrodes of the chamber consisted, as shown, of grids of fine aluminum wire. This open structure harbors little radioactive contamination and renders unnecessary any calculation of a contribution to the observed ionization from secondary x-rays or electrons originating in the electrodes. The large diameter (9.5 inches) of the envelope of the chamber (not shown in Fig. 1) allowed a clearance around the collecting volume adequate to dispose of wall effects from the envelope.

The grid wires in the space between A and B of Fig. 1 constituted the collecting electrode. Grounded guard grids of identical construction extended the plane of the collector and helped to preserve the uniformity of the collecting field. This uniformity was further promoted by a set of Taylor[8] grid loops (C) in the form of six parallel and equally spaced rectangles of wire thrown

[8] L. S. Taylor, Bur. Stand. J. Research **5**, 507 (1930).

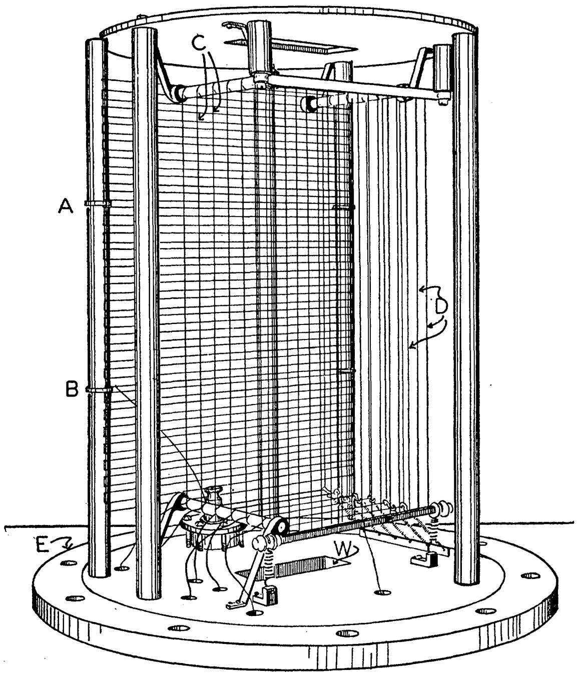

FIG. 1. Internal structure of ion chamber for absolute beam power measurement. Cylindrical brass envelope (not shown) surrounds electrode structure and is held against end plate E by bolts passed through holes shown.

about the collecting field and maintained at equally spaced potentials appropriate to their positions. The effectiveness of these grids in keeping the lines of force straight at the front and rear boundaries of the collecting region was a matter of importance, since it is necessary in absolute radiation power measurement to know the effective length of the collecting region with accuracy. Since the field was highly uniform at both ends of the collecting region it was possible to take as the effective length of the beam segment producing collected ions simply the distance separating the centers of the gaps between the collecting electrode and its adjacent front and rear guards. This distance was 10.075 cm.

In Fig. 1 may be seen the S-shaped glass hooks and spiral springs which kept the Taylor grids taut, the high voltage grid D maintained in tension by its two springs, the brass end plate E which carried the entire structure and admitted the ionizing radiation through its central cellophane window at W. The collecting electrode was fully insulated from adjacent grounded elements by amber. The chamber was filled with dry air at atmospheric pressure after some preliminary measurements with argon had shown that the heavier gas yielded the fewer collectible ions under Ni K radiation. This ineffectiveness of argon resulted from its strong absorption in the space between the entrance window of the chamber and the forward end of the collecting region.

Collected charges were measured by a Compton electrometer. Ion current saturation offers no problem with air in the chamber. The whole measuring system as calibrated by comparison with a standard condenser showed a sensitivity of approximately 10^{13} mm/coulomb. This sensitivity was not exactly constant over the entire range afforded by the electrometer scale so individual deflections were always interpreted and translated into coulombs by reference to a calibration curve.

DETERMINATION OF σ

Eight different nickel targets were used in the course of this investigation, but not all of them yielded useful data. Some were discarded because of wrinkling or fine visible perforations and some were lost through accident. The conclusions to follow were based upon three good targets here designated A, B, and C. The thickness or surface density of a metal deposit produced by evaporation may be roughly determined from the loss of weight of the filament or other source and certain geometrical considerations. In our experience, this method is dependable to about 10 percent, but no better; several other schemes for the determination of σ were considered and abandoned in favor of direct weighing.[9]

After a target had served its purpose in the x-ray tube, it was carefully removed to a punching device which cut out a neat disk 1.616 inches in diameter and concentric with the focal spot. This target specimen, of known area, was transferred to a weighed microcrucible and heated to incipient redness in the presence of oxygen in an electric furnace. This treatment presumably drove off anything that may have been left of the

[9] We are greatly indebted to Dr. J. H. C. Smith of the Carnegie Institution of Washington and Stanford University for suggesting the microbalance techniques, for making the necessary facilities available and for performing all of the weighings and associated operations.

cellulose backing and oxidized the nickel to Ni O. The oxide and crucible were then weighed on a microbalance and the weight of nickel was calculated. The Ni O was then reduced to metallic nickel by heating in the presence of hydrogen. Another weighing at this point furnished a second determination of the weight of nickel. A third value was obtained by weighing again after converting to nickel sulfate by heating with a few drops of nitric and sulfuric acids, fuming off the acid and bringing the sulfate to constant weight by heating almost to redness.

It is most unlikely that any cellulose survived this treatment, and the good agreement among the three determinations tends to justify the view that it departed completely during the initial heating.

The processes just described yielded the mean surface density of each nickel disk, but not that of the focal spot at its center. In the evaporation process the plane, horizontal cellulose film was supported above a concentrated filament of hot nickel. This arrangement deposits a metal film whose thickness is proportional to the fourth power of the cosine of the angle θ between the metal beam and the vertical; the thickest part is thus directly above the source and this is the portion of the target which subsequently receives the electron bombardment. The mean surface density directly determined by the weighing operations is evidently smaller than the required σ at the focal spot. It may be shown from the $\cos^4\theta$ law that the ratio of these surface densities is the inverse ratio of the squares of the cosines of the angles θ for the peripheries of the concentric circular areas to be compared. For all of our targets this argument indicates that the mean surface densities resulting from the weighings should be multiplied by a correction factor 1.023 to give σ.

Table II summarizes these results.

TABLE II. Focal spot surface densities. Tabulated masses are in milligrams.

Target designation	*A*	*B*	*C*
Mass of Ni O	0.926	0.635	0.790
Mass of Ni calculated from Ni O	0.728	0.499	0.621
Mass of Ni after reduction	0.733	0.507	0.630
Mass of Ni SO_4	1.938	1.303	1.644
Mass of Ni calculated from Ni SO_4	0.735	0.494	0.624
Mean mass of Ni	0.732	0.500	0.625
Mean surface density over test disk (gm/cm²)	5.54×10^{-5}	3.78×10^{-5}	4.73×10^{-5}
Mean surface density σ over focal spot (gm/cm²)	5.67×10^{-5}	3.87×10^{-5}	4.84×10^{-5}

DETERMINATION OF N_K

The relation between N_K and the charge collected and measured in the ion chamber involves a number of auxiliary constants. We consider first the ratio of N_K to the real number of K ionizations produced. For a target so thin that it absorbs only a small fraction of the energy of the average bombarding electron, the number of K ionizations may be regarded as proportional to the path length in the metal. For those electrons deviated only by multiple scattering, the ratio of the mean path length to the thickness of a thin target is adequately given[10] by $a=1+(1/2)\lambda^2$ where λ is Bothe's[11] most probable emergence deflection from the direction of incidence. For the present case, which is that of metallic nickel in sheets of surface density σ subjected to normal bombardment at 70 kv, the equation above becomes $a=1+247\sigma$. Values of a for the various targets, computed from the values of σ of Table II, are listed in Table III.

TABLE III. Single and multiple scattering correction factors at 70.0 kv.

Target	*a*	*b*	*ab*
A	1.013	1.011	1.024
B	1.009	1.008	1.017
C	1.012	1.009	1.021

The multiple scattering corrections developed above take care of electron-nucleus collisions where the impact parameter exceeds 0.8×10^{-10} cm, a limit set by Bothe's theory. It remains to consider the effect of the large-angle single scattering which befalls those electrons (about 1 percent of the total in our targets) which experience closer approaches. Correction factors for such collisions were computed by assuming Rutherford scattering and summing the effects of all the paths extended by this cause. The details of this calculation will be explained in another

[10] D. L. Webster, H. Clark and W. W. Hansen, Phys. Rev. **37**, 127 (1931).

[11] W. Bothe, *Handbuch der Physik* (1927), Vol. XXIV, Chap. 1, Sec. 9. A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 76.

connection.[12] Table III presents the results in the form of a constant b defined as a ratio in which the numerator is the mean nickel path length of all electrons under the assumption that those not subject to single scattering pass through by the shortest or normal route, and the denominator is the thickness of the target.

The actual number of K ionizations in a given target, after its determination by radiation measurements, must be divided by the appropriate ab from Table III to obtain N_K. This carries out the general plan explained in the introduction.

Other constants involved in the determination of N_K are the transmission coefficients of the various absorbers through which the x-radiation must pass, the mean x-ray energy expended per ion pair produced in air, the K fluorescence yield, w_K, of nickel, and the ratio c of the number of emitted nickel $K\alpha$ quanta to the total number of emitted quanta in all lines of the K series. This latter constant is easily obtained from measurements[13] of relative intensities of spectral lines. Williams found the intensity ratio of nickel $K\beta_1$ to $K\alpha_1$ to be 0.187 at a thick target face, and calculated this figure to be one percent higher than would have been the case had no x-ray absorption taken place in the target. For the ratio of α_2 to α_1 the figure was 0.495, with or without target correction. Meyer measured the ratio of the intensities of nickel β_2 to α_1, obtaining 0.0020, a result too small and inexact to merit target correction. No other K lines of comparable strength exist. Using the fact that the ratio of the intensities of two lines is the product of the ratio of their frequencies by the ratio of the numbers of quanta emitted, we find $c=0.898$.

TABLE IV. Corrections for absorption of $K\alpha$ radiation by targets.

Target	θ (radians)	σ	k_t
A	0.0486	5.67×10^{-5}	0.967
B	0.0358	3.87×10^{-5}	0.970
C	0.0332	4.84×10^{-5}	0.956

The K fluorescence yield, w_K, is defined as the ratio of the number of fluorescence K quanta emitted by an assemblage of similar atoms in any time interval to the number of atoms ionized in the K shell in the same time. From the six available determinations[14] for nickel, ranging from 0.364 to 0.436, we adopt Stephenson's value of 0.385 as being the most recent and also close to the unweighted mean of the group.

To determine the x-ray energy absorbed in the ionization chamber, it is necessary to apply to the ionization charge measurements the factor ϵ, defined as the mean energy (in ergs) absorbed in the air per ion pair produced. Binks'[15] survey of all work up to 1936 on this often-measured quantity shows that those determinations which seem the most reliable vary by 10 percent among themselves. In adopting the value 5.13×10^{-11} ergs (32 ev) we are introducing at this point the largest single source of uncertainty afflicting the final results of the present paper.

Between emission in the target and arrival in the collecting volume of the ion chamber the nickel radiation was subject to absorption in the target, in the Cellophane windows of tube and chamber, in the filters, and in air both within and without the chamber. The absorption by the filters has already been discussed. The air absorption was determined by investigation of an air sample contained within a brass tube 69.6 cm long between its aluminum windows. This tube was connected to a vacuum pump and placed between an ion chamber and a sheet of metallic nickel, excited to strong fluorescence by a neighboring Coolidge tube. Operation of the pump connections served to admit or remove the absorbing air, and the balanced Co-Fe filters described above separated the nickel α and β fluorescence radiations and excluded the latter. On taking due account of temperature and pressure (though not of humidity), a mass absorption coefficient[16] of 12.0 cm² g⁻¹ for air at λ1.656A was

[12] L. Pockman, D. L. Webster, K. Harworth and P. Kirkpatrick. A paper on the variation of the Ni K-ionization cross section with electron bombardment energy will be submitted to the Physical Review.

[13] J. H. Williams, Phys. Rev. **44**, 146 (1933). H. T. Meyer, Veroff. wiss. Siemens-Konzern **7**, 108 (1929). A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 640.

[14] M. Balderston, Phys. Rev. **27**, 696 (1926); R. J. Stephenson, Phys. Rev. **51**, 637 (1937). This paper cites all previous work except that of Balderston.

[15] W. Binks, *Reports on Progress in Physics* (London Physical Society, 1936), Vol. 3, p. 347.

[16] W. Stockmeyer, Ann. d. Physik **5**, 12, 71 (1931), gives a formula for the mass absorption coefficients of air which likewise indicates a value of 12.0 cm² g⁻¹ at the wave-length of our observations. We also obtained the value 7.78 cm² g⁻¹ at the wave-length of Zn $K\alpha$ as against Stockmeyer's 7.77.

computed. Under the conditions of thin-target measurements an air path of 52.7 cm intervened between the tube window and the collecting region, transmitting a fraction 0.467 of the incident Ni $K\alpha$ emerging from the tube. This fraction we denote by k_a.

By methods similar to those used to determine air absorption, the two Cellophane windows were found to transmit 0.764 of the Ni $K\alpha$ power and this fraction is designated k_w.

It was assumed that the radiation emerging from the thin target had to traverse a mean path length $x/(2 \sin \theta)$ within the target, where x is the normal target thickness and θ is the grazing angle of emergence of those rays destined for the ion chamber. This is merely assuming that radiation is produced uniformly throughout the target thickness and that the target surfaces are plane. The emerging fractions, designated k_t in Table IV, will then be given by $\exp(-(\mu/\rho)\sigma/(2 \sin \theta))$.

The length of the region of the ion chamber within which x-rays could be absorbed with full collection of the resulting ions was stated above to be 10.075 cm. Such a length of air absorbs 0.134 of the Ni $K\alpha$ radiation, a fraction later to be designated as k_c.

The problem of separating line radiation from continuous background may be considered in relation to Fig. 2 which illustrates in a purely schematic manner both constituents of the thin nickel spectrum as incident upon the filters. Vertical lines have been drawn at the K limits of the filters to show the boundaries of the pass bands. It will be noted that the region of the β lines has been avoided. The figure is far from correct in its portrayal of the relative powers of line and continuous, since in reality the continuous radiation in the panel numbered 2 should be of the order of one percent of the $K\alpha$ line power, a fact of which we were unaware when this work began.

The function of the filters isolating panels 1 and 3 was to determine this almost negligible background. The ionization charge collected in some selected time of observation t with the nickel filter in the beam is subtracted from that collected with copper. The difference divided by the transmission coefficient of the pair gives the entire band power represented by the shaded area 1. Further division by the wave-length breadth of the pass band gives a result proportional to the mean ordinate of panel 1. Panel 3 is then treated in the same way and an interpolation is effected which yields the continuous spectrum ordinate of panel 2. Multiplying this ordinate by the breadth of panel 2 gives the ionization charge which would have been collected had it been possible to irradiate the chamber with all the *continuous* radiation of panel 2 without the line. This small indirectly ascertained charge must be deducted from the *total* content of panel 2 to give Q_α, the charge (in coulombs) produced by the Ni $K\alpha$ line alone in the adopted time t of observation.

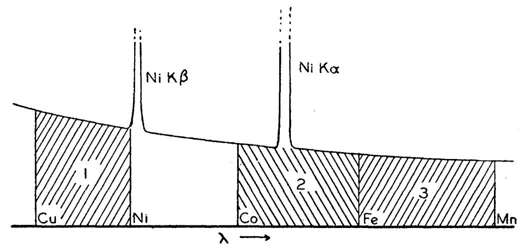

FIG. 2. Schematic plot of a portion of the continuous and line spectra from a nickel target, with spectrum power or intensity plotted against wave-length λ. Vertical lines beside atomic symbols show wave-length positions of the respective K absorption limits and divide the spectra into pass-band panels of which 1, 2, and 3 were measured.

During this time n electrons have struck the thin target, producing $N_K ab$ ionized nickel atoms. From what has gone before we may now set up the relation between the defined magnitudes in the form

$$N_K = 4\pi Q_\alpha \epsilon / abc\Omega w_K h\nu_\alpha e k_a k_w k_t k_c T_2. \qquad (2)$$

In this equation h is the Planck constant, ν_α is the frequency of the nickel $K\alpha$ line and e is the electronic charge in coulombs.

DETERMINATION OF Φ_K

With a current i (in amperes) impinging upon the target for time t the total number n of bombarding electrons is it/e. Substituting this expression and Eq. (2) into Eq. (1), we find,

$$\Phi_K = 4\pi Q_\alpha \epsilon A / abc\Omega w_K h\nu_\alpha k_a k_w k_t k_c T_2 N\sigma it. \qquad (3)$$

The quantities (Q_α/it), a, b, σ, k_t have different values for the differing targets used. The current i also varied from time to time and its mean value during each ionization observation was recorded.

Using Q as a general symbol for a measured ionization charge, with a subscript to indicate the filter in use during the measurement, we may form the dimensionless ratio $(Q/it)_z$ for each set of observations and summarize the results with one of the targets (B) in the manner of Table V. Insertion of this last result in Eq. (3) gives

$$\Phi_K = 3.36\times 10^{-22}\ \mathrm{cm}^2.$$

Each datum in Table V is a mean of ten observations. It is evident that the background measurements are quite undependable and the background deduction may well be wrong by 100 percent. Its effect upon Q_α is slight however, and causes no trouble.

Targets A and C gave, respectively, 3.39 and 3.38×10^{-22} cm² for Φ_K. The ionization measurements are reliable to better than one percent, so the error of the final result is practically the error of (ϵ/w_K), which at present is of the order of ± 5 percent. It is concluded therefore, on the basis of this investigation, that $\Phi_K=(3.38\pm 0.2)\times 10^{-22}$ cm². Future improvement of our knowledge of (ϵ/w_K) may be able to cut the stated error in half.

Theoretical studies in print do not carry the problem far enough to supply an entirely satisfactory check on the experimental result. The classical quantum theory of Thomas,[17] though quite out of date, has the merit that its conclusions may be evaluated without ambiguity. The addition of a refinement due to Webster, Hansen, and Duveneck[18] puts the prediction of this theory relative to K-ionization cross section into the form

$$\Phi_c = \frac{2\pi e^2}{V_K^2}\cdot\frac{1-U^{-1}+(2T/3)(1-U^{-2})}{U}, \qquad (4)$$

where U is the ratio of bombardment energy to K-ionization energy, T is the ratio of orbital kinetic energy to ionization energy, V_K is the K-ionizing potential and e the electronic charge, both in electrostatic units. For our case $U=8.38$, $T=1.19$, and $\Phi_c=3.70\times 10^{-22}$, a result ten percent higher than the experimental value. This finding resembles that of Clark[3] whose observed cross section for silver was somewhat below the prediction of Eq. (4).

[17] L. H. Thomas, Proc. Camb. Phil. Soc. **23**, 829 (1927).
[18] Webster, Hansen, and Duveneck, Phys. Rev. **43**, 839 (1933).

TABLE V. Ratios of collected ion charges to bombardment charges for target B.

$(Q/it)_{\mathrm{Co}}=8.32\times 10^{-9}$
$(Q/it)_{\mathrm{Fe}}=2.15\times 10^{-9}$
$(Q/it)_{\mathrm{Co}}-(Q/it)_{\mathrm{Fe}}=6.17\times 10^{-9}$
$(Q/it)_{\mathrm{Cu}}=5.30\times 10^{-9}$
$(Q/it)_{\mathrm{Ni}}=5.27\times 10^{-9}$
$(Q/it)_{\mathrm{Cu}}-(Q/it)_{\mathrm{Ni}}=0.03\times 10^{-9}$
$(Q/it)_{\mathrm{Mn}}=2.06\times 10^{-9}$
$(Q/it)_{\mathrm{Fe}}-(Q/it)_{\mathrm{Mn}}=0.09\times 10^{-9}$
Background deduction $=0.06\times 10^{-9}$
$(Q_\alpha/it)=6.11\times 10^{-9}$

Turning to wave-mechanical treatments of the problem, we find that the theory of Bethe[19] may almost be applied. His K-ionization cross section may be written as

$$\Phi_B=(2\pi e^2 b/V_K^2 U)\ \ln\ (4U/B). \qquad (5)$$

The quantities b and B are constant for any given element and electron shell. Bethe gives the value $b=0.35$ for K electrons of 29 Cu and since the variation of b with Z is apparently slow and regular, we use the copper value for 28 Ni. Unfortunately B is not defined explicitly; it is said to be of the order of unity, though Webster, Hansen and Duveneck[18] found the value 6 to fit their *relative* measurements of silver K-ionization probabilities best. It is some advantage that this speculative constant occurs under the logarithm. Without an exact theoretical value we cannot do more than remark that Eq. (5) would predict the result we observed *if* B possessed the value 4.5.

These agreements between theory and experiment are neither good enough to be highly gratifying nor bad enough to be alarming. The degree of agreement suggests that no major blunders afflict either the theoretical or the experimental work; the remaining disagreement indicates the need for more work, particularly on the theoretical side.

ENERGY AND PRODUCTION EFFICIENCY OF NICKEL *K* RADIATION

The number n_α of $K\alpha$ quanta emitted within the target is $\Phi_K N\sigma w_K c/A$ per bombarding electron. This expression, which includes all directions of emission, has for nickel targets under 70

[19] H. Bethe, Ann. d. Physik **5**, 325 (1930).

kv bombardment the value 1.19σ if the values we have determined or adopted for Φ_K, w_K and c are correct. The total energy of nickel K series lines, as may be deduced from relative measurements[13] of line intensities, is $1.351\times10^{-8}n_\alpha$. Substituting $n_\alpha=1.19\sigma$ in this result, we have as the total energy of K radiation emitted by nickel subjected to electron bombardment at 70 kv the value $1.61\times10^{-8}\sigma$ ergs per bombarding electron. Again it is noted that σ must be small enough so that all depths of the target are subjected to substantially the incidence bombarding energy and so that the electrons experience, on the average, only small deviations within the target.

It is not difficult to compute the efficiency of x-ray production under these conditions. The energy loss suffered by an electron having the relative speed β in passing through a layer of surface density σ may, by a slight modification of the formula of Williams,[20] be stated in the form $-E=3.38\times10^{-6}Z\beta^{-1.4}\sigma/A$. Upon evaluating this loss for a 70-kv electron in nickel and dividing the result into the K radiation output of the preceding paragraph, we arrive at an efficiency of 0.0035 or 0.35 percent. This is not the efficiency of production of nickel K radiation from a *thick* target under 70 kv bombardment; in such a case the electron remains productive while its energy declines from the initial 70 kev to K-ionization energy at 8.35 kev. Evaluation of the radiant output and efficiency then requires knowledge of the variation of Φ_K with electron energy, a subject beyond the scope of this paper.

[20] E. J. Williams, Proc. Roy. Soc. **A130**, 310 (1932). A factor $2Z/A$ has been applied to Williams' expression, following the recommendation of D. L. Webster.

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Forbidden Lines λ2967.5 and λ2269.8 of Mercury HgI

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The structure of the forbidden lines λ2967.5 ($6^1D_2\rightarrow6^3P^\circ_0$) and λ2269.8 ($6^3P^\circ_2\rightarrow6^1S_0$) of neutral mercury was studied with a high resolving power in order to get evidence for their perturbational nature. It was predicted some time ago by several authors that these lines should be emitted only by the odd isotopes of mercury. The emission would be of the electric dipole type, the selection rule $\Delta J=0, \pm1$ being partially invalidated by the weak interaction of the outer electrons with the nuclear magnetic moment. Only one line, namely λ2655.8 ($6^3P^\circ_0\rightarrow6^1S_0$) of mercury was analyzed in the past and definitely shown to belong to this category. The structure of the line λ2967.5 was fully resolved in the third order of a 30-foot Chicago grating. The structure of the line λ2269.8 was obtained by means of an aluminized Fabry-Perot etalon and a medium size quartz spectrograph. All components predicted for both cases were observed, except a very weak one for the line λ2269.8. The distances and intensities are in a very good agreement with theoretical predictions, hence establishing beyond doubt the nuclear perturbational nature of the forbidden transitions in the spectra of unperturbed atoms of zinc, cadmium, and mercury.

THERE is a certain ambiguity in the definition of a forbidden line. The definition that only the lines emitted by an unperturbed atom and obeying the selection rules for the electric dipole radiation should be called allowed, all the others—forbidden, is a very impractical one, since most of the quantum designations are approximate, the degree of approximation depending from the coupling conditions. It seems most convenient to call forbidden for the atom not perturbed by external forces all the lines not emitted at all or emitted with a transition probability not greater than about 10^{-4} of the highest transition probability found for the given atom in the optical region. Some forbidden lines appear only and acquire a considerable intensity in