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LOSS OF VELOCITY OF CATHODE RAYS IN MATTER

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Abstract

Loss of energy of cathode rays in passing through metallic foils.— Whiddington's apparatus was modified to provide a bundle of homogeneous rays by fitting a Coolidge cathode into a high vacuum tube and exciting it by rectified high tension current of accurately known voltage. After traversing the metal foil, the electron beam is deflected by the magnetic field of a solenoid and is spread into a broad band of which a small section, deflected about 30°, passes through a fixed slit into a Faraday cylinder connected to an electroscope. By varying the solenoid current, energy distribution curves were obtained, and the most probable energy loss for each case was determined from the position of the maximum. Rolled foils of *Ag, Al, Au, Be and Cu* were studied, for 25 to 51 kv, giving rays of 9 to 12.6×10^9 cm/sec. velocity. The results agree with the velocity formula of J. J. Thomson, $v_0^4-v_x^4=ax$, where x is the thickness, and a is a constant which comes out proportional to the density of the metal so that $a/\rho=5.05\times10^{42}$ approximately. In the corresponding voltage formula $V_0^2-V_x^2=bx$, $b/\rho=.40\times10^{12}$.

OBSERVATIONS of the passage of cathode rays through matter were made by Lenard[1] as early as 1894 and some measurements of the loss of velocity were obtained by Leithauser[2] about ten years later, but these results were mainly qualitative. Whiddington[3] measured the velocity loss in thin sheets of gold, copper and aluminum, and his results agreed with the law previously deduced by J. J. Thomson:[4]

$$v_0^4-v_x^4=ax \qquad (1)$$

where v_0 is the velocity of the entering electrons, v_x the most probable velocity of the emerging, x the thickness, and a the constant for the metal. In a later article he gives values of the constant a for tin, silver and platinum obtained from absorption measurements. Von Baeyer[5]

[1] Lenard, Ann. der Phys. u. Chem. **52;** 1894.
[2] Leithauser, Ann. der Phys. **15,** 299, 1904.
[3] Whiddington, Proc. Roy. Soc. **86,** 360, 1912; **89,** 559, 1914.
[4] J. J. Thomson, Conduction through Gases, 378.
[5] Von Baeyer, Phys. Zeit. **13,** 485, 1912.

using slow β rays from mesothorium-2 made a large number of measurements for the velocity loss in aluminum by a photographic method. His results agreed approximately with the above law but gave a somewhat higher value of the constant than obtained by Whiddington. The results of Danysz[6] and Rawlinson[7] were obtained by photographic methods with higher speed β rays and seemed to give approximate agreement with a theoretical relation obtained by Bohr[8] which was expressed in terms of the magnetic field required to deflect the rays. Becker[9] has proposed an expression for the value of dv/dx and Lenard[10] has plotted values of this quantity from the collected results of previous papers, without attempting to give an analytical expression for the law followed.

Method

The present method is a modification of Whiddington's. Using a gas filled tube, Whiddington controlled his initial velocity by spreading the rays into a magnetic spectrum which could be passed over the entrance slit. The final velocity was measured by deflecting the rays in a second magnetic field, the deflections being read by permitting these rays to strike a fluorescent screen. In both cases, the velocities had to be determined from the deflections by calculations based on the dimensions of the coils and currents used.

In the present apparatus, the source of electrons is a Coolidge cathode, the initial velocity being controlled by the applied voltage. The final velocity is measured by magnetic deflection, but the velocities are determined from the field currents which have been previously calibrated by observations on the direct beam. In this method, no errors are introduced by non-uniformities of the field. Instead of observing the impact of the deflected beam upon a fluorescent screen, it is received upon a slit, beyond which is a collecting plate connected to a gold leaf electroscope.

Apparatus

The general outline of the tube is shown in Fig. 1. It consists of two bulbs and a long neck, closed at the top with a removable plug, the joint being accurately ground and sealed with stop-cock lubricant. The stem bearing the cathode is attached to the plug. The tube itself

[6] Danysz, Le Radium, Jan. 1912.
[7] Rawlinson, Phil. Mag. **30,** 627, 1915.
[8] Bohr, Phil. Mag. **25,** 10, 1913; **30,** 581, 1915.
[9] Becker, Sitzungber. Heidelb. Akad. **4,** 1917.
[10] Lenard, Quantitatives über Kathodenstrahlen, Heidelberg, 1918.

is mounted in a transite oven with the long neck projecting through the top so that the ground joint may be kept cool during the baking out process by being wrapped with a wet cloth. For evacuation, a mercury condensation pump backed by a Gaede rotary mercury pump and a fore pump was used, the pumps being run continuously while the tube was operating. A slush of carbon dioxide snow in acetone

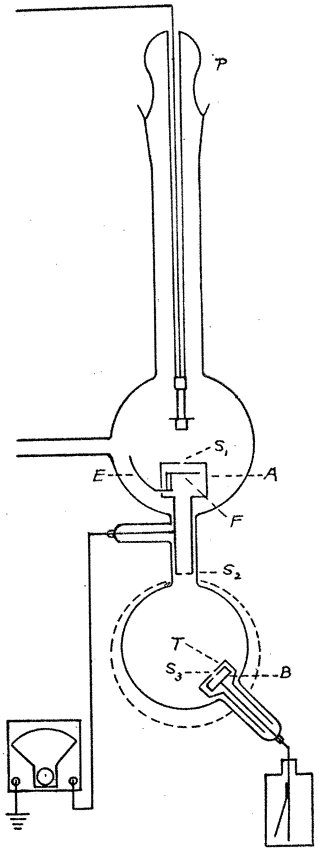

Fig. 1. Diagram of apparatus

was used around the trap to keep out mercury vapor. Before each run it was necessary to bake out at a temperature of about 300°C; then the oven was partially dismantled and the solenoids and electroscope fitted in place.

Referring to Fig. 1, the anode *A* is removable and of such size that it may be inserted and withdrawn through the neck. When in place, electrical connection is secured by its bearing against a small brass

spring projecting from the side tube just below the main bulb. The anode is constructed of brass, faced with copper, and is hollow, providing space for a light metal frame F, carrying the foil. This frame is pivoted, and an attached steel rod E, projecting from the side of the anode may be moved by a magnet outside the tube, so that the foil may be swung clear of the electron stream when desired. The slits S_1 and S_2 are about 9 cm apart; various widths were tried, the best results being obtained with a width of ½ mm.

The lower bulb provides space for spreading the beam into a magnetic spectrum and contains the receiving slit S_3 cut in a grounded metal shield T, inside of which is the collecting box B. The slit is so placed that the electron stream must be deflected about 30° to enter it. In the first tube constructed, the slit was placed so that the beam was bent through 90°, but the wide dispersion so weakened the intensity that readings were very difficult, and better results were found possible by deflecting through a smaller angle. The face of the shield is coated with powdered willemite so that the position of the beam may be roughly located from the fluorescent spot and approximate adjustments of the rheostats made before readings are started. The collecting box is a Faraday cylinder supported on silica insulators and connected directly to a gold leaf electroscope, the connection being made as short as possible in order to keep the capacity small. The image of the gold leaf is projected on a ground glass screen and the time of charging up observed with a stop watch. The grounding key is placed inside the electroscope case. A film of tungsten, evaporated on the walls of the lower bulb, and a platinum wire, sealed just through the surface, provided a ground connection to prevent the walls from becoming charged.

The magnetic field was obtained from two solenoids connected in series and placed outside the lower bulb, the gap between them being about 2 cm. Their cross section is indicated by the dotted circle. Their combined length was 64 cm, and the diameter about 15.5 cm, the winding being composed of four layers of No. 20 enamelled copper wire, 20 turns/cm. The current for these coils, which varied up to about .8 ampere, was supplied by storage cells and was measured by a precision ammeter to about .001 ampere.

The source of high tension current was a transformer supplied by a 500 cycle generator. The current was rectified by kenotrons, and a large glass plate condenser in parallel with the tube maintained the voltage at a constant value. The voltage was measured by an electrostatic repulsion voltmeter, previously calibrated against a 20 megohm metallic resistance, and could be controlled and measured to within

½ per cent. The currents used ranged as a rule from .2 and .5 milliampere, but for certain readings, currents as high as 3 milliamperes were required.

Procedure

To determine the current required to deflect rays of each velocity into the receiving slit, the metal foil was swung clear of the entrance slits, the tube was excited and the direct beam was allowed to pass into the lower bulb, the current in the solenoids being adjusted by rheostats until the beam entered the receiving slit. A reading was made of this current and also of the voltage applied to the tube; and this operation was repeated over the whole range of voltages used, at intervals of about two kilovolts. These readings were plotted and gave a calibration curve. A new curve was constructed for each run in order to prevent error from the solenoids not being returned exactly to their original positions after being removed for baking out the tube.

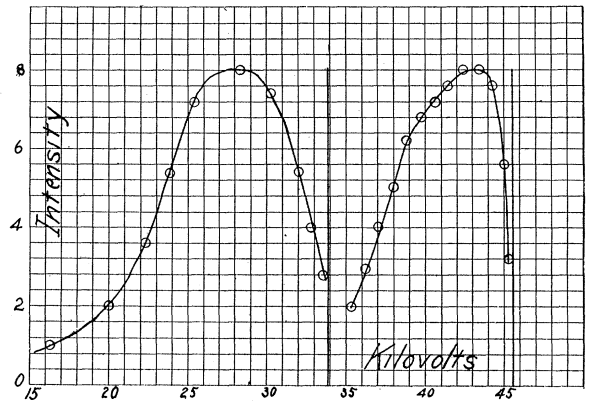

Fig. 2. Velocity distribution curves

The image of the direct beam on the fluorescent surfaces near the slit was narrow and sharp, proving that the condenser capacity was sufficient to smooth out the voltage undulations. Occasionally the sharp image would be accompanied by a fainter diffuse one on the low velocity side. This was presumably due to electrons reflected at nearly grazing incidence from the sides of the slit and was always gotten rid of by adjusting the cathode over the center of the slit.

When the metal foil was swung into place, the sharp image of the direct beam gave place to a diffuse band with a maximum of brightness toward the high velocity end. The distribution of intensities in this band for .00031 cm aluminum and initial voltages of 33.9 and 45.6 kv,

is shown in Fig. 2. These curves were obtained by varying the current in the solenoids by small amounts, thus passing the spectrum across the face of the receiving slit, and reading the rate of charging of the electroscope for each current. As a rule, a distribution curve was not drawn for each applied voltage. The position of the maximum is all that is here required, and this can be located by a very few points.

Velocities were computed from voltages by using the relation $V = 2.830\times10^{-16}v^2\ (1+.83v^2\times10^{-21}+.77v^4\times10^{-42})$, which retains three terms of the series.

Results

Table I gives the results for aluminum of two different thicknesses. Within the limits of experimental error, these quantities satisfy the voltage equation corresponding to Eq. (1)

$$V_0^2 - V_x^2 = bx \qquad (2)$$

and the mean value of b is 1.1×10^{12}. This corresponds to a value of a in Eq. (1) of about 1.4×10^{43}. This value of a is considerably higher than that obtained by Whiddington ($.732\times10^{43}$), and somewhat higher than the value given by Von Baeyer (1.1×10^{43}), but it is in good agreement with the value obtained by Bohr from theoretical considerations. In the first paper, Bohr[8] gives the value for a as 1.9×10^{43}, but in the second paper, he concludes that this value is too large by the factor 1.3, for the range of velocities here considered, and this reduces his value of a to 1.46×10^{43}.

TABLE I

Aluminum foils

Thickness (cm)	V_0 (kv)	V_0^2 (kv)	V_x	V_x^2	$V_0^2-V_x^2$
.00031 (one sheet)	24.6	605	16.9	285	320
	29.8	888	22.6	510	377
	35.6	1267	29.6	876	391
	40.9	1672	36.8	1354	318
	45.8	2097	42.2	1780	317
	51.2	2621	48.1	2313	308
.00062 (two sheets)	34.5	1190	22.2	493	697
	42.2	1780	33.5	1122	658
	46.3	2143	38.3	1466	677
	51.0	2601	43.7	1909	692

The only other metals that could be obtained in thin sheets suitable for this work were copper, silver, gold and beryllium. I wish to express my obligations to Dr. C. S. Brainin, of Baker and Co., for aid in securing sheets of these metals suitable for the work. In every case, the sheets were made by rolling, rolled foil being more homogeneous and in other

respects superior to beaten leaf. In the case of gold, the sheets were required to be of such extreme thinness that it was necessary to overlay a sheet of copper foil with gold and roll out the combination, then dissolve the copper in nitric acid.

The thickness was determined in each case by weighing a sheet of known area. Runs were made with pieces cut from different parts of each sheet in order to average out, in the mean results, any possible errors due to variations in thickness.

Table II gives mean values of the readings obtained.

TABLE II

Metal	Thickness (cm)	V_0 (kv)	Vx (kv)
Silver	.00023	41.7	27.1
		46.1	33.2
		49.8	37.1
Gold	.00012	46.1	30.1
		48.0	33.2
Beryllium	.0025	48.0	16.7
		50.5	20.0
Copper	.00024	36.8	23.1
		40.5	27.1
		45.3	33.2
		50.5	40.0

The values of the constants a and b are given in Table III.

TABLE III

Metal	a (10^{43})	b (10^{12})	ρ	b/ρ (10^{12})	σ (10^{22})	b/σ (10^{14})
Beryllium	0.94	0.75	1.9	.39	51	147
Aluminum	1.4	1.1	2.7	.41	78	141
Copper	4.5	3.6	8.9	.40	244	147
Silver	5.3	4.2	10.5	.40	274	153
Gold	11.2	8.9	19.3	.46	464	192

The accuracy of the values found for these constants should be much higher than values previously given, since the position of maximum intensity of the velocity spectrum was obtained by direct measurements; all previous results were obtained by optical methods applied to fluorescent screens and photographic plates. Other favorable features of the present method are the use of a Coolidge cathode, giving a homogeneous beam of cathode rays with constant potential direct current; accurate voltage determinations based on measurements with a metallic high resistance; and the use of rolled foil rather than beaten leaf.

The value of a for gold obtained by Whiddington is 2.54×10^{43}. The ratio of his values for aluminum and gold is approximately the same as the ratio of the present values for aluminum and copper. The constant for gold given by Bohr, corrected in the same manner as that for aluminum, comes out equal to 5.6×10^{43}. It should be remarked that Bohr's values include a factor that must be obtained from experiments with α rays, and the experiments from which this data was obtained are less accurate for gold than for aluminum, as shown by the values of the atomic numbers computed from the same data.[11] The constancy of the values of b/ρ given in the table shows that the value of b is proportional to the density.

A piece of mica used in the apparatus gave approximately the same values of the constant as aluminum. The observations in the case of mica are less trustworthy, since it is difficult to split mica into sheets that are sufficiently thin and at the same time uniform, but as the density of mica is about the same as that of aluminum, the agreement of the constants is additional evidence in favor of the relation $b/\rho=\text{const.}$

It is possible that b depends on the number of electrons per cubic centimeter, which is not exactly proportional to the density. Calling it σ, we have $\sigma=\text{density}\times\text{atomic number/atomic weight}$.

The values of σ for the metals used are given in Table III together with the values of b/σ. The values of b/σ come out approximately constant, but not quite so closely as the values of b/ρ.

Values of the constant b for molybdenum and tungsten are desirable for application in x-ray theory, but these metals cannot be used in the present apparatus as they cannot be obtained in foil of the required thinness. However, assuming $b/\rho=.40\times10^{12}$, we may compute b and obtain the values, molybdenum 3.6×10^{12} and tungsten 7.6×10^{12}.

It is hoped to give some further results in a later paper, particularly in reference to the distribution curves.

In conclusion, I wish to thank Prof. Bergen Davis, who suggested the research, for his kind interest and helpful advice.

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February 15, 1923.

[11] Bohr, loc. cit. p. 27.