MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

A Determination of *e/m* by Means of Photoelectrons Excited by X-Rays

G. G. KRETSCHMAR, *Ryerson Physical Laboratory, University of Chicago*

(Received December 29, 1932)

A value of e/m has been obtained by a magnetic deflection method by making use of x-ray photoelectrons and the magnetic spectrograph. Electrons were ejected from thin evaporated or sputtered films of gold, silver, copper and platinum by the x-radiation from a molybdenum target metal tube placed close to the film and working at an input of 1.5 kilowatts. The velocity of ejection of the photoelectrons was computed from the difference between the energies associated with Mo K radiation and the various absorption limits of the metal films. Relativity corrections were made since these velocities correspond to from 8000 to 15,000 equivalent volts. The α_1 and α_2 components of the molybdenum $K\alpha$ line were clearly resolved since the magnetic field was kept very constant by the use of a potentiometer and continuous hand control. The weighted mean value of e/m_0 obtained from five plates is $1.7570 \pm 0.0026 \times 10^7$ e.m.u. per gram. This result is based upon a value of $h/e = 1.3737 \pm 0.0005 \times 10^{-17}$ as taken from x-ray crystal measurements. By taking h/e from x-ray data the resulting value of e/m is independent of the uncertainty involved in the crystal grating constant.

DURING the past forty years there have been many determinations of the specific charge of the electron. In the *Handbuch der Radiologie*[1] for instance, there is a compilation of not less than forty-five separate experiments up to the year 1913, for the evaluation of this important constant. Gerlach[2] gives a compilation of the researches from 1901 to 1911, in which he gives the value 1.766×10^7 e.m.u. as the most probable value at that time. More recently, the value of 1.7609 ± 0.0012 obtained by Babcock[3] by the Zeeman effect, and Houston's value[4] of 1.7608 ± 0.0008 by an interferometric measurement of the Rydberg constant of H and He has emphasized a lower result, while the cathode-ray measurement of 1.7689 ± 0.002 made by Wolf[5] has agreed with the prevailing higher estimates. Birge[6] suggested that there might be a difference in the value of e/m depending on whether the electron is free or bound in the atom. This suggestion probably has had the effect of stimulating experimentation in this interesting field, for we have since had a surprisingly large number of researches on the evaluation of e/m.

The work of Campbell and Houston,[7] making use of the Zeeman effect, has given us the value of 1.7579 ± 0.0025 in substantial agreement with the previous spectroscopic determinations. Then, recently, we have had the experiments of Perry and Chaffee[8] and Kirchner[9] giving values corresponding to those obtained by the spectroscopic methods. This work is of especial interest, because the lower values are obtained by a nonspectroscopic method.[10] However, the method is not a deflection method, and it is still extremely important, as Birge[11] suggests in a recent paper, to obtain a really reliable value of e/m from magnetic deflection. The present experiment[12] represents an attempt in this direction.

---

[1] A. Bestelmeyer, Handb. d. Radiologie **5**, 1–79 (1919).

[2] W. Gerlach, Handb. d. Physik **22**, 41–82 (1926).

[3] H. D. Babcock, Astrophys. J. **58**, 149 (1923); **69**, 43 (1929).

[4] W. V. Houston, Phys. Rev. **30**, 608 (1927).

[5] F. Wolf, Ann. d. Physik **83**, 849 (1927).

[6] R. T. Birge, Phys. Rev. Sup. **1**, 48 (1929).

[7] J. S. Campbell and W. V. Houston, Phys. Rev. **39**, 601 (1932).

[8] Charlotte Perry and E. L. Chaffee, Phys. Rev. **36**, 904 (1930).

[9] F. Kirchner, Ann. d. Physik, **8**, 975 (1931); **12**, 503 (1932).

[10] Although the recent determinations of e/m have tended to confirm the lower value, W. N. Bond (Proc. Phys. Soc. **44**, 374 (1932)) from the theoretical work of Eddington, gives reasons for believing that the higher value is correct.

[11] R. T. Birge, Phys. Rev. **40**, 228 (1932).

[12] As early as 1906 A. Bestelmeyer (Ann. d. Physik **22**, 429 (1907)) experimented with x-ray photoelectrons for obtaining a value of e/m. He was able to show experimentally that the value of e/m depends on the velocity, and he made the relativity corrections.

METHOD

The present experiment makes use of the magnetic spectrograph method, originally developed by Robinson and Rawlinson[13] and used by de Broglie[14] and Robinson[15] for determining atomic energy levels, and more recently by Watson[16] for obtaining data on spatial distribution of x-ray photoelectrons. Watson has shown that the optimum direction of ejection of the electrons is a little forward of 90° from the direction of the x-ray beam. Also, he has shown that by the use of very thin films, the lines obtained are very much sharper, and approximate more closely to a true image of the slit than when thicker films are used. These facts have been of great help in the present work. It has been possible by the use of very thin films, and by holding the magnetic field very constant, to produce sufficient resolution to show clearly the doubling in the lines due to the α_1 and α_2 components of the Mo $K\alpha$ line in the radiation which was used.

It is now apparently well established that photoelectrons are ejected by x-rays, with a definite energy, given by the Einstein relation:

$$\tfrac{1}{2}mv^2=hc(1/\lambda_K-1/\lambda_L), \qquad (1)$$

where λ_K is the wave-length of the incident radiation and λ_L is the wave-length of the absorption limit of the electron shell from which the particles have their origin. Also, since the electrons are bent into a circular path, by a magnetic field of H gauss, we have:

$$mv^2/r=Hev. \qquad (2)$$

Solving these two equations for e/m we obtain:

$$e/m=2c^2(h/e)(1/\lambda_K-1/\lambda_L)/(Hr)^2. \qquad (3)$$

The result, it is seen, involves the constant h/e. Fortunately, this constant, as Birge[17] has pointed out, is much more accurately known than e. One of the most precise methods for obtaining h/e is by means of the limit of the x-ray spectrum, as has been done by Duane, Palmer and Yeh[18] and by Feder.[19] It can be shown that if the x-ray value of h/e is used[20] the resulting value of e/m is independent of the grating space assumed since the effect of the grating space on the value of h/e is just balanced by its effect on the value of the wave-lengths. Thus the value of e/m obtained by this magnetic spectrograph method is more reliable than might appear, in view of the discussion of the correctness of crystal wave-lengths.

Since the electron velocities in this experiment were of the order of 8000 to 15,000 equivalent volts ($\beta=0.16$ to 0.24) it is necessary to replace Eqs. (1) and (2) with the equations which involve the relativity corrections. They are:

$$m_0c^2(1/(1-\beta^2)^{\frac{1}{2}}-1)=hc(1/\lambda_K-1/\lambda_L) \qquad (4)$$

$$\beta c/(1-\beta^2)^{\frac{1}{2}}=Hr(e/m_0), \qquad (5)$$

where $m=m_0/(1-\beta^2)^{\frac{1}{2}}$, $\beta=v/c$ and m_0 is the rest mass and m is the mass at the velocity v and c is the velocity of light. Eq. (4) may be put into the form:

$$\frac{\beta c}{(1-\beta^2)^{\frac{1}{2}}}=\beta\frac{e}{m_0}\frac{h}{e}\left(\frac{1}{\lambda_K}-\frac{1}{\lambda_L}\right)+\beta c$$

and equating to (5) and solving for e/m_0 we get:

$$\frac{e}{m_0}=\frac{2c^2(h/e)(1/\lambda_K-1/\lambda_L)}{(Hr)^2-c^2(h/e)^2(1/\lambda_K-1/\lambda_L)^2}. \qquad (6)$$

It is seen that this form is identical with the form obtained with the simple equations with the addition of a second order term in the denominator.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement consists of, first, a metal x-ray tube rigidly mounted with a three-stage mercury diffusion pump on a heavy wooden support. Second, a large solenoid

---

[13] H. Robinson and W. F. Rawlinson, Phil. Mag. **28**, 277 (1914).

[14] M. de Broglie, C. R. **172**, 274, 527, 746, 806 (1921).

[15] H. Robinson, Proc. Roy. Soc. **A104**, 455 (1923).

[16] E. C. Watson, Phys. Rev. **30**, 479 (1927).

[17] R. T. Birge, Rev. Mod. Phys. **1**, 72 (1929).

[18] W. Duane, H. H. Palmer and Chi-Sun Yeh, Proc. Nat. Acad. Sci. **7**, 237 (1921).

[19] Ann. d. Physik **5** (1), 494 (1929).

[20] The value used in the computations of this paper is $1.3737\pm0.0005\times10^{-17}$. This value is obtained from the arithmetical average of the results of the experiments of Duane, Palmer and Yeh, and of Feder as given by R. T. Birge, Phys. Rev. **40**, 247 (1932).

mounted on a rigid framework, so that the axis of the solenoid is parallel to the earth's field. Third, a heavy brass camera with supports so arranged that it may be placed in the middle of the solenoid and carefully aligned with respect to the direction of the x-ray beam and the axis of the solenoid.

The solenoid was 100 cm long and 22 cm in diameter wound with a single layer of No. 18 enameled wire, held in place by layers of shellac, baked on, above and below the wire. The solenoid was very carefully made as it was originally planned to obtain the solenoid constants from the dimensions, but this was found to be impractical, and the field was finally calibrated by a standard solenoid and flip coil method, which will be described later. Two heavy brass rings were securely fastened to the ends of the solenoid and two pins projecting into the lower one and a special clamp on the upper one permitted the exact alignment of the solenoid and insured its return to the same position whenever it was necessary to remove it. A hole in the middle of the solenoid, 6 mm in diameter was made into the wall during its construction, and the wire was distorted slightly on the two sides of this hole during the winding, thus producing a small opening through which the x-ray beam was sent.

The source of x-rays was a metal tube designed by Dr. Elmer Dershem of this laboratory. It contained a water-cooled molybdenum target such as is used in commercial tubes. The vacuum system to which the tube was permanently attached, was made as short and direct as possible, of large diameter tubing. The excitation was from a large capacity transformer (20 kw) and it was found possible to run the tube consistently for long periods with an input of 75 to 85 milliamperes with a voltage of approximately 30,000 volts.

The camera was in the form of a circular disk 21.5 cm outside diameter and 6.5 cm high. The bottom and top were made of heavy brass plate 1.22 cm thick and the side wall was a short length of large diameter seamless brass tubing. A groove cut into the bottom plate contained a rubber gasket. Twelve screws clamped the upper part onto this gasket making a convenient and vacuum-tight joint.

The distribution of parts inside the camera is best described from the diagram Fig. 1, which represents a section through the middle of the camera and perpendicular to the axis of the solenoid. The surfaces in the planes AB and CD were carefully scraped flat to within 0.003 mm and these surfaces were parallel to each other to the same accuracy.

Eastman x-ray plates were used. They were held in contact with the plane AB by the spring T. A fine slit at S' served to make a fiducial mark on the plate by means of optical light. The slit S, through which the electrons passed, was very carefully made by working the two parts down to a knife edge and finishing by means of the finely ground surface of a glass flat. This slit was 0.12 mm wide. The lead shield L served to keep any scattered x-rays from affecting the plate, and the heavy lead well W was for absorbing the main x-ray beam after it had passed through the metal film at M. The x-rays were admitted to the camera in the direction shown through a 6 by 10 mm opening in the camera wall which was covered with a thin window of cellophane on the outside, cemented on so that it was vacuum tight, and a thin sheet of black paper on the inside to keep out any optical light.

The metal films used were gold, silver, copper and platinum. The first three were evaporated onto cellophane by the method suggested by Cartwright and Strong.[21] The platinum was a sputtered film on cellophane. The films were very thin and transparent, of about the thickness known as "half-silvered" or less. In use a strip was cut out of the metalized cellophane about 3 mm wide, and cemented across the two prongs so that the center line of the strip was exactly under the slit. Of course, it was necessary to get the metal side above, as the x-rays passed through the cellophane before driving electrons out of the film.

The fixed dimensions of the camera focussing device were measured on a small Gaertner comparator the least count of which was 0.001 mm. This instrument was carefully checked against a standard decimeter, which has been checked by the United States Bureau of Stand-

---

[21] C. H. Cartwright and J. Strong, Rev. Sci. Inst. **2**, 189 (1931).

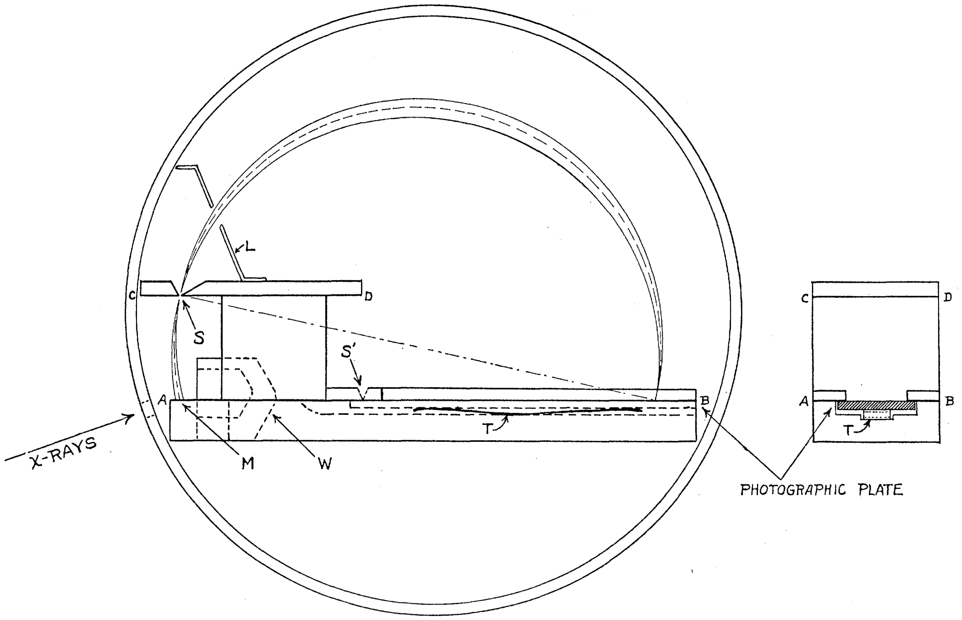

Fig. 1. Diagram of camera box.

ards. The vertical distance was 31.868±0.002 mm and the horizontal distance from the center of S to the center of S' was 52.890±0.002 mm at 23°C. Temperature corrections were always made in the computations.

The support for the camera was built up from four brass rods securely anchored to the supporting framework. It was independent from the solenoid, thus producing no distortion in the latter. The top of this support, consisted of heavy brass rings which contained two pins which projected into the base of the camera. These pins served to orient the camera so that the small hole through which the x-rays entered could be put into exact alignment with the hole in the solenoid. The camera support also served as a rigid support for the standard solenoid by extending one of the rods.

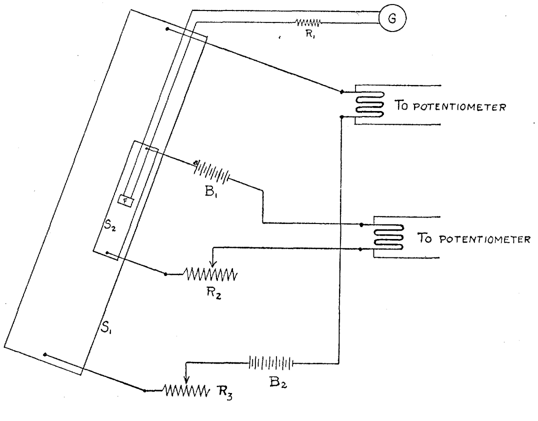

Fig. 2. Circuit diagram showing method of calibration of solenoid.

Calibration of the Magnetic Field

The standard solenoid was wound on a bronze cylinder which was cast from S. A. E. 62 bronze made up from virgin metals to avoid any trace of magnetic impurity. This bronze cylinder was 6.4 cm in diameter and turned perfectly true. It had a 90° thread cut into the surface as accurately as possible, and the wire was wound into these thread grooves. Before winding on the wire the cylinder was supported on the bed of a large Geneva Society comparator and measured at short intervals by sighting the cross hair in the exact centers of the thread cuts. A series of six sets of measurements made in this way were found to agree within one part in 28,000. A check measurement made a number of weeks later after the wire was wound on the cylinder, agreed with the original measurement to one part in 10,000.

The cylinder was insulated with three coats of lacquer and wound with 243 turns of No. 18 enamelled wire, and the ends were taken off at right angles and along the same element of the cylinder. The diameter of the solenoid was obtained from micrometer measurements on the outside of the winding in different azimuths. The thickness of the enamel was estimated from tables and from measurements.

The magnetic field strength of the solenoid was computed from the formula: $H=KI$ gauss, where I is the current in amperes and $K=0.4\pi N \cos\alpha$. N is the number of turns per cm and α is the angle subtended at the center by the radius at one end. This simple formula is applicable in this case since the flip coil is small and located at the center of the solenoid. The flip coil mechanism contained a coil of nearly 12,000 turns of No. 40 enameled wire 32 mm outside diameter and 16 mm wide. This coil was mounted in the center of the solenoid on carefully aligned pivots, and arranged with a trip mechanism so that it could be controlled from a distance, and caused to turn quickly through exactly 180°, under the tension of small rubber bands.

The mounting of the standard solenoid was so placed that the flip coil rotated in a position which corresponded to the centers of the electron trajectories during the exposures.

The actual calibration was by a null method. The diagram Fig. 2 gives the connections during a calibration. By using two separate potentiometer circuits, the current was held constant in the large solenoid at one value and simultaneously, in the standard solenoid, at a series of values above and below the neutral point, and the deflections of a ballistic galvanometer observed at these points. It was found possible to plot a straight line through the resulting points, the intersection of which on the axis, gave very accurately the current required in the standard solenoid to neutralize the field of the large solenoid. The galvanometer used for the field calibration was a type HS Leeds and Northrup instrument of 25,000 ohms external critical damping resistance. It was used critically damped by placing an extra 20,000 ohm unit in series, in the galvanometer circuit.

The calibrations were made under the same conditions as obtained during the exposures, for the current was maintained in the large solenoid during calibrations, at the value which was used while most of the plates were being made. The earth's field, including any stray field effects, was determined by running the calibration currents both in the normal and the reversed directions.

A series of measurements taken over a period of ten days showed very excellent agreement. The weighted mean of nine calibrations was taken. It is 11.434 ± 0.005 gauss per ampere and this value was used in all the computations of this paper. The weights were taken with respect to the accuracy with which the ballistic galvanometer deflections corresponded to a straight line, and the closeness with which the conditions of the calibration simulated the conditions during the exposures.

A small magnetometer, designed by Mr. A. E. Shaw of this laboratory, was mounted on the apparatus. This served to show the effect of the placement of magnetic objects, such as tools, steel chairs, and the opening of the steel windows. No ferromagnetic materials were used in the construction of any of the apparatus or supports, and a slight magnetic effect of running the x-ray tube was neutralized by placing a steel chair in a position about two meters distant from the apparatus. This was afterward verified by making calibrations both with and without the tube running. These calibrations failed to show a detectable difference.

MAKING THE EXPOSURES

The high input into the x-ray tube and the short distance which was about 8 cm from the target to the metal film in the camera, made possible the obtaining of plates in a shorter time than would be possible with a glass x-ray tube. It was found possible to get good lines with about 18 hours exposure and some of the later exposures were made in 8 and 10 hours, but a little more time would have been an advantage.

During the exposures the magnetic field was kept constant to about one part in 5000 by fine rheostatic controls. The current was measured by means of a standard 0.1 ohm shunt and a Wolff potentiometer. The shunt was calibrated recently by the Bureau of Standards, and was certified to an accuracy of one part in 4000 for the current used. Two Weston normal cells were used, which were frequently intercompared and checked against a Weston cell with a recent Bureau of Standards certificate. These cells were contained in insulating boxes and corrected for temperature variations.

It was found that the careful control of the solenoid current permitted sufficient resolution to show all the lines as close doublets. The separation is accounted for as due to the α_1 and α_2 components of the Mo $K\alpha$ line. Fig. 3 is a reproduction of two of the plates. C-3 was taken with a gold and C-7 with a silver film. The arrow at A indicates the position of the line due to Mo $K\alpha$—Au M_{111}. The arrow at B shows the position of the line due to Mo $K\alpha$—Ag L_{111}. These lines show very plainly as close doublets on the original plates.

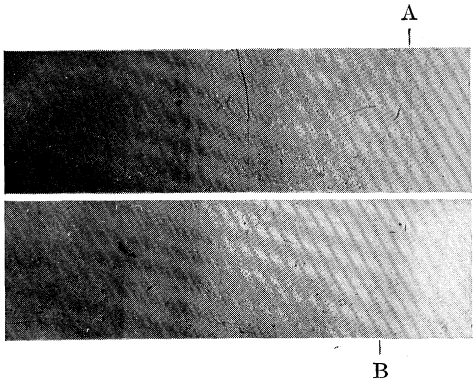

FIG. 3. Reproduction of two plates, C-3 with gold and C-7 with a silver film; A indicates position of line due to Mo $K\alpha$—Au M_{111}; B the position of line due to Mo $K\alpha$—Ag L_{111}.

The plates were measured on a large comparator built by the Sociétè Gènèvoise. The instrument was checked by comparison with the decimeter standard and found to be accurate within the errors of reading. The lines were best seen by reflected light and it was found possible to place a mark in the center of the line with a fine needle point and then measure to this mark. This process gave very consistent measurements as may be seen from column 5 of Table I in which the probable error computed from 6 or more measurements on each line is given.

RESULTS

The results of all measurements on five plates are given in Table I. The values given in the last two columns have been calculated from Eq. (6). The wave-length of Mo $K\alpha_1$ (λ_K) has been taken as 0.707830A as recently determined by Compton.[22] While it is recognized that this wave-length is not known absolutely, the recent work of Tu[23] shows that it is probably a very excellent value. There is considerable variation in the data on the absorption wave-length limits (λ_L). The values chosen are taken from the more recent work and are believed to represent the most accurate data available at present.

The value of h/e was taken as 1.3737×10^{-17}. As already mentioned[20] this value is taken from an average of two h determinations by the method of the limit of the x-ray spectrum.[24] The last column of the table gives one value selected from each plate which gives what the author believes to be the best values of e/m_0 obtained from the present work. The basis of the selection was that the lines selected were the most intense and the easiest to see on the plates. The last three plates were made each in a single day, giving less opportunity for any changes due to temperature variations, and plate C-13 was washed in ice water giving less possibility for the gelatin to soften. The values from C-11 and from C-12 have, therefore, been given double weight and the value from C-13 has been given three times the weight of the first two.

Taking, then, the weighted average of the last column of Table I we obtain the value: $e/m_0=1.7570\pm0.0026\times10^7$ e.m.u. per gram in which the precision has been estimated by assuming that the data on the wave-lengths of the absorption limits is accurate to approximately 0.1 percent.

---

[22] A. H. Compton, Rev. Sci. Inst. **2**, 365 (1931).

[23] Y. Tu, Phys. Rev. **40**, 662 (1932).

[24] By taking the value of $h/e=1.3751\times10^{-17}$ as obtained from the work of Duane, Palmer and Yeh,[18] I obtain for the weighted mean value of e/m_0, 1.7588×10^7 e.m.u. This is in excellent agreement with the very recent value of 1.7592×10^7 given by Dunnington (Phys. Rev. **42**, 734 (1932)). (See also the preceding paper in this issue. Editor.) It also agrees closely with the value of $1.759\pm0.001\times10^7$ given by Birge in a new summary of values of e/m. Phys. Rev. **42**, 736 (1932).

TABLE I. *Data and computed values of* e/m_0.
Weighted mean of the selected values of e/m_0 is $1.7570 \pm 0.0026 \times 10^7$ e.m.u. per gram.

Plate	Line Mo K	Absorption L	Authority	Plate measurement	Hr	$e/m_0 \times 10^7$ (e.m.u.)	$e/m_0 \times 10^7$ (e.m.u.)
C-3	Au $M_{\rm I}$	3603	Johnson[25]	8.0493 ± 0.0009	402.201	1.7565	
	$M_{\rm II}$			$8.1918 \pm .0017$	406.240		
	$M_{\rm III}$	4508	Lindberg[26]	$8.3952 \pm .0005$	412.043	1.7569	1.7569
	$M_{\rm IV}$	5330	Lindberg[26]	$8.6183 \pm .0008$	418.439	1.7532	
	$M_{\rm V}$	5529	Lindberg[26]	$8.6647 \pm .0009$	419.741	1.7521	
C-7	Ag $L_{\rm I}$	3247.4	V. and L.[27]	$7.8663 \pm .0003$	396.960	1.7543	
	$L_{\rm III}$	3690.8	V. and L.[27]	$8.0972 \pm .0002$	403.537	1.7554	1.7554
C-11	Cu K	1377.7	Average[28]	$8.3832 \pm .0023$	311.891	1.7581	1.7581
C-12	Pt $M_{\rm I}$	3742	Johnson[25]	$8.1314 \pm .0008$	404.317	1.7539	
	$M_{\rm II}$	4085	Johnson[25]	$8.2658 \pm .0012$	408.125	1.7556	
	$M_{\rm III}$	4676	Lindberg[26]	$8.4563 \pm .0009$	413.588	1.7554	1.7554
	$M_{\rm IV}$	5544	Lindberg[26]	$8.6658 \pm .0004$	419.565	1.7542	
	$M_{\rm V}$	5746	Lindberg[26]	$8.7221 \pm .0008$	421.176	1.7496	
C-13	Pt $M_{\rm I}$	3742	Johnson[25]	$8.1259 \pm .0021$	404.165	1.7555	
	$M_{\rm II}$	4085	Johnson[25]	$8.2559 \pm .0009$	407.868	1.7580	
	$M_{\rm III}$	4676	Lindberg[26]	$8.4470 \pm .0010$	413.318	1.7580	1.7580

It is, of course, recognized that this method cannot claim to produce an absolute value of e/m in view of the fact that the wave-lengths are taken from crystal measurements, and since it involves also a knowledge of h/e. Nevertheless, since the factor involving the crystal grating constant balances out of the equation, as suggested earlier in this paper, the value of e/m_0 obtained is believed to be quite reliable and it is of more than ordinary interest since it has been obtained by the magnetic deflection of free electrons.

In conclusion, the author wishes to express his appreciation to Professor A. H. Compton who suggested the problem and gave valuable advice, and to Dr. Elmer Dershem for much helpful counsel and assistance. It is a pleasure, also, to acknowledge the friendly interest and helpful suggestions of Professor A. J. Dempster and Professor S. K. Allison. The work of Mr. Ivar Kalberg, who constructed the standard solenoid and flip coil, is also, very much appreciated.

---

[25] Arthur J. M. Johnson, Phys. Rev. **34**, 7 (1929).

[26] E. Lindberg, Zeits. f. Physik **54**, 632 (1929).

[27] G. D. Van Dyke and G. A. Lindsay, Phys. Rev. **30**, 562 (1927).

[28] M. Siegbahn, *Spektroskopie der Rontgenstrahlen*, 2nd edition, page 265 (1931). The average of the last five values, which have been obtained since 1925, was taken.

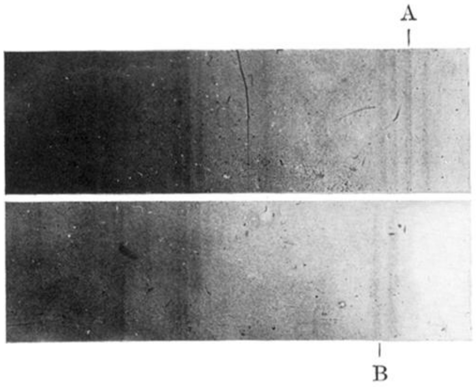

FIG. 3. Reproduction of two plates, C-3 with gold and C-7 with a silver film; *A* indicates position of line due to Mo $K\alpha - \text{Au}\ M_{\text{III}}$; *B* the position of line due to Mo $K\alpha - \text{Ag}\ L_{\text{III}}$.