Direct Determination of the Charge of the β-Particle[1]

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The charge of radium E β-particles was measured by first measuring the charge carried per second by a magnetically analyzed beam and then, after the beam had been reduced by a known fraction by the decay of the source, by counting the number of particles per second in the beam. The average value obtained was $-4.80_0 \pm 0.03_8 \times 10^{-10}$ e.s.u. in agreement with the accepted value of the charge of the electron. Also a half-life of 4.99_0 days for radium E was observed. No dependence of either the charge or the half-life upon $H\rho$ was detected.

INTRODUCTION

THE method of this experiment[2] is to measure the current carried by a beam of radium E β-particles emerging from a β-ray spectrometer by means of a Faraday collector and a vacuum tube electrometer and then to replace the collector by a Geiger counter and to count the number of particles emerging per second. This is a modification of the method which has been used to measure the charge of the alpha-particle.[3] Until recent developments in Geiger counter technique it has not been possible to determine the charge of the β-particle in this way, but instead the first experiment of this type on β-particles[4] was performed to measure the efficiency of the counter for β-rays.

Because it was necessary to have a current larger than 5×10^{-15} ampere (3×10^4 electronic charges per second) for accurate current measurements while it was not possible to measure accurately counting rates greater than 300 per sec., for the counting measurements it was necessary to reduce the strength of the beam by a known fraction by allowing the source to decay for nearly ten half-lives. The amount of the decay could not be calculated accurately over such a long period of time from the known half-life of radium E because of impurities of radium D. Therefore the spectrometer was equipped with a second exit slit and set of baffles similar to the first ones through which the beam could be sent by reversing the magnetic field into an ionization chamber which could be connected to the vacuum tube electrometer. (See Fig. 1.) At the times of the collector current and counting measurements the corresponding ionization currents (I_S and I_W, respectively) were observed, these being measures of the relative strengths of the source. Then if e is the charge of the β-particle, I_F the collector current, and n' the number of counts per second,

$$I_F = n'e(I_S/I_W) \quad \text{or} \quad e = (I_F/I_S)/(n'/I_W) \qquad (1)$$

(I_F, I_S, I_W, and n' are all measured at the same value of the magnetic field).

The collector current and both ionization currents were measured by means of an electrometer tube and the null method of Townsend,[5] in which the grid is maintained at zero potential by inducing upon it through a condenser a charge equal in magnitude but opposite in sign to that being measured. The current is given by the product of the condenser capacity C and the rate of change of potential V' supplied to the condenser such that the grid is maintained at zero potential. A condenser C_1 of small but very accurately known capacity was used for measurements of the small currents I_F and I_W, and a large condenser C_3 was used for the "strong" ionization current I_S. Hence Eq. (1) becomes

$$e = C_1\left(\frac{C_1}{C_3}\right)\frac{V_F'/V_S'}{n'/V_W'}, \qquad (2)$$

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[1] This paper contains a portion of a dissertation submitted to the faculty of Princeton University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Further information concerning this work can be obtained by consulting the complete dissertation, a copy of which is available for inter-library loan at the Princeton University Library.

[2] A preliminary report of this work has been published previously: R. Ladenburg and Y. Beers, Phys. Rev. **58**, 757 (1940).

[3] E. Schopper, Zeits. f. Physik **93**, 1 (1934); **94**, 649 (1935).

[4] A. F. Kovarik, Phys. Rev. **13**, 272 (1919).

[5] J. S. Townsend, Phil Mag. **6**, 603 (1903); H. G. S. Mosely, Proc. Roy. Soc. **87**, 230 (1912).

where the subscripts F, S, and W refer, as before, to the collector current and to the "strong" and "weak" ionization currents, respectively. It is to be noted that the absolute value of C_3 is not involved but only its ratio to C_1.

APPARATUS

The double β-ray spectrometer, Faraday collector, and the ionization chamber are illustrated in Fig. 1. The sides of the spectrometer were made of Armco iron blocks 18 cm×12 cm×1 in. which became the actual pole pieces when the apparatus was placed in position. These were held 6 cm apart by a brass frame which contained the entrance slit (4×15 mm), the two exit slits (2×40 mm), and the aluminum baffle system. These were designed to give as large an intensity as possible and still restrict the emerging beam to within 30 degrees to the normal of the exit slit so that the beam could easily be trapped in either the collector or counter. The radius of the trajectory was about 3 cm. The spectrometer and Faraday collector were evacuated to a pressure less than 10^{-4} mm Hg by means of a diffusion pump.

The magnetic field was measured by means of a flip coil and fluxmeter, the calibration of which could be checked with a mutual inductance. Because of uncertainty in the average radius, the absolute values of $H\rho$ given herein may be in error as much as 10 or 15 percent, but the results of this experiment depend only upon the accuracy of reproducing the magnetic field which is estimated to be about $\frac{1}{2}$ percent. As most of the measurements were made near the maximum of the spectrum, small errors in reproducing the field produced little effect upon the results.

The Faraday collector F (see Fig. 1) consisted of a rectangular box which, except for the bottom, was made of aluminum. In the bottom ($\frac{1}{16}''$ brass) was cut a slit 9 mm ×48 mm. The inside surfaces were covered by graphite or soot. This box was suspended from the roof of a larger box by amber insulators so that its bottom was less than 2 mm above the exit slit of the spectrometer. The outer box served as an electrical shield, and it was made air-tight with wax so that it could be evacuated. Rough estimates of the efficiency of collecting β-particles entering the collector based upon consideration of the solid angle subtended by the slit

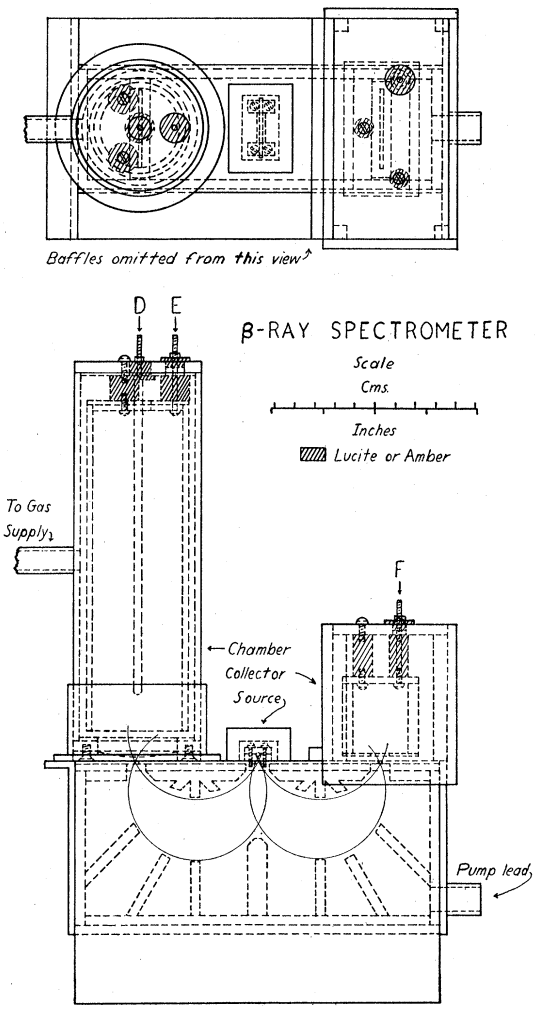

FIG. 1. Double β-ray spectrometer with Faraday collector and ionization chamber.

at the opposite wall and of the reflection coefficient of the surfaces[6] indicate that it was at least 99.5 percent.

The ionization chamber (see Fig. 1) consisted of a copper cylinder 2″ in diameter and 18 cm long closed at its lower end by a copper gauze with a $\frac{1}{4}''$ copper rod mounted coaxially. These were supported from the interior of an air-tight brass cylindrical case by amber insulators. For admitting the beam there was in the bottom of this case a hole $1\frac{1}{2}''$ in diameter covered by an 0.1-mm aluminum foil which was held between two flat brass rings with Apiezon Q as a gasket. The foil could withstand a pressure difference of

[6] B. F. J. Schonland, Proc. Roy. Soc. **A108**, 187 (1925).

at least four atmospheres, and when the chamber was mounted in place with the spectrometer previously evacuated, it could be evacuated for filling. The pressure of the gas (argon) was measured by the aid of an open ended mercury manometer 2 meters long. The concentration of the gas (P/T) was maintained between 7.00 and 8.00 mm Hg/degree absolute (about 3 atmospheres). All measurements were corrected to a standard concentration of 7.50 mm Hg/degree absolute by use of some empirical correction factors found by determining the dependence of the ionization current due to a constant source upon gas concentration. The voltage upon the chamber was supplied by a 750-volt bank of "B" batteries. With the strongest source ever used, a reduction in the voltage to 400 volts caused the current to decrease by a factor of 0.997 ± 0.003 as a probable error, indicating that the systematic error in the final results due to imperfect saturation was very small, not more than 0.2 percent. The background current was about 4×10^{-15} ampere. The largest source of experimental error in the "weak source" measurements was due to fluctuations in this background current, mainly due to alpha-particle contamination of the chamber. Numerous precautions were taken to reduce this contamination to a minimum. The probable error in a determination of the background lasting for 450 seconds was 3.4×10^{-16} ampere.

The Faraday collector and ionization currents were measured by means of a vacuum tube electrometer employing a Western Electric D-96475 tube in a modified Barth circuit.[7] In order to reduce the grid (background) current, the entire grid circuit was placed in an evacuated shield. This current varied between $+6$ and $+12\times10^{-16}$ ampere, and the largest source of experimental error in the Faraday collector measurements was due to fluctuations in it. The probable error in a determination of the grid current which required 450 seconds was 5.8×10^{-17} ampere and seemed to be independent of the magnitude of the current. To obtain the most stable operating conditions, the electrometer circuit ran 24 hours a day, and the storage battery which supplied the power was charged by a trickle charger with an Acme-Delta voltage stabilizer on its input.

[7] D. B. Penick, Rev. Sci. Inst. **6**, 115 (1935).

This electrometer was operated according to the null method of Townsend,[5] as mentioned in the introduction. An especial advantage of this method is that the capacity of the grid and its circuit are not directly involved.

The three cylindrical condensers used with this electrometer were equipped with special shielding[1] so that the capacity between the lead wires was eliminated. The smallest of these condensers (referred to as C_1) was a primary standard of 11.77 ± 0.03 micromicrofarads. The largest condenser (referred to as C_3) was designed to have high capacity rather than to have high accuracy as a primary standard. Only the ratio of its capacity to that of C_1 is involved in the final result, as is explained in the introduction. This ratio was obtained by using both condensers to measure the same steady current and was equal to the reciprocal of the ratio of the corresponding rates of change of potential. In this way a value of 364.3 micromicrofarads was found for the capacity of C_3. C_1 was also compared by this same method with another primary standard C_2 and was found to be in excellent agreement with it. The value of C_2 found from its geometry was in good agreement with the calibration by the National Bureau of Standards.

The counters were made of 1″ diameter brass tubing. On one side was milled a flat place, in the center of which was cut a slit 48 mm $\times$6 mm over which was waxed a 4.65 mg/cm^2 aluminum foil. Into the ends were waxed closed glass tubes supporting the counter wire of 3-mil tungsten which was kept taut by a spring. To obtain a more uniform field the ends of the wire were shielded by $\frac{1}{4}$″ glass tubes which extended into the cylinder for 1″. These counters were normally filled by a mixture of 9 cm Hg of argon and 1 cm of alcohol and were self-extinguishing.[8] Only Apiezon wax was used as this absorbed alcohol very slowly, if at all. In the principal experiments no counter was used for more than a total of six million counts or later than ten days after its previous filling. Usually before filling the wires were heated in vacuum by passing a current of one ampere for several periods of a second or two. Only those counters with an essentially flat region in their plateaus were used; otherwise the measured counting rate could have no unambiguous

[8] A. Trost, Zeits. f. Physik **105**, 399 (1937).

connection with the true number of particles entering the counter. The absolute efficiency of these counters will be discussed later. The circuit consisted of a two-stage amplifier followed in turn by a pulse sign discriminator,[9] a vacuum scale of eight,[9] a thyratron scale of eight,[10] and a Cenco recorder. The method which was used to correct for losses in the counting rate due to the resolving time of the counter has been described elsewhere and will not be discussed here.[11] The radium E sources (practically free of radium D but containing radium F) were deposited upon 40-mil nickel wires from a solution containing about 7 millicuries of radium D and its products, which had been prepared previously in this laboratory from old radon tubes. The deposit was restricted to a portion of the wire 1 cm long by covering other portions with collodion. For work with the Faraday collector the source strength was usually 2 to 3 millicuries. The procedure used in depositing the sources was the usual one[12] but it should be mentioned that the process apparently depends critically upon the constitution of the wire. Pure nickel from Baker and Company of Newark, New Jersey gave very good results, but some wire from another manufacturer gave hardly any yield at all.

No difficulty was caused by the presence of radium F (polonium) in the source because the alpha-rays were prevented from entering the detecting devices by the magnetic spectrometer, and the gamma-rays were too weak to be observed when the source and counter were mounted in their normal positions.

FOIL CORRECTIONS; INFLUENCE OF SCATTERING AND OF SECONDARY ELECTRONS

The slit on the counter and the exit slit of the spectrometer were each covered by a 4.65-mg/cm^2 aluminum foil. A certain fraction of the beam is lost when the counter is used which is not lost with the Faraday collector (unless an equivalent amount of foils is placed in front of the collector). Therefore, if n' of formulae (1) and (2) is

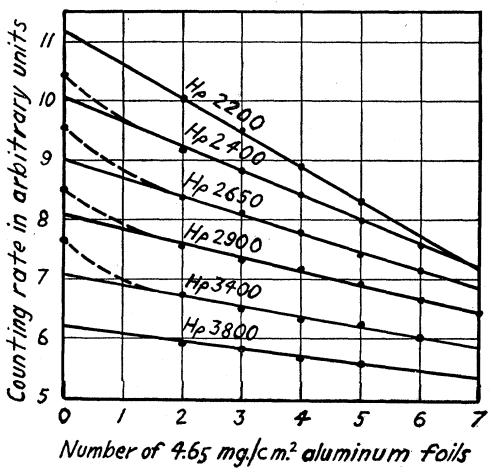

FIG. 2. Foil correction data. The counting rate is plotted against increasing foil thickness as extra foils are placed in front of the counter. The Geiger counter data are extrapolated to zero thickness (solid lines). Also is indicated (dashed lines) the behavior at small thicknesses as inferred from the Faraday collector measurements.

to be construed to be the observed counting rate (corrected, however, for resolving time losses), its value must be multiplied by a correction factor J.

One value of J (hereafter called J_g) can be found by placing additional foils between the counter and the spectrometer slit and measuring the corresponding counting rates due to a constant source. In Fig. 2 are plotted such data for the values of $H\rho$ which were of interest in the present work. Each point represents the average of two values involving 60,000 or more counts each. These data are well represented by straight lines which have been extrapolated to zero foil thickness (solid lines). The correction factor J_g is found by dividing the extrapolated value of the counting rate for zero foil thickness by the value for 2 foils.

Another value (hereafter denoted J_F) of this correction factor can be found by measuring the current from a constant source, first with no foils and secondly with two foils (connected electrically to ground) in front of the Faraday collector. J_F is given by dividing the first of these quantities by the second. Values of J_F (somewhat less accurate than the corresponding J_g values) were obtained at four of the same values of $H\rho$. These turned out to be consistently larger than the corresponding J_g values, the discrepancies being too large to be accounted for by errors in the

[9] H. Lifschutz and J. L. Lawson, Rev. Sci. Inst. **9**, 83 (1938); H. Lifschutz, Rev. Sci. Inst. **10**, 21 (1939).
[10] J. Giarratana, Rev. Sci. Inst. **8**, 390 (1937).
[11] Y. Beers, Rev. Sci. Inst. **13**, 72 (1942).
[12] O. Erbacher and K. Phillip, Zeits. f. Physik **51**, 309 (1928); W. F. Libby and D. D. Lee, Phys. Rev. **55**, 252 (1939).

measurements. It can be inferred that the behavior at small foil thicknesses must be according to the broken line curves of Fig. 2 and not according to the extrapolations of the straight lines.

There are two possible causes for a discrepancy between the values found by these two methods. If there are any secondaries ejected from the foil, these will be recorded separately by the collector but not by the counter, and J_f will be smaller than J_0. On the other hand, if there are some very low energy particles emerging from the spectrometer after having been scattered therein, these are completely stopped in the first one or two foils, and will cause J_f to be larger than J_0. The latter process gives the observed sign of the discrepancy, and it must be concluded that this is the predominant one. Therefore, it can be concluded that the value found with the collector (J_F) is the more reliable. Instead of attempting to measure this quantity accurately, however, there was employed in the final experiment the much simpler procedure of placing in front of the collector during the measurements of I_F a foil thickness equal to that used with the counter. Then the measured values of I_F and n' were used for the calculation of the charge, and no numerical correction was necessary.

Evidence for scattering was found by photographing the beam at a known distance from the exit slit. A slight indication that the beam was not confined entirely to within thirty degrees to the normal was detected. Particles emerging at large angles cause the measured value of the charge to be too large, for while they fail to enter the counter and are not recorded by it, they may be recorded by the collector even though they strike the outside surface.

Secondary electrons, if ejected from the foil into the collector, make the collector current too large, while secondaries ejected from the collector produce a reverse effect. Because of the large stray magnetic field, it is not to be expected that either effect is large, and the number of secondaries leaving the collector must be relatively very small because of solid angle considerations. To investigate the possibility of errors due to these sources an experiment was performed in which the foils were insulated from the spectrometer and in which various potentials were applied to them. The application of a positive potential gave no detectable effect, while negative potentials of 45 and 200 volts both gave an increase in current of about one percent, slightly greater than the probable error, which indicated that there might be secondaries of this amount being emitted from the foil in excess of those emitted from the collector.

As the pressure was normally 10^{-4} mm Hg or less it was unlikely that a large error could have been caused by the production of ion pairs. A rough calculation based on the specific ionization of β-particles, the length of path, and the pressure indicated that the probability that a β-particle produced one ion pair was about 0.01 percent. Also an experiment was performed in which the pressure was raised to 5×10^{-2} mm Hg with no appreciable change in collector current.

THE ABSOLUTE EFFICIENCY OF COUNTERS

The absolute efficiency of a counter has been shown to obey the following theoretical formula based upon an analogy with the mean free path theory of statistical mechanics. (The mean free path for producing a primary ion pair is the reciprocal of the primary specific ionization.)

$$E=100(1-e^{-KP}), \tag{3}$$

where

$$K=(\omega s d T_0/P_0 T), \tag{4}$$

s = number of primary ion pairs produced per unit path at standard pressure P_0 and temperature T_0; P and T are the pressure and temperature, respectively, of the gas in the counter; d = path of the particle in the counter; ω = probability that a primary ion pair causes the counter to discharge.

Some workers[13–15] have assumed that ω was equal to unity and have used the measured efficiencies of Geiger counters for determining the primary specific ionizations of the gas, while other workers[16] find that ω must be considerably less than unity if their data are to be consistent with values of s obtained by independent methods. All are agreed, however, upon a dependence of the efficiency on pressure of the type given by Eq. (3).

[13] W. E. Danforth and W. E. Ramsey, Phys. Rev. **49**, 854 (1936).
[14] M. Cosyns, Bull Tech. Ass. Ing. Brux. 173–265 (1936).
[15] T. Graf, J. de phys. et rad. [7], **10**, 513 (1939).
[16] J. DeVries and G. J. Sizoo, Physica **6**, 593 (1939) and references quoted therein.

If one assumes ω is unity and uses the following values: $s=29.4$ per cm at $P_0=76$ cm Hg (see reference 14), $d=1.9$ cm, $P=9$ cm Hg, and $T=T_0$ (assumed), the efficiency of the counters used in this work is calculated to be 99.94 percent.

For checking the absolute efficiency experimentally a method of comparing counters having different pressures was used. If two counters are used to measure the same beam of particles, the measured counting rates are proportional to their efficiencies. If E and E_α refer, respectively, to the efficiencies of two counters which have pressures of P and αP but which are identical otherwise,

$$E_\alpha/E=(1-e^{-\alpha KP})/(1-e^{-KP}). \qquad (5)$$

In practice e^{-KP} is a very small quantity and if α is roughly 2 or greater, this ratio becomes $1+e^{-KP}$ approximately.

Several comparisons were made of the efficiencies of counters having 1.1 cm Hg alcohol vapor in addition to 4.7, 9, and 12 cm argon, respectively. While these did not agree within the probable error there was no systematic dependence of efficiency upon pressure. The largest discrepancy was observed in one experiment in which a counter containing 9 cm argon gave a counting rate 2 percent greater than the others. Even if such a large change in efficiency could be shown to be attributed to changing the argon pressure from 4.7 cm Hg (P) to 9 cm Hg (αP), e^{-KP} must be not larger than 2 percent and the efficiencies of the higher pressure counters must be at least 99.9 percent except for the "inherent error" (that is, discrepancies between the counters which cannot be attributed to a change in pressure).

The "inherent error" was further investigated by comparing a number of counters all having the same pressure (9 cm Hg of argon and 1.1 cm Hg of alcohol), and these were found to disagree by amounts large enough to account entirely for the discrepancies observed with the counters having different pressures. Comparison of the five counters used in the final experiment of the charge of the β-particle showed that a probable "inherent" error of 1.2 percent should be assigned to each counter. This result was in agreement with earlier experiments of this type. Therefore, such errors are included in the summary of errors. (See Table III.) Otherwise, the counters are considered to have perfect efficiency.

The explanation of this "inherent" error is by no means clear, and this matter could bear further investigation. Undoubtedly some of it is connected with the fact that no counter has a perfectly "flat" plateau and that there is some uncertainty in selecting the correct operating voltage. A small amount of it may be due to temperature effects in the counter and in the voltmeter used to measure the counter voltage.

PROCEDURE

Altogether three separate sets of experiments upon the charge of the β-particle were carried out. The first two of these, especially the first set which was very rough, are to be regarded as preliminary experiments. The procedure of the final experiment, now to be described, was based upon the experience gained from the other two.

Separate sets of measurements were taken at each of five values of $H\rho$, and therefore five nearly independent values were obtained. A source of radium E having an original strength of roughly 3 millicuries was used. The Faraday collector measurements (with foils in front of the collector) were carried out during the first six days. The individual values at each $H\rho$ were corrected to their average time by the use of an assumed half-life of 5.00 days, and the corrected values were then averaged together. The ionization current was measured at intervals of about every three days until the currents were too small to be measured conveniently with the large condenser (C_3), 25 days after the start of the experiment. These values were corrected for decay to the average time of the corresponding set of collector measurements and then were averaged together. Various values of the half-life, differing only very slightly from 5.00 days, were tried until one was found which gave a minimum probable error in the average value, and the corresponding average value of I_S was divided into the average value of I_F to give the quantity I_F/I_S [see Eq. (1)].

While this quantity was obtained by determining average values of I_F and I_S and by calculating their quotient, the analogous "weak source" quantity, n'/I_W, was measured directly

by making practically simultaneous observations upon n' and I_W, and the individual values of n'/I_W were averaged for calculating the final result. In obtaining the individual values, first the beam was sent into the counter and a reading was made upon it (by using at least 75,000 counts) while simultaneously the background current of the ionization chamber was measured. Then the field was reversed and the beam was measured twice by using the ionization chamber while at the same time the background of the counter was determined. Then the field was reversed and measurements upon the beam with the counter and upon the background of the chamber, similar to the first ones, were taken. The average value of the counting rate was divided by the average value of the beam current (after these had been corrected for background) to give n'/I_W. In this way corrections for decay, which are unreliable with such an old source because of the possible presence of impurities, were usually avoided, though they were made when necessary (never greater than 0.2 percent). These measurements were started when the counting rate had decreased to 300 counts per second, some forty days after the experiment was started, and were continued for several days. At each of the five values of $H\rho$ a separate Geiger counter was used. The resolving time of each counter was measured three times: at the beginning, in the middle, and at the end of "weak source" measurements. The results of the resolving time measurements are published elsewhere.[11]

The largest source of experimental error in the collector current and "weak source" ionization current measurements was due to fluctuations in the background current. If the error caused by these fluctuations is assumed to be inversely proportional to the square root of the time duration of the reading,[17] it can be easily shown[1] that one obtains the greatest accuracy by dividing the available measuring time equally between the beam and background measurements. It can also be shown[1] that if all the individual values of the same quantity are to have the same relative accuracy, the time duration of each reading should be made inversely proportional to the square of the strength of the beam. (Therefore, there is little advantage to be gained in carrying on measurements on such quantities for more than one half-life.) These principles were followed throughout these measurements.

The first preliminary experiment was so rough that it is sufficient to say that it gave a result of the correct order of magnitude. The procedure of the second preliminary experiment is different from that of the final experiment in several respects. The foils were not placed in front of the collector, and therefore a numerical correction had to be made. Also only two counters were used, but each was used at all values of $H\rho$. As a weaker source was used and fewer observations were made, the results were not as accurate.

TABLE I. Results of second experiment.

$H\rho$	Charge of β-particle: Counter foil corrections used	Collector foil corrections used
2200	-1.62_7	—— $\times 10^{-19}$ coulomb
2400	-1.63_4	-1.58_2
2650	-1.67_7	-1.58_3
2900	-1.68_4	-1.60_4
3400	-1.69_8	-1.57_6
Unweighted average	-1.66_4	$-1.58_6\times 10^{-19}$ coulomb
Or	-4.99	-4.75×10^{-10} e.s.u.

RESULTS

The results of the second preliminary experiment are given in Table I. While the foil corrections determined with the Faraday collector are the more reliable, values of the charge based upon both sets of corrections are given for comparison. It is to be noted that the values obtained with the counter foil corrections increase with $H\rho$, while those employing the collector foil corrections show no such dependence. The probable error in the average value is estimated to be less than 1.5 percent.

The results of the final experiment are shown in Table II and a summary of the experimental error of this experiment is given in Table III.

The first three items of Table III were found

[17] This assumption is based upon an analogy with the theory of counting (with a Geiger counter). If B counts are observed in a time T, the counting rate $N\equiv B/T$. The mean error in B counts is $B^{\frac{1}{2}}$ and the mean error in N is $B^{\frac{1}{2}}/T=(N/T)^{\frac{1}{2}}$. Therefore, as N is constant, the error is inversely proportional to the square root of the time. This assumption is probably more valid in the case of the ionization current measurement, for the fluctuations in the background are mainly due to the alpha-particle contamination of the chamber than in the case of the collector current.

TABLE II. Results of final experiment.

$H\rho$	I_F (10^{-15} amp.)	I_S (10^{-12} amp.)	$I_F/I_S \times 10^3$ (pure number)	n'/I_W (reciprocal coulombs $\times 10^{16}$)	Charge $= \frac{I_F/I_S}{n'/I_W}$ 10^{-19} coulomb
2200	-9.35_8	-4.11_4	2.27_5	-1.42_6	-1.59_5
2400	-8.74_2	-4.64_4	1.88_2	-1.18_3	-1.59_2
2650	-8.78_8	-5.37_4	1.63_5	-1.01_3	-1.61_4
2900	-8.31_0	-5.59_0	1.48_7	-0.92_7	-1.60_4
3400	-7.01_2	-5.30_9	1.32_1	-0.79_5	-1.66_2
				Average	$-1.61_3 \times 10^{-19}$ coulomb
				Or	$-4.83_6 \times 10^{-10}$ e.s.u.

If the value at $H\rho$ 3400 gauss cm is excluded (see text) the average value is $-1.60_1 \times 10^{-19}$ coulomb or $-4.80_0 \times 10^{-10}$ e.s.u

TABLE III. Summary of experimental errors of final experiment.

Origin	Probable error at $H\rho$ 2200	2400	2650	2900	3400
Collector current	0.15%	0.07%	0.05%	0.18%	0.23%
"Strong source" ionization current	0.18%	0.11%	0.11%	0.11%	0.15%
"Weak source" measurements (n'/I_W)	0.34%	0.55%	0.23%	0.39%	0.30%
Error due to error in resolving time	0.15%	0.10%	0.07%	0.17%	0.16%
Inherent error of counter	1.2%	1.2%	1.2%	1.2%	1.2%
Total (square root of sum of squares)	1.3%	1.3%	1.2%	1.3%	1.3%

by application of the theory of error to the data. The fourth item was determined by the method described in another paper.[11] It is to be noted that the fifth item, the "inherent error" of the counter, is so much larger than the others that these can be nearly neglected and therefore the five values are essentially equally accurate. The probable error in the average value due to these items is found by dividing 1.3 percent by the square root of 5, giving 0.58 percent. These are not, however, the only experimental errors involved. Others to be included [see Eq. (2)] are: error in ratio of the condenser capacities 0.1 percent; error in calibration of small condenser 0.3 percent; and the error in the calibration of the potentiometer 0.1 percent. The total experimental error in the average value is 0.7 percent.

It is debatable whether the $H\rho$ 3400 value should be included because of the large discrepancy between it and the other values. If it is omitted, the average deviation between the remaining individual values is much smaller than one has a right to expect on the basis of Table III, while its inclusion leads to an average deviation of just the right size. It should be remarked, however, that the application of the theory of error to so few values is hardly justified. The discrepancy is probably largely due to the particular counter used for this value, which gave a lower value than the other counters when they were all used to measure the same beam. (This counter was No. 8 of Table I of the paper giving the resolving time data.[11]) If this value is omitted, the average becomes -1.601×10^{-19} coulomb or $-4.80_0 \times 10^{-10}$ e.s.u. with a probable error of 0.7 percent, which because of the reason just stated is to be considered as the final average of the present measurements.

In addition to these experimental errors, there were some systematic errors which are listed in Table IV. These have all been discussed previously.

DECAY OF RADIUM E

In the final experiment the decay of the source was followed until 50 days after the start. The half-lives used to correct the "strong source" ionization were found to predict the activity accurately except at the very end when a slight amount of radium D content became apparent. Because of this impurity these half-lives were 0.1 percent too large. The corrected values are shown in Table V. The probable error of each is about 0.2 percent, and they may be 0.2 percent too large because of a systematic error caused by imperfect saturation of the ionization chamber.

CONCLUSIONS AND DISCUSSION

(1) The charge of the β-particle is found to be $-4.80_0 \pm 0.03_5 \times 10^{-10}$ e.s.u., independent of the portion of the momentum spectrum from which the particles are selected. This value is in agreement within the uncertainty of the measurements with the charge of the electron of $-4.8025_1 \times 10^{-10}$ e.s.u.[18]

(2) The half-life of radium E is found to be 4.99_0 days with a probable error of 0.1 percent and is found to be independent of the portion of the momentum spectrum from which the particles are selected. This value is in fair agreement with that of 4.975 days found by Curtiss.[19]

(3) Geiger-Mueller counters can be used for absolute measurements with probable "inherent" errors of about one percent. This error was the largest single error in this work. Before any attempt is made to perform another experiment of this type in which counters are used the cause of this error should be investigated in the hope of building counters which agree with each other more accurately.

The electron multiplier suggests itself as a possible alternative to the Geiger counter in such an experiment. As the resolving time[20] is much smaller, it might be possible to make the counting measurements with the same strength of beam as is used for the collector measurements. Another advantage is that it requires no foils as it operates in a high vacuum. However, much development work must be done on this instrument before it can be used in such an experiment.

The ninety-degree type of β-ray spectrometer is much better suited to this work than the 180-degree type, which was used in the present experiment, for, according to Stephens,[21] the ninety-degree type brings the beam to a focus at a point outside the magnetic field. Therefore, the focal point can be made to be at the center of the detecting instruments (counter, collector, and ionization chamber) rather than at a point in front of their entrance slits. The source should be mounted at the bottom of the spectrometer rather than at the top so that active deposits could not fall into the spectrometer and contaminate it.

TABLE IV. Systematic error.*

Origin	Estimated upper limit	Sign
Imperfect efficiency of Faraday collector	0.5%	Negative
Scattering	—	Positive
Secondary electrons	1%	Positive
Imperfect saturation of ionization chamber	0.2%	Positive

* Positive and negative systematic errors are defined, respectively, as those which give too large and too small a magnitude of the charge of the β-particle.

TABLE V. Half-life of radium E.

$H\rho$	Half-life (days)
2200	4.97_5
2400	4.99_5
2650	4.99_5
2900	5.00
3400	4.98_5
Average	4.99_0

The method developed in the present work could be used for measuring the charge of the positive β-particle (positron), but there would be some difficulties not encountered in the present work. There would be an inherent error due to the annihilation gamma-rays. As it would be very difficult to prepare a source entirely free of negative particles, one would have to equip the apparatus with reliable shutters for measuring the background, while in the present experiment the background was measured by reversing the field, for the shutters which were included in the apparatus were not found reliable.

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