The Application of the FP-54 Pliotron to Atomic Disintegration-Studies

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The possibility of utilizing the high inherent sensitivity of the FP-54 Pliotron in nuclear disintegration-studies, particularly in connection with the problem presented by the discrepancies in present experimental results on resonance-disintegration of aluminum, has been investigated. The usable sensitivity of the tube is found to be limited only by a residual fluctuation of about $\pm 3 \times 10^{-5}$ root-mean square volt. A theoretical consideration shows that this fluctuation is of the order of magnitude to be expected from shot-effects and thermal effects in the grid-circuit.

Disintegration-Experiments on Aluminum.—Preliminary observations on the disintegration of aluminum when using a thick target gave the following results. The yield was about 20 protons, of ranges between 30 and 50 cm per 10^8 α-particles, in good agreement with the results of Pose. Groups with ranges of about 30 cm and 60 cm were found to show the abrupt drop in the absorption-curve characteristic of Pose's results. (The present series of observations failed for purely technical reasons to give a conclusive result in the range 45 to 50 cm.) A "differential" curve neglecting the smallest deflections gave a maximum in the region 45 to 50 cm, suggesting the presence of a strong group of about this range. A discussion of other discrepancies in experimental data on the basis of FP-54 results must await further observations with a more suitable α-particle source.

INTRODUCTION

QUANTUM-MECHANICS as applied to the nucleus by Gurney and Condon[1] and by Gamow[2] has successfully accounted for the principal features of nuclear phenomena such as radioactive decay and the Geiger-Nuttall relation. To explain these effects it is only necessary to assume a potential barrier (U_r) surrounding the nucleus and compute by means of Schroedinger's equation the relative amplitude of the ψ-waves as a function of r. Since the probability of finding a particle at any point is, according to wave mechanics, proportional to the square of the amplitude of the ψ-wave at that point, this may be interpreted for the case of many nuclei as representing a large number of α-particles within the barrier with a few particles moving out through the barrier in numbers and with energies depending on the size and shape of the potential barrier. The form of the barrier, that is of U_r, for actual nuclei is given sufficiently well by observations on the scattering of α-particles for the above theory to give results in good agreement with experiment when applied to such nuclei.

By a slight extension of the above ideas the case of a nucleus bombarded by α-particles, that is, ψ-waves, incident on the potential barrier can be considered. It is found that the wave is partly transmitted and partly reflected and, as above, the probability of penetration of the barrier by an α-particle may be obtained from the relative amplitudes of the transmitted and reflected ψ-waves. However, because of the form of the solution within the barrier, two cases arise, each equally valid. In the ordinary case the reflected wave is large, giving a small probability of penetration and a correspondingly small yield of disintegration-protons. In the other case, which arises when the energy of the incident α-particle is nearly equal to that of one of the eigen values of the nucleus, the reflected wave is very small. Hence most of the impinging α-particles must penetrate the barrier, giving a yield of disintegration-protons far in excess of that produced by α-particles of other energies. This is the case of resonance-disintegration pointed out by Gurney.[3]

Experimental evidence which seemed to prove the reality of this effect was first obtained by Pose.[4] By bombarding an aluminum target with a heterogeneous beam of α-particles and by using a Hoffmann electrometer to detect the disinte-

[1] Gurney and Condon, Nature **127**, 439 (1928).

[2] Gamow, Zeits. f. Physik **51**, 204 (1938).

[3] Gurney, Nature **128**, 565 (1929).

[4] Pose, Zeits. f. Physik **64**, 1 (1930).

gration-protons, an absorption-curve was obtained which showed the presence of several groups of protons with definite ranges. By varying the ranges of the incident α-particles, it was possible to show that two of these groups were produced only by α-particles of definite ranges in agreement with the theory outlined above. However, Meitner,[5] de Broglie and Leprince-Ringuet,[6] and Chadwick and Constable and Pollard[7] in repeating this work, using other methods, failed to observe resonance. Consequently, considerable doubt was thrown on Pose's work and his results have been to a large extent ignored.[8] Recently Chadwick and Constable[9] have found indications of resonance but with energy-values differing from Pose. Steudel,[10] on the other hand, obtained evidence on the basis of which he denies the existence of resonance, while Diebner[11] working under Pose checked Pose's work in every detail.

Development of Apparatus

Up to the present time the three instruments which have been used in this work, namely, the point-counter, the linear amplifier, and the Hoffmann electrometer, have been the only ones with a sensitivity great enough to detect individual disintegration-protons. The possibilities of each of these methods have been fairly well covered by the above investigations, so that observations by an entirely independent method seems the most likely to lead to an explanation of the discrepancies. The possibility of developing such new instrument was suggested by the announcement of the FP-54 Pliotron, as a comparison of the constants in Table I will indicate. However, with the usual circuit nothing even approaching the sensitivity implied by the above constants can be obtained over the extended periods of observation required in disintegration-experiments. The single-tube circuit, for instance, was originally recommended only for currents greater than 10^{-14} ampere and the two-tube balanced circuit gives full sensitivity only for a few minutes immediately after opening the key. It was evident that radical changes in operating conditions were needed to adapt the Pliotron to the stringent requirements of artificial disintegration-studies.

Table I. *Comparison of Hoffmann duant and FP-54 Pliotron.*

	Hoffmann duant	FP-54 galvanometer
Capacity	3 cm	3 cm
Voltage-sensitivity	20,000 mm/v	250,000 mm/v
Period	30 sec.	5 sec.

The single-tube circuit as used by DuBridge,[12] shown in Fig. 1 was chosen for study since its sensitivity is inherently twice that of the balanced circuit. The most serious limitations of the original single-tube circuit were the erratic drifts (closed key) attributed to batteries, and the short-period fluctuations (open key) due to unknown causes.

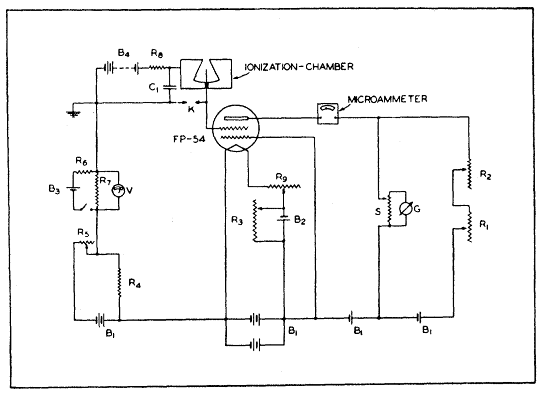

Fig. 1. Single-tube circuit used by DuBridge.

It was found that the closed-key drifts were primarily due to two things. The first cause was the erratic voltage-change in the batteries due to major readjustments of the circuit being made at intervals less than the time required for the batteries to reach equilibrium. This was overcome by running the tube continuously so that only

[5] Meitner, Phys. Zeits. **32**, 661 (1931).

[6] M. de Broglie et L. Leprince-Ringuet, C.-R. Acad. sci. **193**, 132 (1931).

[7] Chadwick, Constable and Pollard, Proc. Roy. Soc. **A130**, 463 (1931).

[8] Hoffmann, Zeits. f. Physik **73**, 578 (1932).

[9] Chadwick and Constable, Proc. Roy. Soc. **A135**, 48 (1932).

[10] Steudel, Zeits. f. Physik **77**, 139 (1932).

[11] Diebner, Zeits. f. Physik **75**, 753 (1932).

[12] DuBridge, Phys. Rev. **37**, 392 (1931); see also Ortner und Stetter, Zeits. f. Physik **54**, 468 (1929); Rasmussen, Ann. d. Physik **2**, 357 (1929).

minor readjustments were necessary after the first day. As it was found possible to run the tube for two months on a single battery-charge, continuous operation introduces no serious inconvenience. In fact, the fluctuations appear to decrease continuously for the first week. The second cause for closed-key drift was the variation in battery-voltage with room-temperature. This effect was eliminated by placing the apparatus in a constant-temperature room. It was then found that the drifts could be sufficiently reduced to permit preliminary observations of the short-period fluctuations (open key) to be made.

In order to take full advantage of the high input-resistance of the FP-54 tube, attempts were first made to operate the tube with the grid floating at its rated voltage, the open-key drift being compensated by balancing out the grid-current. Though this method had been used by Loveridge[13] at low sensitivities, the method failed because of the usual polarization-effects of the resistances in this work where the highest possible sensitivity is required.

Efforts were then transferred to the operation of the tube with the grid floating at its equilibrium-potential.* The input-impedance of the tube in this condition was considerably reduced, but this disadvantage was offset by the great gain in stability, the rate of drift being exactly the same with the key open as with the key closed. It was immediately evident that the expected residual ionization in the air about the tube was producing very large fluctuations. These were eliminated by evacuation of the case surrounding the tube.

Observations were next made by recording photographically the remaining fluctuations in order to determine the limits set by discontinuous emission, etc., in the tube itself. It appeared that sensitivities comparable to those of the two-tube balanced set could be obtained by this method. The above observations were repeated by Dr. Loveridge and the conclusions as to the limiting sensitivities checked by many measurements with different tubes and batteries and with altered operating conditions. The final conclusions reached, based on evidence then available, were communicated to Dr. Hull in connection with the symposium on electronic devices at Cambridge and were published by him in *Physics*.[14]

On the basis of these results, the writer attempted the photographic registration of pulses due to disintegration-protons in a manner similar to that used by Pose. This work requiring continuous runs of many consecutive hours, it was soon learned that the low drift-rates in the earlier work were of a temporary nature only, and that after the first several hours the rate of drift at a sensitivity of 50,000 mm per volt was always about 30 cm per hour in the direction of decreasing current. This represented a change in plate-current of 3 microamperes per week and corresponded roughly to that which would be expected because of the running down of the filament-batteries. To test this hypothesis a countercell—B_2 in Fig. 1—was inserted in the filament-circuit and a resistance across it so adjusted that the electromotive force of the countercell dropped at a rate just sufficient to keep the plate-current constant, as indicated by zero-drift of the galvanometer.[15] It was then found that the filament-voltage instead of remaining constant was gradually increasing, thus indicating that an appreciable part of the drift was due to a deactivation of the filament. This is an effect which cannot be compensated for in the usual bridge-circuits, so that the countercell-method of drift-compensation has distinct advantages when highest sensitivities are required.

Details of Apparatus

In Fig. 1 the batteries marked B_1 are ordinary lead-cells of about 100 ampere-hour capacity. New batteries were used, for it has been found that they are usually free from the spasmodic voltage-changes which are often, though erroneously,[16] attributed to "bubbling" of the batteries. The battery B_3 is a 1.5-volt dry-cell, while B_4 is a 144-volt Burgess *PL* battery. For the countercell, the battery B_2 in the figure, an Edison cell of 75 ampere-hours with a load-resistance of about 20 ohms was finally used. This cell is particularly

[13] Loveridge, *Dissertation*, University of California.

* I am indebted to Dr. A. E. Ruark for emphasizing the advantages of this method.

[14] Hull, Physics **2**, 409 (1932).

[15] Hafstad, Phys. Rev. **40**, 1044 (1932).

[16] Jaeger and Kussmann, Phys. Zeits. **28**, 645 (1927).

suitable for this purpose, for its discharge-curve (voltage *vs.* ampere-hours) is somewhat steeper than that for a lead-cell, so that a given rate of change of voltage can be maintained with a small drain on the battery.

A dry-cell has an even steeper discharge-characteristic, but cannot be used in the filament-circuit because of the relatively large currents flowing. It is very convenient, however, to compensate for the drift by using a dry-cell loaded with 20 to 30 ohms to balance out the plate-current in the galvanometer-circuit. In this case, the rate of fall of potential of the dry-cell can be adjusted so that the balancing current is always equal to the gradually falling plate-current and the galvanometer-drift is nil. While this method is satisfactory for most purposes, there is a gradual change in sensitivity corresponding to the gradual change in plate-current, so that when constant sensitivity over periods of weeks is desired the filament-circuit compensation has decided advantages.

The resistances R_1 and R_5 in the figure are General Radio decade-boxes (1 to 10,000 ohms) and were chosen in the original design to reduce contact-troubles. No trouble has been experienced from this cause, however, and any good variable resistance, such as the General Radio 371-A, should be satisfactory. In case the decade-boxes are used, it is advisable to mount them on insulating supports, as the insulation provided is not sufficient to prevent leakage-currents from affecting a sensitive galvanometer. The resistances R_2 and R_4 are General Radio units, type 510, giving 10,000 to 100,000 ohms, in steps of 10,000 ohms. These were used in order to give great flexibility while studying the circuit. R_3 and R_9 are ordinary filament-rheostats, while R_6 and R_7 are fixed resistors chosen to give a reading of about one millivolt on the meter when the key is closed. $R_8(50\times 10^6$ ohms) and $C_1(4\times 10^{-6}f)$ form a filter to reduce fluctuations in B_4. The galvanometer is a Leeds and Northrup type R of sensitivity 2600 megohms, with a period of about 10 seconds.

The ionization-chamber is of copper, made with a conical hole to reduce the volume and with a rounded end to permit each particle which enters to produce ionization along exactly 1.5 cm of path. No special treatment was found which would reduce the number of residual counts of the chamber below that obtained by cleaning with steel wool and mounting in place in the apparatus in a stream of commercial CO_2 with as little exposure to air as possible. The lowest residual-count obtained of pulses greater than 4000 ions was 0.5 particle per hour. This corresponds to about 6 particles per 100 sq. cm of exposed surface per hour, and is in good agreement with the value given by Ziegert[17] for clean copper.

The details of the mounting for the ionization-chamber and electrometer may be seen in Fig. 2. In the early stages of the investigation when frequent changes were necessary, all seals were made with ordinary soft red universal wax. This proved a great convenience, for no heating was necessary. Slow leaks were prone to develop, however, so picein was finally used and it was then found possible to hold a vacuum of less than one millimeter for over a month. By test it was found that pressures up to 2 or 3 millimeters gave no fluctuations due to residual ionization.

The lead for the collecting potential shown to the right of the tube in the figure is in reality behind the tube, that is, rotated through 90° into the paper, so as to avoid interfering with the grounding-key. A similar conductor was brought into the case on the opposite side of the tube to provide a connection for a grid-leak which, when used, was mounted on a key similar to but opposite the grounding-key. The high resistance leaks used were from 10^{10} to 10^{12} ohms and were purchased from the S. S. White Dental Supply Company, 152 West 49th Street, New York, N. Y. The thin foils used for the target and for the absorbers were obtained from the American Platinum Works, Newark, N. J. Information as to the stopping power of different metals was taken from Meyer-Schweidler, *Radioaktivität*, page 103.

Study of the Limits of Sensitivity Set by Residual Fluctuations

Before using the FP-54 under these conditions for recording pulses it was thought advisable to investigate its possibilities and limitations as a current-measuring device. Since by the counter-

[17] Ziegert, Zeits. f. Physik **46**, 677 (1928).

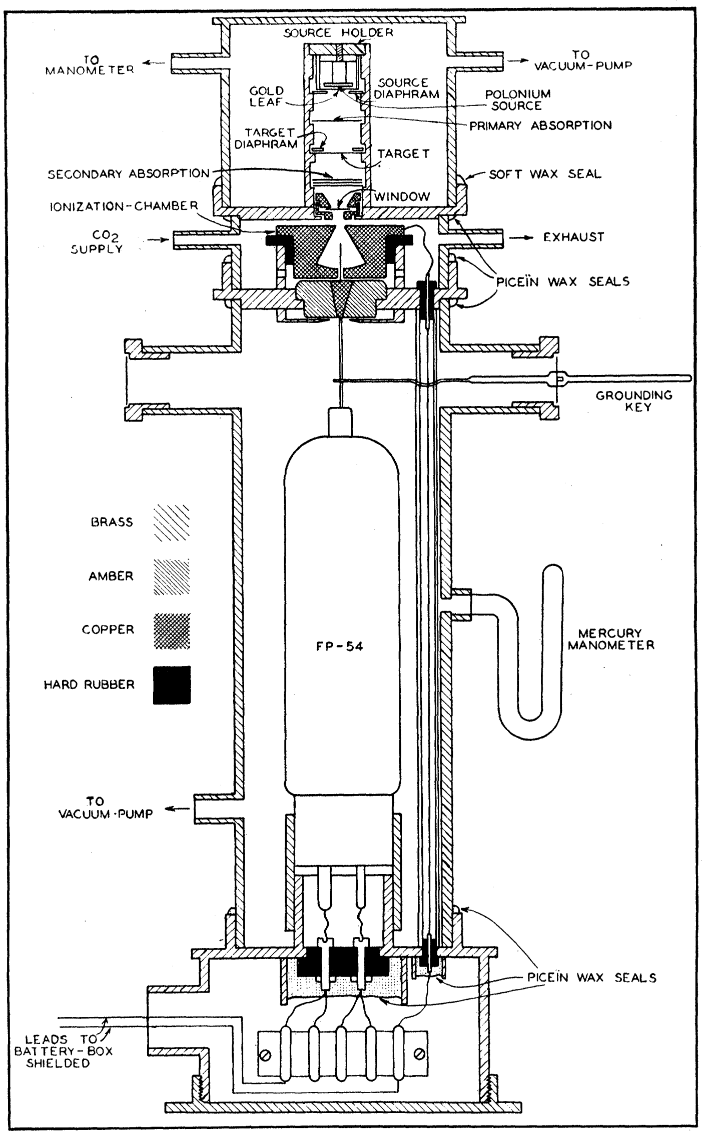

FIG. 2. Ionization-chamber and electrometer-mounting.

cell-method the plate-current may be made to increase or decrease at will, it is possible (with reasonable care and patience) to reduce the drift to any required degree. Furthermore, it has always been found that the fluctuations with the key open are greater than with the key closed, as shown by the two traces in Fig. 3. So long as this is true the fluctuations due to the batteries are smaller than those due to other causes and may be neglected insofar as limiting sensitivity is concerned.

The residual fluctuations might be attributed to any one of a multitude of causes, and a great deal of effort was spent in trying to eliminate them. Different tubes and different mountings in two completely independent sets of apparatus, one of Johns Hopkins University and one at the Department of Terrestrial Magnetism, however, gave approximately the same final value of the residual fluctuations. Most of the possible explanations of these fluctuations, such as mechanical vibration, stray electric or magnetic

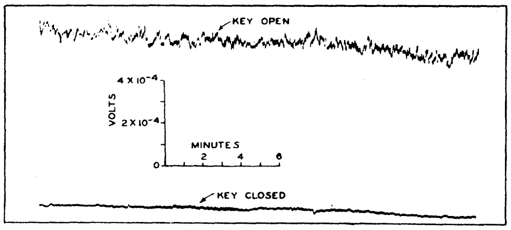

FIG. 3. Record showing fluctuations key open and key closed.

fields, charges on exposed insulators, etc., having been eliminated by direct tests, shot-effects or thermal effects seemed the only possible means of explanation. To check this possibility, traces were taken at a sensitivity of 250,000 millimeters per volt with the tube isolated in vacuum, that is, with no connection whatever to the grid. A short section of a representative trace is shown in Fig. 4. In justice to the tube it must be emphasized that this ragged trace was obtained at the extreme charge-sensitivity of 80 electrons per millimeter, since the capacity is 3 cm, or for convenience of comparing with other claims, a current-sensitivity of 4×10^{-20} ampere per millimeter, since the input-resistance is about 10^{14} ohms.

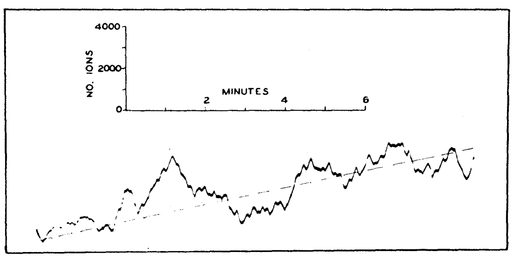

FIG. 4. Record showing fluctuations at 250,000 millimeters per volt.

The proper way of obtaining the mean-square deviation $\overline{\sigma^2}$ for this curve would be to obtain $(1/T)\int_0^T S^2 dt$ for this curve, where S is the deflection from the mean after correcting for the remaining drift.[18] A sufficiently good approximation for our purpose (order of magnitude only) may be obtained by scaling ordinates, measured from an arbitrary "mean" line at frequent intervals giving $(1/N)\Sigma^N{}_{K=1}S^2{}_K=\overline{\sigma^2}$. In the present case, ordinates were taken at 30-second intervals for a period of 40 minutes, giving $\overline{\sigma^2}=60$ mm, or a root-mean-square (r.m.s.) fluctuation of $\sigma=\pm8$ mm $\cong\pm3\times10^{-5}$ volt. This then is the experimentally determined value of the standard deviation to be compared with that predicted from theory on various possible hypotheses.

The usual formulas for shot-effect[19] and Johnson effect[20] give values which suggest that while the fluctuations might well be due to either shot-effect or Johnson effect in the grid-circuit, the disagreements in numerical values indicate that the ordinary formulas were used improperly, as will be clear from a discussion given below.

It occurred to the writer that an independent estimate of the magnitude of the shot-effect could be obtained in the following way. With the grid floating at its equilibrium-potential, it is known that the grid-current, which is zero by definition, is really composed of two components[21] equal in magnitude but opposite in sign. For the FP-54 each of these is about 10^{-15} ampere,[14] so that on the average a certain number of ions, say N, of each sign reach the grid every second. As this number varies due to shot-effect, there will be corresponding changes in the potential of the grid and consequently a similar variation in the plate-current as indicated by the galvanometer. The problem may be stated as follows. Suppose the grid to be the insulated electrode of an electrometer of sensitivity S mm/volt, with a capacity C, a negligible leak, and negligible period. What will be the root-mean-square deviation of the indicator from its mean position over any arbitrary length of time t?

This problem is identical with that raised by Von Schweidler's theory of the fluctuations in α-particle ionization with two identical sources, and has been treated at length by Campbell[22] and Kohlrausch.[23]

For the case assumed

$$\sigma=a(2Nt)^{\frac{1}{2}},$$

[18] Campbell, Cambridge, Proc. Phil. Soc. **15**, 126 (1910).

[19] Williams and Vincent, Phys. Rev. **28**, 1250 (1926).

[20] Johnson, Phys. Rev. **32**, 97 (1928).

[21] Nottingham, J. Frank. Inst. **209**, 287 (1930).

[22] Campbell, Cambridge, Proc. Phil. Soc. **15**, 521 (1910).

[23] Kohlrauch, Ergebn. Exakt. Natw. **5**, 192 (1926).

where σ = root-mean-square deviation and a = deflection of electrometer per electron. It is seen from this formula that σ increases indefinitely with t, as it should in the absence of leakage.

However, insulation-leakage and all other effects which tend to decrease the deflections with a velocity proportional to the deflection may be taken into account by imposing the additional condition that

$$ds/dt = -\beta s,$$

where s is the deflection.

If the question is then asked, what is the probability (w) of finding the galvanometer-spot between some deflection s and $s+ds$ at the time t, the equation

$$\partial w/\partial t = a^2 N(\partial^2 w/\partial s^2) + \beta(\partial(S\cdot w)/\partial s)$$

is finally obtained. This, however, is an equation which was solved by Smoluchowski[24] in a study of the Brownian movement of a particle in a viscous medium bound to its equilibrium-position by elastic forces.

The solution is

$$w(s_0, s, t)ds = \left[\frac{2\pi a^2 N}{\beta}(1-e^{-2\beta t})\right]^{-\frac{1}{2}} \exp\left[-\frac{(s-s_0 e^{-\beta t})^2}{(2a^2N/\beta)(1-e^{-2\beta t})}\right]ds,$$

where s_0 is the mean deflection. From this equation the deviation from the mean may be obtained and can be shown to be $\sigma^2 = a^2NRC(1-e^{-2t/RC})$ for our case where essentially $\beta = 1/RC$. When t is large this reduces to

$$\sigma^2 = a^2NRC = (e^2NR/C)S^2,$$

whence $\sigma = \pm 18$ mm $\cong \pm 7\times 10^{-5}$ volt.

On the basis of this result, we are led to believe that the residual fluctuation is caused by shot-effect in the grid-circuit, and it becomes of interest to consider more closely the failure of the ordinary formulas to give a correct answer in this case. Reference to the original sources shows that the ordinary formulas were derived for the general case of a tuned circuit containing both L and C, and which therefore responds only to a narrow band of frequencies in such a way that the input-impedance may be assumed constant over the band. In the present case, the variation of the input-impedance with frequency must be taken into account.*

The input-circuit may be considered as a resistance R and a capacity C in parallel. Following Schottky,[25] the grid-current may be expressed as

$$i = \sum_{k=0}^{\infty} B_k \sin(\omega_k t + \varphi_k),$$

where $\overline{B_k^2} = 4ie/T$ and where T is the time of the observation.

For the above combination of resistance and capacity in parallel, the conductance is $1/R$ and the susceptance is ωC, so that the impedance will be given by

$$Z = [R^2/(1+\omega^2C^2R^2)]^{\frac{1}{2}},$$

hence the voltage across the impedance due to a current i will be $v = iZ$ and

$$\overline{v_s^2} = \overline{i^2}R^2/(1+\omega^2C^2R^2)$$
$$= \sum_{k=0}^{\infty} \overline{B_k^2}\,\overline{\sin^2(\omega_k t+\varphi_k)}R^2/(1+\omega^2R^2C^2).$$

Then since $\omega_k = (2\pi/T)k$, $\Delta\omega_k = 2\pi/T = d\omega$ (when $\Delta\omega$ is sufficiently small), and the summation may be expressed as

$$\overline{v_s^2} = (4ei/T)(1/2\pi)\int_0^{2\pi} \sin^2(\omega t+\varphi)d\omega \int_0 [R^2/(1+\omega^2C^2R^2)]d\omega/\Delta\omega = eiR/2C.$$

* We are indebted to Dr. G. Breit for the derivations which follow.

[24] Smoluchowski, Ann. d. Physik **48**, 1105 (1915).
[25] Schottky, Ann. d. Physik **68**, 157 (1922).

Returning to the actual case, we have two currents statistically independent, hence

$$\overline{v_s^2}=\overline{v_{s1}^2}+\overline{v_{s2}^2}=eiR/C=e^2NR/C$$

in agreement with the previous calculation. This then is the proper formula for calculating shot-effect under the specified conditions.

Turning to the thermal effect, Nyquist[26] has calculated that the square of the voltage across a resistance R_v, at the temperature T, contributed by a frequency-interval dv is

$$\overline{v_T^2}(v)dv=4R_vkTdv=4R_vkT(d\omega/2\pi),$$

where k is Boltzmann's constant. For the grid-circuit as assumed above, the complex impedance is

$$z=R/(1+j\omega CR)=R(1-j\omega C)/(1+\omega^2C^2R^2)$$

and the real part of this is

$$R_v=R/(1+\omega^2C^2R^2).$$

Since the indicator (the galvanometer in this case) will respond to frequencies higher than the circuit itself, the observed fluctuations will be due to a summation of all frequencies permitted by the circuit; hence

$$\overline{v_j^2}=\int_0^\infty v_T^2(v)dv$$
$$=(2kT/\pi)\int_0^\infty [R/(1+\omega^2C^2R^2)]d\omega=kT/C.$$

Whence for the actual case $v_j=\pm3\times10^{-5}$ volt and $\sigma=\pm8$ mm.

A comparison of the values of fluctuation calculated by means of these new formulas with the observed fluctuation is given in Table II.

TABLE II.

Fluctuation	Volt	σ (mm)
Observed	3×10^{-5}	8
Computed, $v_s=(eiR/C)^{\frac{1}{2}}$	7×10^{-5}	18
Computed, $v_j=(kT/C)^{\frac{1}{2}}$	3×10^{-5}	8

From this comparison, the writer believes that there is sufficient evidence for attributing the residual fluctuations to either shot-effect or Johnson effect, or both, and that the limiting sensitivity for the present tube has been attained.

It is important to note that the formula for the Johnson effect is independent of the resistance and applies to the Hoffmann electrometer as well as to the FP-54. Since in any case the accuracy of a measurement is given by the ratio of the mean deflection to the fluctuation it is possible from the above formulas to determine the direction which further efforts to increase sensitivity must take. For steady deflection methods it appears from this ratio that there can be no gain in a further reduction in C contrary to reports in the literature. For rate-of-charge methods however the accuracy increases with $C^{-\frac{1}{2}}$. Vacuum-tube circuits and designs offer new possibilities in this direction.

CURRENT-MEASUREMENTS

For the measurement of moderately small currents it has been customary to use an input-resistance of the order of 10^{10} ohms. The stability of the present circuit has made it possible to use a resistance of 10^{12} ohms with a corresponding increase in sensitivity. It has always been found that in this case as well as in the case of the floating grid, the fluctuations are greater with the key open than with the key closed. Traces showing this effect are given in Fig. 5, the upper

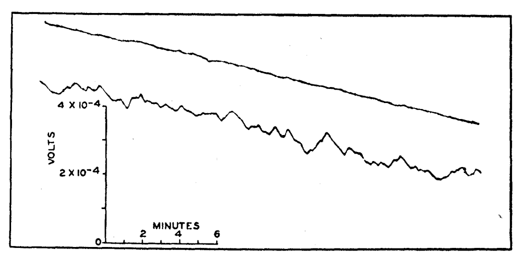

FIG. 5. Record showing fluctuations with resistance in circuit.

trace being taken with the key closed while the lower was taken with the key open. The sensitivity attainable in this way reaches the maximum which is useful in measuring ionization-currents produced by x-rays, β-rays, etc., since in such cases the unit of charge is really about 300ϵ (the average charge produced by a single particle) and the natural fluctuations are correspondingly large. The possibilities and limitations of the

[26] Nyquist, Phys. Rev. **32**, 110 (1928).

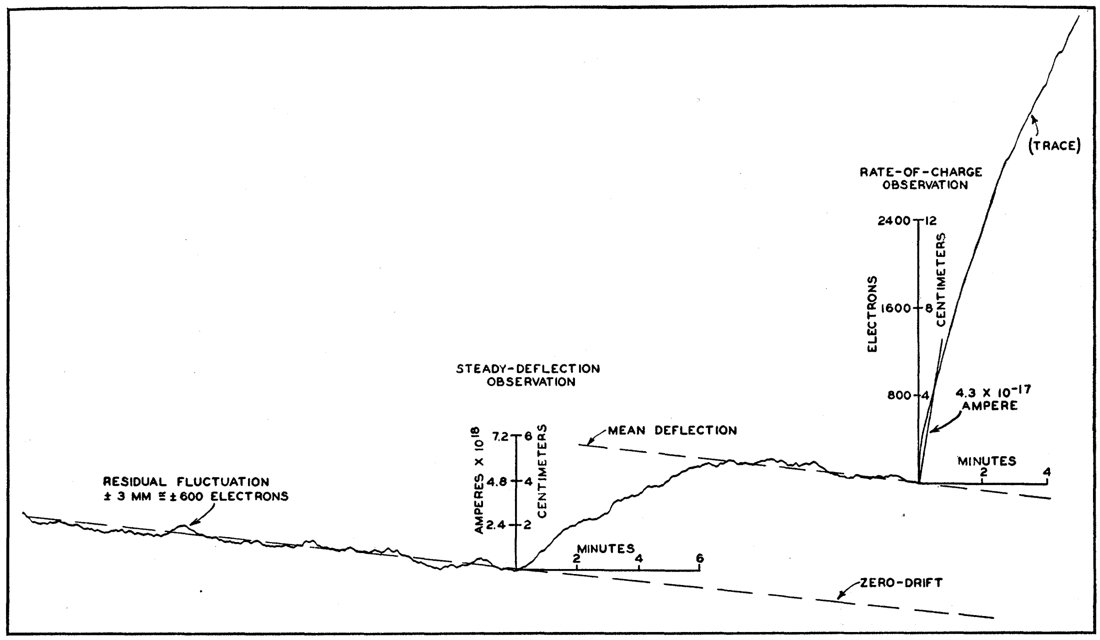

FIG. 6. Record showing deflection due to small steady current.

FP-54 for such measurements have been investigated by Bearden.[27]

In the case of photoelectric currents, however, the fluctuations depend only on ϵ and much higher sensitivities such as may be obtained with a floating grid are useful.

With the magnitude of the residual fluctuations known, it becomes possible to specify the smallest steady currents which can be measured. If we take as the criterion for detection a displacement of the mean equal to the observed root-mean-square deviation, then for the case shown in Fig. 4, $R=10^{14}$ ohms, $C=3$ cm, and $V=250{,}000$ v/mm, a current of 3×10^{-19} ampere or 2 electrons per second could be detected. The time-constant of the grid-circuit being 300 seconds, such a current could be detected in a time of several minutes. This may be taken as the practical limit of the present tube as set by the fluctuations themselves.

As an example of a small current-measurement, an observation was made by producing a current in the "evacuated" space surrounding the tube by gamma-ray ionization at an ordinary recording-sensitivity, no effort being made to attain maximum sensitivity. The resulting trace is shown in Fig. 6. In this case $C\cong 3\mu\mu f$ and $R\cong 10^{14}$ ohms from the time-constant for the curve and the voltage-sensitivity was 85,000 mm/volt. As calculated from these constants, the current-sensitivity and the charge-sensitivity are 1.2×10^{-19} ampere/mm and 200 electrons/mm, respectively. Two measurements are shown, one using a steady-deflection (galvanometer) observation and the other a rate-of-charge (electrometer) observation. In the first case, the deflection of 6 cm represents a current of 7.2 $\times10^{-18}$ ampere or 45 electrons per second. The fluctuations are roughly ± 3 mm so that this current may be measured to ± 5 percent in a time of several minutes. It is significant that the

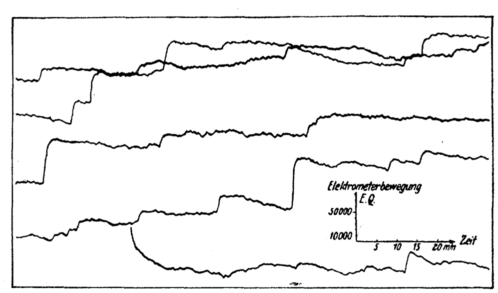

FIG. 7. Specimen record by duant electrometer (after Pose).

[27] Bearden, in preparation.

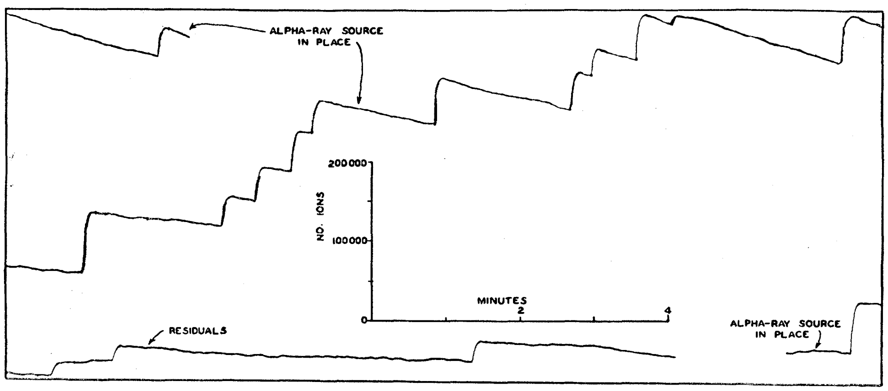

FIG. 8. Record showing alpha-particle deflections by FP-54.

fluctuations of ± 3 mm $\cong \pm 600$ electrons in this trace taken April 2, 1933, are the same as those in Fig. 4 taken on September 5, 1932, for this is independent evidence that the fluctuations represent an absolute limit independent of the state of the batteries, etc., and in agreement with the value predicted from theory.

In view of the above discussion, it might be questioned as to whether it is ever permissible to use the FP-54 as an electrometer for rate of deflection-observation. This obviously is entirely a question of the time-constants involved.

In general, for an electrometer used with a leak the deflection s at any time t will be

$$s = s_f(1 - \epsilon^{-t/RC}),$$

where s_f is the final deflection. This reduces to

$$s = (s_f/RC)t$$

when t is very much smaller than RC, that is, the deflection is strictly proportional to the time, and electrometer-methods may be used, so long as this condition is satisfied. The second measurement in Fig. 6 shows an observation of this kind. The deflection of 41 mm in 30 seconds represents a current of 4.3×10^{-17} ampere, while the magnitude of the fluctuations gives the accuracy as about 7 percent.

An immediate measure of the effectiveness of the FP-54 for pulse-measurements may be obtained by a direct comparison of traces secured with this instrument with those obtained by Pose using the Hoffmann electrometer (Figs. 7 and 8).

Preparation of Radioactive Source

Until very recently there has been little interest in the preparation of strong α-particle sources in this country and as a result both the highly specialized technique of their production and the material from which they might be prepared are largely confined to European laboratories. Because of this situation a really suitable source comparable in strength and purity to those used in Europe has not as yet been obtained, and it has been necessary to begin observations with such sources as it was possible to prepare with imperfect technique from a limited amount of material.

The writer was particularly fortunate in obtaining a considerable quantity of dead radon-bulbs from various hospitals,* from which sufficiently strong polonium sources for preliminary measurements could be obtained. Such bulbs are originally filled with radon and used for clinical

* The present work, as well as the program of nuclear disintegration-studies, when using radioactive sources, undertaken by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, was made possible only by the generous cooperation of the following individuals and institutions, for which grateful acknowledgment is made: Dr. C. F. Burnham and Dr. F. West, Kelly Hospital, Baltimore, Maryland; Dr. G. Failla, Memorial Hospital, New York, New York; Dr. J. L. Weatherwax, Philadelphia General Hospital, Philadelphia, Pennsylvania; Dr. M. C. Reinhard, State Institute for the Study of Malignant Disease, Buffalo, New York; Dr. Carl E. Nurnberger, University Hospitals, Minneapolis, Minnesota; Dr. Otto Glasser, Cleveland Clinic Foundation, Cleveland, Ohio; and Dr. Roscoe W. Teahan, Jeanes Hospital, Philadelphia, Pennsylvania.

purposes. Because of the short life of radon and the succeeding products—RaA, RaB, RaC—the radon quickly decays into RaD which has a half-life of 25 years. As RaD decays, RaE and finally RaF are formed in minute quantities of the order of 10^{-7} to 10^{-8} gram per bulb. The latter substance is polonium, which emits only α-particles and forms an almost ideal source for atomic disintegration-studies. It is this material which must be extracted from the bulbs, freed from impurities, particularly from the relatively large amount of mercury which is usually trapped in sealing off the bulb, and concentrated on as small an area as possible to approximate a point-source for the disintegration-experiments.

In order to avoid contamination of the laboratory in which the observations were to be made, permission was obtained to carry out the chemical reductions in an attic room at the Bureau of Standards in Washington. To further insure against spreading the highly active material and thus increasing the residual counts of the observing apparatus, a complete change of clothes was made when working in the chemical laboratory, rubber gloves were worn throughout the manipulations, and finally a direct test for contamination on fingers and clothes was made by means of a point-counter before entering the observing laboratory.

The procedure followed in the chemical purification was that given by I. Curie,[28] in which the final source is obtained by electrochemical deposition on silver without current, though some sources were also made using the electric-current technique.[29] The purification-process proved to be extremely tedious, since the β-ray activity of each beaker, filter-paper, precipitate, and solution (after evaporation to dryness) was measured after each step in the process and followed for several days thereafter to insure against loss of the minute quantities of active material present.

After several weeks of work a source of about 1.1×10^8 alpha-particles per second was obtained which was moderately free from β-rays. The strength of this source was measured by placing it at one end of a long evacuated tube and recording photographically by means of a linear amplifier like that of Wynn-Williams and Ward[30] the number of α-particles which passed through a small hole in the other end.

Resonance-Disintegration of Aluminum

The procedure in the study of disintegration-protons from aluminum was identical with that used by Pose. The first question to be settled was whether or not an absorption-curve for protons from a thick target obtained with this instrument would agree with those of Pose and Diebner. Obtaining such curves is an exceedingly slow process. Many protons must be counted for each point in order to keep statistical errors small so that several days of observation may be required to obtain a single point on the curve. Fortunately, the instrument runs without attention (except for changing traces), so that usually ten or more hours of usable records can be obtained each day. From these records, graphs were made for each of a number of different amounts of secondary absorption. These graphs in turn gave the yield in protons per hour. Data were obtained in this way for proton-ranges up to 50 cm, at which stage the series of observations was brought to an abrupt stop by an accident whereby the evacuated source-chamber was filled with pump-oil.

The data already obtained, however, were reasonably good. The statistical error should be small, for about 200 protons were counted for each point; the angles were small and well defined, since any point on target could "see" the ionization-chamber; and the strength of the source was quite accurately known. Under these conditions, a calculation could be made of the number of protons produced per 10^8 α-particles incident on the target in order to obtain a direct comparison with the yields given by Pose. The results of this calculation are shown by graphs *a* of Fig. 9. It will be noted that the yield for the range from 30 to 50 cm is in almost perfect agreement with that obtained by Pose. Furthermore, the pronounced maximum at about 45 cm in the lower curve, in which only deflections greater than 8000 ions are counted, suggests the

[28] I. Curie, J. chim. Phys. **22**, 471 (1925).

[29] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, 554 (1930); Erbacher, Naturwiss. **20**, 390 (1932).

[30] Wynn-Williams and Ward, Proc. Roy. Soc. **A131**, 391–404 (1931).

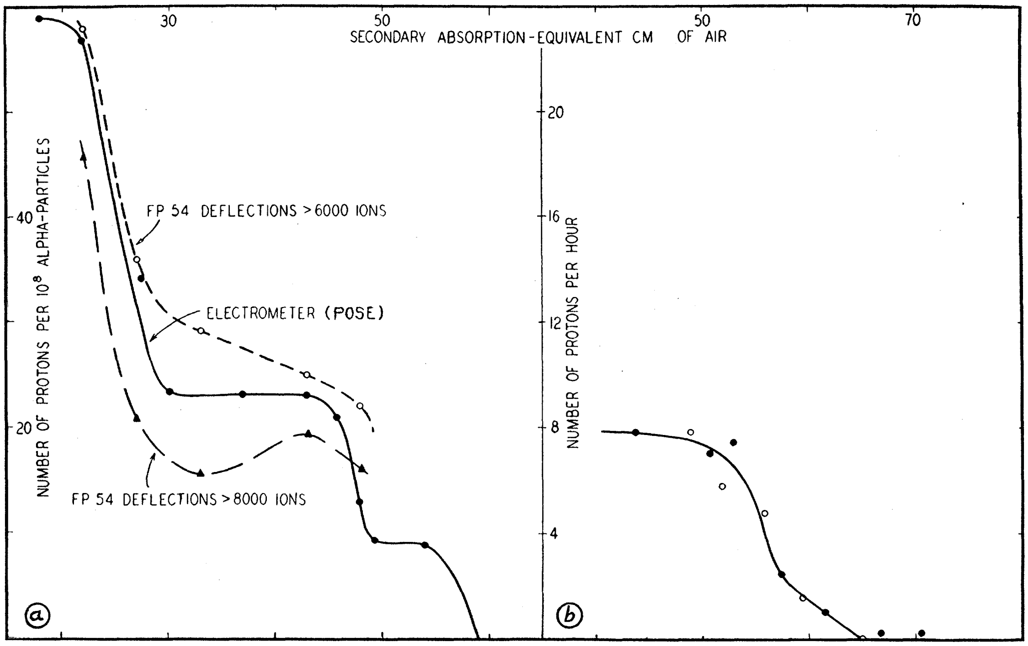

FIG. 9. (*a*) Comparison of disintegration-yields; (*b*) Absorption-curve for disintegration-protons.

presence of a strong group of about this range, since the larger deflections are due to slow protons near the end of their path. Both of these results are in direct contradiction to Steudel, who finds only a very weak group of range 49 cm and a yield many times smaller than that of Pose. In addition to these results we may also note that the absorption-curve taken with FP-54 shows the abrupt drop at 30 cm characteristic of Pose's results rather than the more gradual drop of Steudel's curve. In making this comparison two points must be emphasized. The first is that the scale of ordinates in Steudel's curve is quite arbitrary, since only Pose and Diebner give their results in terms of absolute yields, that is, number of protons per 10^8 α-particles, and that in view of the diversity of sources and angles used by the different investigators it is practically impossible to make comparison on any other basis. The other point is that the FP-54 curve *a* in Fig. 9 for deflections greater than 6000 ions may be too high, because of sudden displacements of the trace caused by β-rays which can be mistaken for protons, but is certainly not too low, for such deflections are greater than 6 mm and cannot be accidentally ignored. This statement, of course, does not deny that protons producing only 2000 or 4000 ions might be missed. The important fact is that for sensitivities comparable to those used by Pose the yield is the same as his. At higher sensitivities the yield might be greater but certainly would not be less as found by Steudel.

In order to complete the curve the chamber was cleaned, the source washed in benzol, and a new series of observations begun. It was found, however, that the proton-yield was so much reduced, presumably due to absorption of the α-particles by hydrocarbons on the surface of the emitter that an arrangement with larger solid angles was required. Unfortunately, in increasing the solid angles to give greater proton-yields, the solid angle subtended by the ionization-chamber at the source was so much increased that β-ray troubles became very serious and observations below 50 cm could not be made. The form of the absorption-curve for ranges beyond 50 cm is shown by *b* in Fig. 9. Two sets of observations were made as indicated by the circles and dots in the figure. While the conditions under which these observations were taken obviously were not as good as for the first series, the two sets of points are still fairly consistent, and it must be concluded that there is an abrupt drop beyond

50 cm, again in agreement with Pose and contrary to Steudel. In this case, a calculation of the yield may be expected to give a low result, since no doubt many of the α-particles leaving the source have energies greatly reduced by absorption on the source itself. As a further check of the yields, however, the strength of the source was again measured and a rough calculation gave 13 protons per 10^8 α-particles at 50 cm secondary absorption compared to 22 for Pose and perhaps about 3 for Steudel.

The above work having shown the necessity of using a better source, before attempting to study such questions as the sharpness of resonance, the observations were stopped and efforts directed toward obtaining a source both stronger and more free from β-rays. A new supply of radon-bulbs was acquired through the courtesy of the hospitals listed above and the chemical reduction is now under way.

This work was begun at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in the spring of 1931, carried forward at the Johns Hopkins University where the writer was in residence during the academic year 1931–1932, and brought to completion in 1933 at the Department of Terrestrial Magnetism. The writer wishes to take this opportunity for acknowledging his indebtedness to the many whom he has consulted regarding various phases of this problem. The following should be especially mentioned: Professor J. A. Bearden, under whose immediate direction the work at the Johns Hopkins University was done; Dr. L. F. Curtiss of the United States Bureau of Standards, for generous assistance in connection with the preparation of sources; Dr. M. A. Tuve, for continuous advice and encouragement; and Acting Director J. A. Fleming of the Department of Terrestrial Magnetism, whose active support has made the work possible.