

Secondary Electron Emission of Crystalline MgO

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Secondary emission is measured from single crystals of MgO cleaved along the (100) plane. The maximum ratio of secondary to primary current, δ_{\max} , is about 7 at about 1 000 volts and room temperature. The cross-overs are at 33 volts and far above 5 000 volts. Most probable energy of emission is 1 ev or less. A definite effect of temperature is established, δ decreasing with increasing temperature, in accord with expectations for an insulator.

OBJECT

THIN insulating films made in a variety of ways have long been used as "dynodes" in devices operating on the basis of secondary emission, and the emission properties of many of these films have been studied, particularly those of MgO. The results have varied widely with the methods of production and treatment. There often appears the abnormal emission associated with the Malter effect. Because of experimental difficulties, however, work on insulators in bulk form has not been extensive.¹

The purpose of the present work was to obtain data on the secondary electron emission evoked by electron bombardment of a simple massive insulator of known structure and properties, for elucidating the mechanism of secondary emission from insulators. Magnesium oxide in the form of single crystals was chosen as the material studied. It has the advantages of having simple body-centered cubic structure and good cleavage and of being very inert and refractory so that it can withstand the severe heat treatment in vacuum needed to insure the cleanness of its surface. Besides this, many of its physical properties are well known.

METHOD AND APPARATUS

The method employed here is essentially the one used earlier in the measurements on the oxide cathode,² with differences in detail. The primary electrons bombard the uncharged target in short pulses. By applying to the nearby collector electrode a steady

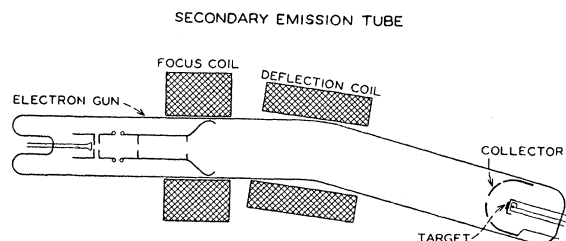


FIG. 1. Secondary emission tube.

negative or positive potential, the current in the target circuit becomes either the primary electron current alone, or the difference between the secondary and primary current, so that the ratio δ of secondary to primary current can be established. The problem with the insulating target is to obtain the measurement with the target initially neutral and before appreciable charge is accumulated during the measurement. The essentials of the present method are that the target is heated to about 600°C before each measurement to relax surface or volume charge by conduction, and that then the single measurement is made at room or other temperature with a pulse of primary electrons of low current density and short duration.

EXPERIMENTAL TUBE

The experimental tube is shown schematically in Fig. 1, with details of the target structure in Fig. 2. At one end of the tube is an electron gun of conventional design for electrostatic control. The cathode is a flat ribbon of tungsten and all other metal parts are of tantalum. The electron beam is focused principally by a magnetic focus coil and is positioned on the target by a magnetic deflection yoke, as shown in Fig. 1. The tube is bent at an angle of 15° in order to protect the target from negative ion bombardment and from the direct light of the filament.

The target assembly is located at the other end of the tube. The target is a thin plate of the MgO mounted on the flat end of a cup-shaped base of tantalum $\frac{5}{16}$ in. in diameter. It is held in place by hooks of thin molybdenum wires. Within the cup is a coil of tungsten wire for

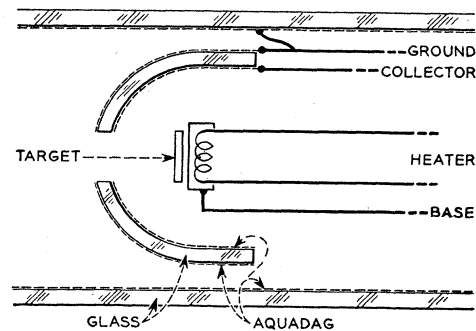


FIG. 2. Target and collector assembly.

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¹ For a review of this field see K. G. McKay in *Advances in Electronics* (Academic Press, Inc., New York, 1948), Vol. 1, p. 65.

² J. B. Johnson, *Phys. Rev.* **73**, 1058 (1948) and **83**, 49 (1951).

heating the base and target. The collector is a graphite coating on a hemispherical glass dome of one in. diameter with the target at its radial center. A $\frac{1}{4}$ in. hole at the apex admits the electron beam. The outside of the dome and the inside of the main tube are covered with colloidal graphite, serving as an electrostatic shield and as a connection to ground for the second anode. The tube was constructed with great attention to cleanliness. Before assembly of the tube the graphite coatings were baked at 500°C in flowing CO_2 or air. The metal parts of the tube were vacuum pre-glowed, as far as possible. Welds were freed from copper by chemical treatment. The electron gun was degassed at high temperature in a separate tube before assembly. The tube was exhausted on a clean vacuum system with mercury vapor pumps, with extended baking and outgassing. It was sealed off, without getter, at a pressure of about 10^{-8} mm Hg. Each target was mounted in a separate tube.

The target specimens were cleaved along the (100) plane from a clear single crystal of MgO, grown by Rochow³ some years ago. Details are given in Table I. Spectro-chemical analysis of the present crystal revealed the following impurities: Ca < 0.3 percent

TABLE I. Thicknesses and electrode elements used on MgO targets.

Sample identification	Thickness cm	Backing element for contact with base plate
A	0.165	platinum
B	0.127	colloidal graphite
C	0.025	colloidal graphite
D	0.035	palladium

(probably substitutional in the lattice); very slight trace, < 0.001 percent, Ag, Al, Cr, Cu, Fe, Na, Si. No analysis is available on the Pt used on target A. The Pd used on target D is thought to have impurities Mg, Al, Fe, Au, to a total of 0.1 percent. The colloidal graphite contained the following impurities: Fe 0.1–3 percent; Ca, Mg, Mn, Si, 0.01–0.03 percent; Al, Cu, Na, Pb, Sn, Ti, < 0.03 percent.

CIRCUIT AND OPERATION

The circuit is indicated in Fig. 3. The electron beam is turned on by a pulsing circuit with variable amplitude (microamperes), duration (microseconds), and repetition rate (single pulse, 4 pulses per second, 60 pps geared to the power frequency, etc.).

The current in the target circuit flows to ground through the input resistance of an amplifier which has a frequency band-width of about 10 megacycles and drives the beam of a 5XP11 C.R.O. operated at 10 kv. Deflections in a single sweep of 20- μsec duration can be observed visually or photographed against a fine line reticle.

³ E. G. Rochow, J. Appl. Phys. 9, 664 (1938).

Except for the lowest values of V_p the collector was usually held at -40 or $+40$ volts. The -40 is set by the fact that by far the larger fraction of secondary electrons leave the target with energy less than 40 ev, so that the current in the target circuit is then essentially the primary current. The $+40$ volts is set to keep down the effect of charging of the target. When the collector is positive and when $\delta > 1$, then the target surface accumulates a positive charge until its potential approaches that of the collector or even exceeds it by a few volts so that the sum of incoming primary current

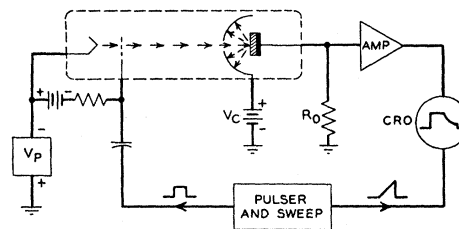


FIG. 3. Block diagram of circuit.

and escaping secondary current is eventually zero. Before this condition is reached the secondary current begins sharply to decrease when the target potential passes the collector potential and the slower secondary electrons cannot escape to the collector against the opposing field. Arrival at this condition is delayed by making the positive collector potential large, the beam current small, the beam area large, and the target thin so that the electrostatic capacity of the bombarded area is large.

A photograph of some pulses will make these considerations clearer. In Fig. 4 are shown four pairs of primary and secondary pulses, the primary pulse downward and the secondary pulse up, *a* and *b* single traces,

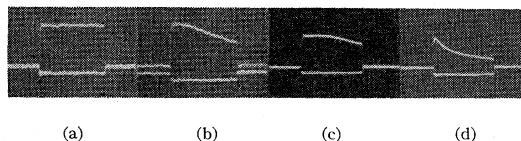


FIG. 4. Primary and secondary pulses. Target D, room temperature. Downward pulse, primary current; upward pulse, secondary current. V_c lowered in order *a*, *c*, *b*, *d*. *a* and *b* are single traces; *c* and *d* show 30 repetitions in 0.5 sec.

c and *d*, 30 repetitions in 0.5 second. In Fig. 4(a) conditions were such that there was no visible effect of charging during the period of $10 \mu\text{sec}$; in (b) and (c) the point where the target potential passes the collector potential is marked by a break in the line; in (d), where the beam was sharply focused and the collector voltage low, the break came in less than the resolving time of the system.⁴ In this work the conditions were always

⁴ Proposals for using the break and the subsequent curve shape for analysis of initial energy distribution of secondaries from insulators have been made by K. G. McKay, J. Appl. Phys. 22, 89 (1951) and R. Barthelemy, Compt. rend. 232, 20 (1951).

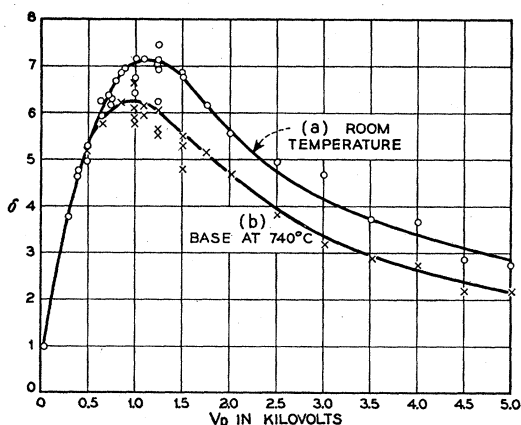


Fig. 5. Yield δ versus bombarding voltage V_p . Target C.

adjusted so that readings could be made before the break in the flat top of the curve.

The temperatures quoted are the optical pyrometer temperatures of the base plate. The temperature of the crystal was presumably somewhat lower.

EXPERIMENTAL RESULTS

δ vs V_p

The yield curves for specimen C are shown in Fig. 5, and these are typical of the curves for the other specimens. At room temperature, curve (a), the yield δ reaches a maximum of about 7, when V_p is about 1200 v.⁵ The first crossover, V_p^I , where $\delta=1.00$, is at very low primary energy, and the curve suggests that the second crossover is far above 5 kv.

The results for the other specimens of MgO were qualitatively similar, but nevertheless disclosed some quantitative differences. At room temperature, for example, the maximum yield δ_{max} was 5.5 for specimen A and 6.8 for specimen D. It seems unlikely that the treatment of these similar crystals could have introduced lattice distortions sufficient to cause such differences. Rather it must be the surface that in either physical structure or in work function was altered by the treatment after cleavage. A fresh surface of MgO tarnishes slowly on exposure to moist air, and the products of this tarnish might well persist after the heat treatment and affect the work function of the surface.

δ vs Temperature

With the base plate at 740°C the yield is substantially reduced, as shown by curve (b) Fig. 5, in the range of high V_p . In the lower range the yield is little changed by temperature. The primary energy of maximum yield V_{pmax} is lowered slightly but definitely as the temperature increases. Figure 6 gives the variation of yield with heater setting and temperature for this specimen,

⁵ This is in general agreement with work on MgO recently reported by K. C. Nomura, Phys. Rev. 89, 894 (1953).

in the region of V_{pmax} . Such curves are reproducible, and there is no doubt of this temperature effect. This is in striking contrast to the behavior of clean metals which show no variation of yield with temperature.¹ This temperature sensitivity at higher V_p , and the shift of V_{pmax} has a clear meaning. Temperature cannot appreciably affect the collisions and depth of penetration of the primary electrons, especially the higher energy ones. What is involved must be rather the probability of escape of the internal secondaries. The escape process can change either by variation of the work function at the surface or by changes in the rate of energy loss of the internal secondaries. Change in work function would alter the whole curve because it would affect all escaping secondaries alike, whether liberated by low energy primaries near the surface, or at greater depths by high energy primaries. It is assumed that, as with metals, the energy distribution of the emitted secondaries is essentially independent of V_p . Lattice disturbance by temperature, on the other hand, would hinder the escape of the internal secondaries, the more so the greater the depth from which they come. The yield at low V_p and low penetration of the primaries would be little affected by elevated temperature except for possible changes in work function. In the region of high V_p , however, the increased lattice interaction at higher temperatures would decrease the yield and thus shift V_{pmax} to lower values. The observed lowering of yield and of V_{pmax} is then undoubtedly caused by the increased temperature vibration of the lattice.

FIRST CROSSOVER

The primary energy V_p^I at which the yield is unity can be determined quite accurately, because at this point the net current in the target circuit is zero, even though the primary current may be large. The value of V_p^I is remarkably independent of temperature, as shown by Fig. 7 for specimen C, and is here 32.8 ± 0.2 volts over the temperature range.

At this low energy the range of the primary electrons must be not over two or three atom layers, and the escape of the secondaries depends more on the work function than on the lattice. The constancy of V_p^I therefore suggests that the work function is relatively

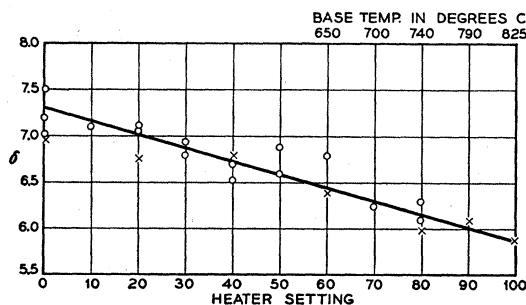


Fig. 6. Yield δ versus heater setting and temperature. Target C. V_p near V_{pmax} .

insensitive to temperature change and that lattice vibrations are responsible for the change in yield at higher V_p .

SURFACE CHARGE AND INTERNAL FIELD

When an insulating target is bombarded by electrons whose energy lies between the two crossovers, positive charge collects on the surface so as to make the potential eventually slightly more positive than that of the collector. An electric field is then set up through the target. There is a question as to whether such a field can change the secondary yield.

The simplest approach is merely to calculate the field uniformly distributed through the thickness of the sample that is developed when the target surface is at collector potential. For a collector potential of 40 volts and a crystal thickness of 0.025 cm, this gives a field of 1600 volts/cm which is far too low to affect the secondary yield. However, a more stringent limit is set by the transient behavior. From pulses such as those shown in Fig. 4(a) we know that the yield remains constant for at least 10 μ sec following its rise time of 0.1 μ sec. Thus, if field enhancement plays a role, it must set in and reach a final constant value during the rise time with a field which is then no more than 16 volts/cm. If we assume that all the positive charge resulting from the charging-up process resides on the surface, then the internal field will depend solely on the net positive charge and thus will be independent of the sample thickness by Gauss' theorem. Specifically, this means that even if the entire target voltage drop is concentrated across a layer that lies within a few hundred angstroms of the surface, the field will still be no more than 16 v/cm at 0.1 μ sec. Any distribution in depth of the net positive charge will reduce this subsurface field. Moreover, the mobility and finite lifetime of the internally produced electrons and positive holes result in a local conductivity which opposes the formation of a field in this subsurface region.

If there are no strong local fields built up in the process, it should then be possible to remove the surface charge of the target and restore the potential to a desired uniform value after a measurement by bombarding the target with the collector potential at a value near zero instead of by our customary heat treatment. That this may not happen is shown by the two curves

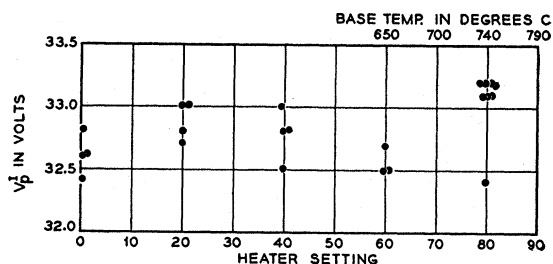


FIG. 7. First crossover V_p^I versus heater setting and temperature. Target C.

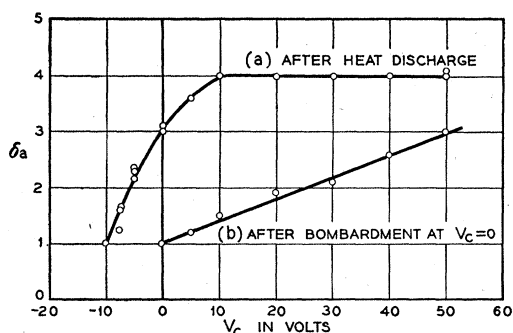


FIG. 8. Effect of surface charge. Apparent δ versus collector voltage. Target A. $V_p=300$ volts.

of Fig. 8, displaying apparent secondary yield as a function of collector potential. In both curves the yield was obtained at room temperature for specimen A. In curve (a) the target was heated and cooled down after each reading, while in curve (b) the surface was bombarded at $V_c=0$ after each reading. The latter curve lies considerably below the former, showing that bombardment discharge is not equivalent to heat discharge. The difference is probably ascribable to a patch-field effect rather than the formation of internal dipole layers. At the bombarded area primary electrons arrive and slower secondary electrons leave, and this area takes nearly the potential of the collector. The surrounding area receives slow electrons—secondaries that come from the bombarded area, or tertiaries from the collector—for which δ is usually less than unity. It can therefore become more negative than the collector and the bombarded area.⁶ The field set up by this negative charge acts in a grid-like manner to suppress the emission from the bombarded area when the collector is positive. There seems to be nothing in Fig. 8 that cannot be ascribed to this process rather than to dipole layers in the target.⁷

ENERGY DISTRIBUTION

The distribution in energy of the secondary electrons was observed roughly by the retarding-potential method, the potential of the collector being varied in successive bombardments by a fixed primary current. A retarding-potential curve for specimen D is shown in Fig. 9. Like the δ measurements, the curve is based on the slightly erroneous assumption that no secondary electrons have energy higher than 40 ev. Differentiating a smooth line drawn through the points of Fig. 9 gives the curve of Fig. 10 which is the distribution-in-energy of the secondary electrons from this target. The most probable energy comes at the right of the zero axis, which indicates a difference in contact potential between the MgO and the carbon film. The work

⁶ F. C. Williams, Proc. Inst. Elec. Engrs. (London) 96, 81 (1949).

⁷ The results of H. Hintenberger may involve such an effect of patch-fields [Z. Physik 114, 98 (1939)].

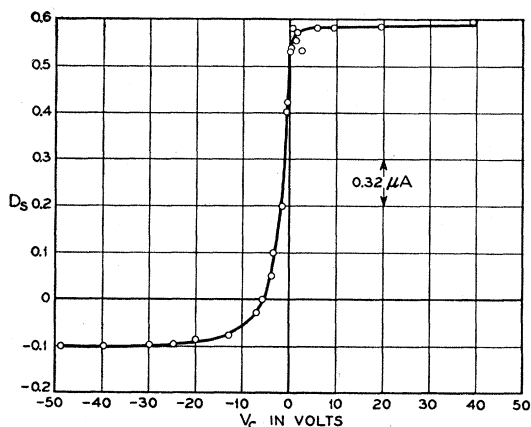


FIG. 9. Retarding potential curve. Target *D*. $V_p = 1000$ volts. Room temperature.

function of MgO is thought to be about 3.0,⁸ and that of carbon about 4.7. The collector would then be over 1.5 volt negative with respect to the target, and the curve should be shifted to the left by this amount. The most probable energy of emission is therefore approximately 1 ev.

DISCUSSION

Insulators generally have higher secondary yields than metals. This difference is usually ascribed primarily to two sources: (1) the energy required of a free electron to escape from the solid, (2) the rate of loss of energy of the internal secondaries as they approach the surface. These two factors do not act independently, for, if the rate of energy loss is high for all energies of the internal secondaries which lie between their initial energy and that required for escape, the yield should be low. This represents the situation in metals where there are many free and bound electrons with which the secondaries can make allowable collisions involving either large or small transfers of energy. This process quite overshadows the effects of electron-phonon interaction, and it continues until the secondaries approach thermal equilibrium. This concept fits well with the universally low secondary yield of the pure metals and is in accord with the observation that the yield from clean metals is quite insensitive to change in temperature of the target over a wide range.

In a similar way, in insulators the rate at which high energy internal secondaries lose energy is large, through interaction with the bound electrons of the valence band. However, neglecting collisions with impurities, the minimum energy that can be lost in this process is equal to the forbidden energy gap E_G . In MgO ultraviolet absorption measurements suggest that E_G must be at least 5.6 ev,⁹ and the energy required for escape is less than 3 ev.⁸ Thus for electrons with kinetic energy lying between about 3 and 6 volts, the only available

mechanism for energy loss is through interaction with the phonon field.¹⁰ Although the collisions be frequent, the energy lost per collision is very small. These electrons have, therefore, a higher probability of reaching the surface from a considerable depth with sufficient energy to escape. This implies a high yield with δ_{max} occurring at a large value of bombarding voltage and also an energy distribution with a large preponderance of electrons of less than about 3 ev energy. Moreover, the rate of energy loss by electron-phonon interaction should increase with the temperature, thus reducing the yield. Our experiments agree with these expectations.

The specimens studied showed a wide range of resistance. If this is attributed to a volume effect, the observed resistivities varied from about 10^{10} ohm cm to about 10^{16} ohm cm. This must involve lattice disturbances by either impurity atoms or stoichiometric excess of one of the component elements. Weber⁹ and Nomura⁵ have studied the effect of these disturbances on the properties of the crystal. In the present case the

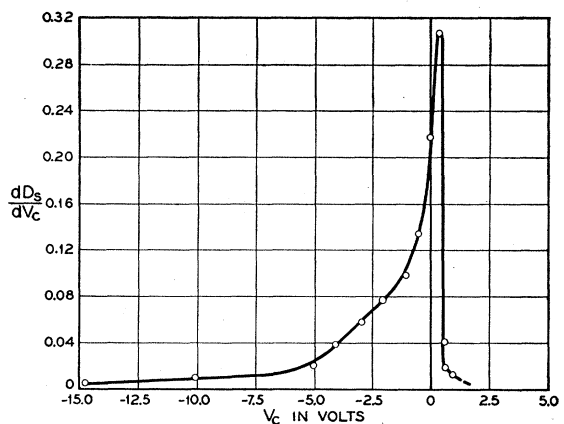


FIG. 10. Energy distribution curve from Fig. 9.

crystals were relatively pure to begin with. There is a question whether with some of the specimens impurities were added in the preparation. It is fairly certain, for instance, that at the temperatures used carbon would tend to reduce the MgO, leaving excess Mg in the lattice. Other impurities in the graphite or Pd backing might migrate into the lattice and create mobile holes or electrons in the lattice to contribute to the conductivity. Tantalum would reduce MgO, but the Ta plate was not in direct contact with the crystals.

If this impurity content is responsible for the conductivity of some of the crystals, there is no evidence that it reduced the yield. In fact, specimen A with the lowest conductivity had also the lowest yield. Conductivity increased by impurity content would probably have less effect on the yield than a similar increase by

⁸ A. Eisenstein, private communication.

⁹ H. Weber, *Z. Physik* **130**, 392 (1951).

¹⁰ This may also be true for somewhat more energetic electrons. The probability of ionization by an electron with energy between E_G and $2E_G$ depends on the role played by the lattice in such an interaction, and at present this is not known.

heat, since the heat vibrations involve all of the atoms in the lattice, the impurity content relatively few.

SUMMARY

We can sum up our results as follows:

(1) The high secondary yield from large single crystals of MgO is in accord with current band theory. Specifically, it implies that the high yields observed from thin film MgO targets that are used commercially, are not merely a consequence of thin film behavior but are related to body properties of the MgO.

(2) The temperature dependence of the yield can be used to obtain data on the interaction between the lattice and the internal secondaries which have several electron volts of energy.

(3) Field-enhanced emission is not observed in these experiments.

(4) Neutralization of surface charge by bombardment must be approached with care because a lack of uniformity may easily produce highly erroneous results.

(5) No correlation was found between conductivity and yield. However, the causes of the observed conductivity have not been determined.

We are indebted to Conyers Herring for many valuable discussions of the interpretation of the data presented. The MgO crystal used was supplied by E. G. Rochow through the good offices of A. J. Ahearn, and the individual specimens were prepared by J. Andrus. The spectrochemical analyses were performed by E. K. Jaycox. Finally we wish to express our thanks to the group working under the direction of H. W. Weinhart who constructed the various experimental tubes.

Theory of Alpha Decay. I*

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A preliminary report on the application of the perturbation of boundary conditions theory of Feshbach, Weisskopf, and Peaslee to the problem of the decay of a virtual state is presented. In particular, the formulas for alpha decay are derived. The derivation assumes no model of the nucleus nor of nuclear forces. It contains the slope of the logarithmic derivative of the wave function *versus* energy as the only factor related to the nuclear structure; therefore, it includes earlier theories of alpha decay as special cases.

1. INTRODUCTION

IN 1928 Gamow and, independently, Condon and Gurney¹ made use of quantum mechanics to explain the tremendous variation of alpha-decay half-lives with small variations in alpha-particle energy (from 1.4×10^{10} years to 3×10^{-7} second, for alpha-particle energies of 4 to 9 Mev, respectively). The foregoing theories correctly accounted for the exponential-type behavior of the half-life as a function of energy, but solved only the Coulomb barrier penetration problem. This paper presents a preliminary attack upon internal alpha-decay theory. The most frequent assumption of older theories for the internal problem was that of a single particle in a square well ground state. In fact, the spontaneous decay of an alpha particle from a square well bounded by a Coulomb barrier has been rigorously solved as an eigenvalue problem by Preston.² Another,³ admittedly

approximate, attack postulated that the intrinsic alpha-decay probability (the decay probability without Coulomb barrier) is roughly the same as that of a neutron of the same energy. The application of the WKJB approximation to the model of a single particle in a square well surrounded by a Coulomb barrier is widely used, but sometimes incorrectly. Sufficient care is not always taken at the joining point R (defined as the edge of the square well and considered in actuality to include the "naked" nuclear radius, the range of alpha-nucleus forces, and the "naked" alpha-particle radius), where Kramers type joining formulas are not applicable even when the drop in potential from Coulomb to the nuclear is gradual through a distance of the order of the nuclear force range. If this drop is taken to be vertical, the wave equation then has a singular point and no Taylor expansion whatever is possible, so that joining of the solutions in this manner completely breaks down.

Although our treatment assumes no model of the nucleus nor of nuclear forces, it does postulate that the alpha particle is an entity at the radius R and thereafter. In addition, this paper asks for a certain smoothness, to be defined below, in the nuclear wave function at the nuclear surface. Because of the generality of this

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† This report is based on a thesis submitted by the author to the Massachusetts Institute of Technology, 1950 (unpublished).

¹ G. Gamow, *Z. Physik* **51**, 204 (1928); G. Gamow and F. Houtermans, *Z. Physik* **52**, 495 (1928); R. W. Gurney and E. U. Condon, *Nature* **122**, 439 (1928); and *Phys. Rev.* **33**, 127 (1929).

² M. A. Preston, *Phys. Rev.* **69**, 535 (1946); **71**, 865 (1947).

³ H. A. Bethe, *Revs. Modern Phys.* **9**, 69 (1937). See also B. L. Cohen, *Phys. Rev.* **80**, 105 (1950).

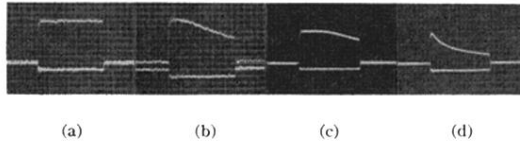


FIG. 4. Primary and secondary pulses. Target D , room temperature. Downward pulse, primary current; upward pulse, secondary current. V_c lowered in order a, c, b, d . a and b are single traces; c and d show 30 repetitions in 0.5 sec.