Microsecond Transient Currents in the Pulsed Townsend Discharge

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The transient current resulting from the release of a very short (0.1 μsec) pulse of photoelectrons at the cathode of a gas-filled tube has been observed experimentally. The current-time patterns agree quantitatively with theory within the limitations of the theory and experimental accuracy. The experiment provides a method for studying fundamental parameters and processes occurring in the noble gases; drift velocities of positive ions and electrons, identification of molecular ions, cross section of formation of molecular ions, and the importance in the Townsend discharge of electron emission at the cathode caused by positive ion neutralization there.

INTRODUCTION

IN the classical Townsend discharge light from a steady external source liberates a current of photoelectrons at the cathode of a gas-filled tube, and the total current is observed as the applied voltage and electrode separation are varied under space-charge-free conditions. Engstrom and Huxford[1] introduced time as a controlled variable in studies of the Townsend discharge by using a step-function light source obtained with a rotating shutter. They showed that the diffusion of metastable atoms to the cathode is the cause of the millisecond time-lag observed in a phototube filled with a rare gas. Molnar[2] extended this technique and showed that the relative amounts of electron emission from the cathode caused by positive ions, photons (from excited gas atoms), and metastable atoms could be studied under certain conditions. Newton[3] predicted theoretically the form of the transient current of microseconds duration following the release of a very short burst (a delta-function) of photoelectrons from the cathode of a Townsend tube with plane-parallel electrodes across which the applied voltage is held steady. In this paper, a pulsed Townsend experiment on a microsecond time scale is described, experimental confirmation of Newton's theory is given, and the application of this experiment as a technique for studying some electrical processes in gases is discussed.

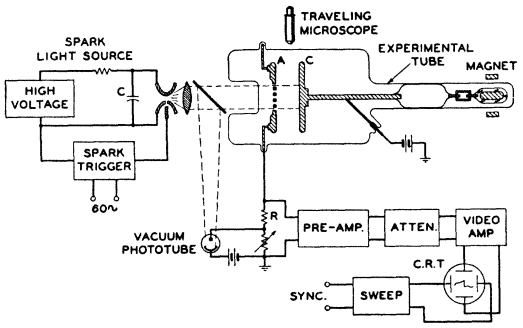

FIG. 1. Experimental arrangement for studying the microsecond transient current.

The experiment is arranged to cause the release of a 0.1-μsec pulse of photoelectrons from the cathode of the experimental tube and to observe the current transient that follows. Ionization and excitation of the gas molecules occur by electron impact during the light pulse. Because the electron drift velocity in the field is the order of 100 times the positive ion drift velocity, the transient consists of a sharp spike, attributable to current carried by the initial photoelectrons and their progeny electrons, followed by a smaller current lasting the order of ten microseconds. The slower component originates primarily from the motion of the positive ions in the field and the release of "secondary" electrons at the cathode by positive ion bombardment, or more accurately, neutralization.

The experiment provides a direct, time-of-flight method for measuring: (a) the drift velocity of positive ions in a gas as a function of E/p, the ratio of electric field strength to gas pressure, up to very high E/p and (b) the variation with E/p of the drift velocity of electrons in the low E/p range. It confirms again the importance of positive ion neutralization at the cathode as a source of secondary electrons in the Townsend discharge and affords a semiquantitative method for measuring the efficiency of electron emission by this process. The time resolution inherent in the experiment has led to the identification of molecular ions of the noble gases and measurement[4] of their drift velocity.

APPARATUS

A combination block diagram-schematic of the experiment is shown in Fig. 1. All operations are synchronized from the spark light source, which operates at a repetition rate of 60 cycles/sec.

Light in pulses is focused by a quartz lens system, passes through the multiply perforated anode, and is intercepted by the cathode. The separation between the plane parallel electrodes is varied by means of an external magnet and measured by a travelling microscope. The potential difference across the electrodes, measured by a potentiometer, is established by a continuously variable dc power supply comprising stacked "B" batteries. The tube current of the order of 0.1

[1] R. W. Engstrom and W. S. Huxford, Phys. Rev. **58**, 67 (1940).
[2] J. P. Molnar, to be published.
[3] R. R. Newton, Phys. Rev. **73**, 570 (1948).
[4] J. A. Hornbeck, Phys. Rev. **80**, 297 (1950).

μamp is controlled so that negligible space charge distortion of the applied field occurs. It flows through a series resistor R, developing a voltage that is amplified and impressed across the vertical plates of a cathode-ray tube. The horizontal sweep circuit is triggered through a low capacitance coupled to the spark electrodes. To prevent blocking of the amplifiers by the large initial electron current, or photopulse, part of the incident light is reflected by a partial mirror into a vacuum phototube, thus developing current in phase with the light pulse. This current flows through a small, variable series resistor in the input of the amplifier so as to develop a voltage opposing that developed by the tube current. The amplifier[4a] gain is varied by changing the input resistor R and by a series attenuator situated between the preamplifier and the main amplifier. The maximum voltage gain of the system is 110 db at a band width of 7 megacycles.

The light source, a modification of one described by Beams *et al.*,[5] is shown schematically in Fig. 2. The principal changes consist in (1) replacing the distributed capacitance transmission line by a small (1000 $\mu\mu$f) lumped capacity and (2) triggering the source regularly at a fairly low repetition rate, e.g., 60/sec. This is easily accomplished by using an ac transformer as the high voltage supply and arranging for the trigger voltage to be applied in the proper time phase. The light source meets the requirements of the experiment fairly satisfactorily: *viz.*, it gives a light pulse that is short compared with ion transit times; it is intense, with appreciable energy in the ultraviolet; it can be adjusted so that successive flashes are constant in intensity to within a few percent.

The experimental tube, similar to one described by Molnar,[2] is shown in Fig. 3. The electrodes are nickel disks, two inches in diameter, and the cathode was coated with a mixture of $BaCO_3$ and $SrCO_3$ at a density of 0.5 mg/cm^2. During outgassing the carbonates are reduced to oxides, and the surface[5a] is made uniform by subsequent high frequency spark treatment. The tube envelope with a quartz window in one end is 3″ outside diameter, small enough so that the metal parts can be heated readily by rf induction. The choice of these dimensions, however, necessitates coating the inside of the envelope with Aquadag (not shown in Fig. 3) so that a uniform, known wall potential can be established. The currents measured were not sensitive within wide limits to the choice of this wall potential, and a value intermediate between the anode and cathode was adopted. The electrode surfaces are parallel to about 0.1°. The light transmission of the anode is about 30 percent.

[4a] I am indebted to Dr. R. W. Hull for the loan of an intermediate amplifier and to Dr. Hull and to Dr. K. G. McKay for advice on amplifier construction.

[5] Beams, Kuhthau, Lapsley, McQueen, Snoddy, and Whitehead, J. Opt. Soc. Am. **37**, 868 (1947).

[5a] Pure metal electrodes are equally as satisfactory except for decreased photoelectric sensitivity.

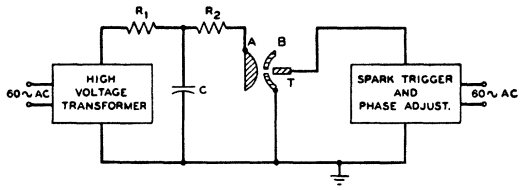

FIG. 2. Schematic diagram of light source. A and B are the main electrodes, T the trigger electrode. $C=1000$ $\mu\mu$f, $R_1=1$ megohm, $R_2=21$ ohms. The peak voltage of the transformer is about 5000 volts.

Time measurements were made both by the use of calibrated sweeps and by employment of a single timing "pip" that was introduced into the vertical deflection system just prior to the push-pull stage. In the latter scheme, copied from a circuit devised by T. R. Finch of these Laboratories, the pip may be moved continuously along the horizontal axis. The accuracy of the circuit is about 0.02 μsec. A zero-time reference for the marker was established by feeding the trigger pulse, derived from the firing of the main spark source, through a calibrated delay line of 1.15 μsec and causing this pulse to modulate the intensity of the electron beam in the cathode-ray tube.

Two circuits have been used to "buck out" the initial photoelectric pulse. The objection to the method described above, employing a passive network, in addition to the normal difficulties one expects caused by stray capacities, finite wire inductances, etc., is that the photoelectric current pulse in the experimental tube is not exactly in phase with the light pulse. On account of the finite drift velocity of the electrons in the gas, an asymmetry is introduced: current flow builds up in the gas-tube circuit about as fast as in the vacuum phototube circuit, but the transit-time effect causes the current fall to lag in the gas tube, particularly at low E/p. Attempts to improve the bucking by using a cathode follower for shaping the phototube pulse have not been more succesful than the original scheme, although exhaustive investigation of this difficulty has not been undertaken. With either procedure the height of the photoelectron pulse can be reduced by a factor of five.

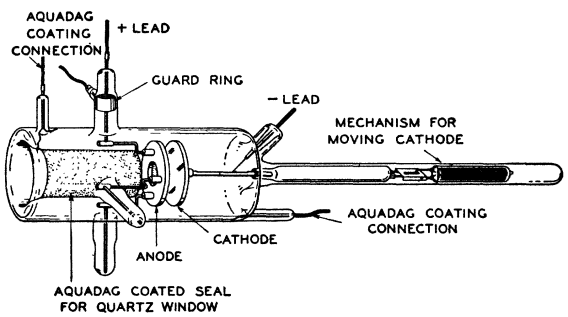

FIG. 3. The experimental tube. The Aquadag coating on the inside of the tube envelope is not shown.

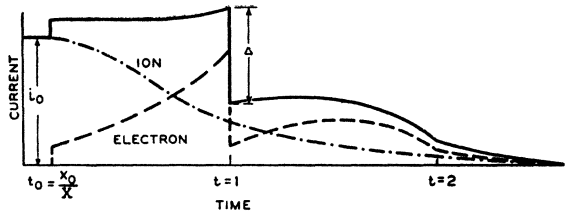

FIG. 4. Drawing (not to scale) of the idealized transient current *vs* time following the formation at $t=0$ of an exponential distribution of positive ions between the electrodes. The currents carried by electrodes and by ions are shown also as separate components. The unit of time is that of one ion transit between the electrodes.

GAS HANDLING AND VACUUM TECHNIQUES

One advantage of this experiment is that gas purity is not so much of a problem as in an experiment that lasts milliseconds and longer. For example, effects associated with the production of an impurity ion by a collision between a metastable atom of the noble gases and an impurity molecule will not be observed, in general, because the time constant associated with this process is the order of milliseconds. Low concentrations of impurities will affect the breakdown voltage and the cathode emission efficiency, but not the general form of the transient current associated with the ion motions.

The tube has been operated on a pumping station with a mercury cutoff and large liquid nitrogen trap. The spectroscopically pure gases used, helium, neon, and argon, have been introduced from "gettered" bottles both through stopcocks and through porous ceramic leaks in which the rate of leak is controlled by the height of a mercury column. Additional large Ba—Mg getters have, on occasion, been fired after the introduction of a gas sample. In no case has the current pattern indicated the presence of impurity effects. Also, on occasion, samples of the gases in the experimental tube have been sealed off and analyzed in a mass spectrometer. No impurities have been detected by this instrument, which has a sensitivity limit of about 0.005 percent.

Before the gas was introduced into the tube, standard evacuation procedures were followed. The tube could be baked to 450°C and the electrodes (Ni) heated to about 1000°C.

COMPARISON OF THEORY AND EXPERIMENT

Consider the case of a noble gas at low pressure ($\sim$1 mm Hg) in the region between two infinite, plane-parallel electrodes separated a distance X across which is maintained a steady voltage. We desire to know the current as a function of time following the instantaneous release of a pulse of n_0 photoelectrons/cm^2 from the cathode. For simplicity we assume (1) that the photoelectrons and progeny electrons, created by ionizing collisions, have essentially an infinite drift velocity compared to the positive ion drift velocity, (2) that ionization may be accounted for under the assumed uniform field conditions by a single coefficient α_i defined as the number of ions produced per cm of path per electron, (3) that all ions created have a unique velocity, their drift velocity v, which is in the field direction, and (4) that for each ion collected at the cathode there are released γ_i "secondary" electrons that subsequently behave as did the initial photoelectrons. We shall ignore for the present electrical effects resulting from the production by electron impact of radiating atoms and metastable atoms.

The initial condition resulting from these assumptions is an exponential distribution, ρ_i, of positive ions between the electrodes, each ion moving with a velocity v. The initial ion current, therefore, is proportional to the product of v and the total number of ions present, i.e., to the area under the initial distribution function. If, originally, ions are not formed until the photoelectrons have fallen through a potential difference roughly equal to the ionization potential, corresponding to a distance x_0 from the cathode, the current will remain constant for a short time, $t_0=x_0/v$, because no ions are lost immediately. Subsequently, the ion current will decrease as the total number of ions decreases through neutralization at the cathode.

Electrons will be released from the cathode as the positive ions are collected. The electron-carried current component is proportional to γ_i and the rate of arrival of ions, i.e., proportional to γ_i, v, and the instantaneous density of ions at the cathode. Because we have assumed that the electron transit time is very fast compared with the ion transit time and because γ_i and v are constant, the electron current component as a function of time depends directly upon the amplitude of ρ_i as a function of x, the distance from the cathode. Thus, any structure in ρ_i appears in the current transient through the electron component. Since ρ_i has two spatial discontinuities, one at $x=x_0$ where ionization begins abruptly, and the other at $x=X$, the anode, we expect two current discontinuities: a large one at $t=X/v$ and a small one at $t_0=x_0/v$.

Both current components and both discontinuities are shown in Fig. 4, in which the transient current is plotted as a function of time t, where t is in units of one ion transit time X/v. The current actually lasts longer than $t=1$, as shown in Fig. 4, on account of regenerative effects: the "secondary" electrons released by the γ_i-mechanism produce more positive ions, which in turn produce more electrons, etc. Inclusion of these higher order effects, as Newton[3] has shown, adds tails to both current components and additional structure to the electron component in the form of a discontinuity in slope at $t=2$. The slope discontinuity follows as a consequence of the large current discontinuity at $t=1$.

An experimental transient current pattern reproduced from a photograph of the cathode-ray tube trace is given in Fig. 5 for comparison with Fig. 4. The principal differences between the two appear to be readily explainable. The ions, of course, do not all move with a

unique drift velocity but have a random velocity distribution with a mean component v in the field direction. The randomness in velocity originates not only from thermal motions but more importantly at high E/p from elastic collisions between the ions and neutral gas atoms. Diffusion will, therefore, smear out the large mathematical discontinuity of Fig. 4 into the sharp break observed in Fig. 5. Diffusion and other effects generally mask the discontinuity at t_0, as in Fig. 5, although this is not always the case. The slope discontinuity clearly shows up in Fig. 5.

The explanation of the ripple structure in Fig. 5 after $t=t_0$ is found in the well-known inexactness[6] of the assumption regarding α_i. In practice ρ_i is not a smooth exponential function of x for $x>x_0$. Electrons begin to make ionizing collisions in the neighborhood of x_0, but the act of ionization reduces the number of electrons possessing ionizing energy. Hence, fewer ions are formed at x larger than x_0 until the electrons have moved roughly another x_0 distance in the field direction, at which place ionization becomes more probable. At large distances from the cathode the electrons approach a stationary velocity distribution, which implies that α_i is independent of x. It will be noted that, as with the discontinuities, structure in ρ_i manifests itself in the observed current through the γ_i-mechanism.

Metastable atoms diffuse to the cathode and also release electrons which contribute to the current, the time constant associated with this mechanism being, in general, two orders of magnitude longer than positive ion transit time. Thus, a current component of metastable origin is not observed in the microsecond time-scale experiment, whereas it is prominent in millisecond experiments.[1,2]

Radiation from excited atoms presents a more troublesome problem because resonance radiation, which originates from transitions between excited states and the ground state, may require,[7] to reach to cathode, times in the microsecond range at 1 mm Hg. Radiation that arrives at the cathode essentially instantaneously after the decay of an excited atom cannot alter the form of the ion transient and hence can be ignored for our present purposes. One must rely on experiment to evaluate the relative magnitude of the delayed current component of radiation origin. Although the experiment is not very reliable on this point at the present time, there has been some indication of the radiation component in the lower E/p range (for argon, <75 volts/cm-mm Hg). Of course, even if the ion and radiation components overlap, the latter may still be so small that it is not observed if $\gamma_i \gg \gamma_r$, where γ_r stands for the electron yield per photon striking the cathode.

APPLICATIONS OF THE PULSE EXPERIMENT

Let us now investigate the pulse experiment as a technique for measuring the parameters α_i, γ_i, and v and also other possible applications of the experiment. Readily observable quantities in the experiment are the integrated area A under the initial photopulse, the magnitude i_0 of the initial positive ion current ($t<t_0$), the magnitude Δ of the discontinuity at $t=1$, and the ion transit time T. It can be shown that these quantities, neglecting diffusion, can be expressed as follows:

$$\left.\begin{aligned} A&=(Cn_0/\alpha_i X)\{\exp[\alpha_i(X-x_0)]+\alpha_i x_0-1\},\\ i_0&=(Cn_0 v/X)\{\exp[\alpha_i(X-x_0)]-1\},\\ \Delta&=(Cn_0\gamma_i v/X)\exp[\gamma_i(X-x_0)]\\ &\qquad\times\{\exp[\alpha_i(X-x_0)]+\alpha_i x_0-1\},\\ T&=X/v. \end{aligned}\right\} \quad (1)$$

Here C is the calibration constant of the amplifying system. From Eq. (1) it follows directly that to a good approximation

$$\left.\begin{aligned} \alpha_i&=i_0T(1+\sigma)/AX,\\ \gamma_i&=[\Delta/i_0(1+\sigma)]\exp[-(i_0T/A)(1+\sigma)(1-x_0/X)],\\ v&=X/T. \end{aligned}\right\} \quad (2)$$

The approximation made is the neglect of all but the linear term in σ in the expansion

$$\alpha_i X=i_0TA^{-1}(1+\sigma+D\sigma^2+\cdots), \quad (3)$$

where

$$\sigma=(i_0Tx_0/AX)\{\exp[i_0TA^{-1}(1-x_0/X)]-1\}^{-1}. \quad (4)$$

At most, σ is about 20 percent, and in many cases it is negligible; $D\sigma^2$ is never more than about 1 percent. It should be noted in the above that γ_i as here defined is the product of the true electron emission efficiency per positive ion neutralized and an escape, or back-diffusion, factor for the electrons from the surface. This factor has been measured by Molnar,[2] among others, and can be determined independently from this experiment.

At present, measurement inaccuracies and difficulties resulting from inexact assumptions in the theoretical treatment permit only semiquantitative evaluation of γ_i and α_i. The determination of v is not so limited. Because of the existing roughness in the method, only a single example of the results on γ_i will be presented

FIG. 5. Oscillogram showing the experimental transient current-time pattern in argon. The time scale indicated is the same as Fig. 4. The photopulse has been bucked out and therefore is not seen.

[6] M. J. Druyvesteyn and F. M. Penning, Revs. Modern Phys. 12, 98 (1940), for example.

[7] T. Holstein, Phys. Rev. 72, 1212 (1947).

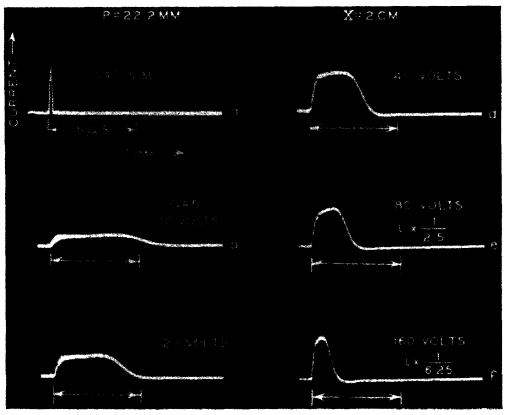

FIG. 6. Oscillograms showing the photoelectric pulse in vacuum and in helium at constant plate separation and constant gas pressure. For traces *b* through *f* the applied voltage is increased, as indicated. The scale of the horizontal time axis is the same for all traces as is the scale of ordinates excepting traces *e* and *f*, for which the scale change is indicated.

here.

Experimental data	Ba—O—Ni cathode
$p_0=0.82$ mm Hg argon	$\Delta=0.3$ cm
$X=1.00$ cm	$i_0=0.5$ cm
$V=70$ volts	$A=7.0$ μsec-cm
$E/p_0=85$ volts/cm-mm Hg	$T=15.0$ μsec

From these data, since x_0 corresponds to about 15 volts, $x_0/X\simeq 15/70$, $\sigma=0.17$, and $\gamma_i=0.19$. The total γ of the classical Townsend equation, which includes all secondary emission processes at the cathode, *viz.*, ion, radiation, and metastable atom, may be obtained approximately from a breakdown measurement and substitution of a published[8] value for α_i at the corresponding E/p_0.[8a] Breakdown occurred at 83 volts, which yielded $\gamma\simeq 0.35$, and thus $\gamma_i/\gamma=54$ percent. The significance

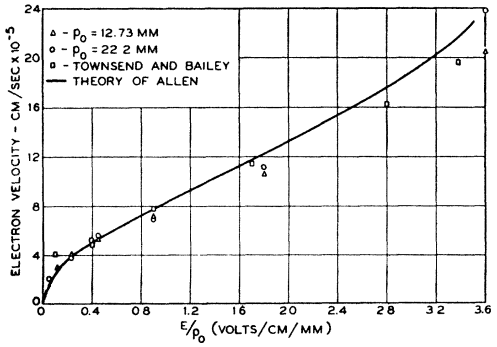

FIG. 7. Experimental data on the drift velocity of electrons in helium at low E/p_0. The data of Townsend and Bailey and the theory of Allen are also shown. p_0 indicates pressure corresponding to gas density (see footnote).

[8] A. A. Kruithof, Physica **7**, 519 (1940).

[8a] The pressure p_0 corresponds to gas density, i.e., the observed gas pressure p at T°C is corrected to pressure p_0 at 0°C. E/p_0 is actually implied wherever E/p is written in this paper.

of this result is that ions probably are an important, perhaps the most important, source of electron emission in the Townsend discharge at moderate and high E/p.

We may also compare with Kruithof's measurement values of α_i obtained from substituting the above data in Eq. (2). The close agreement between these values ($\alpha_i=1.25$, whereas Kruithof quotes 1.30 per cm) is undoubtedly fortuitous because of the crudeness of the present measurements. It gives confidence, however, in the general interpretation of the experiment.

The measurement of ion drift velocity[9] can be made directly and accurately, its limitation being only one of time resolution. Advantages of this technique are (1) the extremely short lifetime of the ions observed, (2) the ability to detect the coexistence of ions of different mobilities, and (3) the applicability of the method up to high E/p. Disadvantages of the technique are that (1) as now used, it applies only to ions of the parent gas and (2) the method is not satisfactory at essentially zero-field conditions where the ion mobility is independent of the field.

The experiment provides a direct method for measuring the electron drift velocity, v_e, at sufficiently low E/p that ionization by collision may be ignored. In this case the photoelectric current pulse is that shown in oscilloscope trace *b* of Fig. 6. With the sudden creation of the electrons by the external light pulse, the current rises abruptly from zero. The current i_e then remains constant, while the packet of n_0 electrons crosses from cathode to anode, its value being

$$i_e=Cn_0v_e/X. \tag{5}$$

The current would drop discontinuously to zero at one electron transit time $T_e=X/v_e$ except for diffusion and the finite time duration of the light pulse. The other traces in Fig. 6 show the photoelectric current pulse as the voltage is increased at constant electrode separation, except for trace *a*, which is the photocurrent in vacuum. Increasing the applied voltage increases v_e and thereby increases i_e while decreasing T_e. The area would remain exactly constant ($\alpha_i=0$) if n_0 were constant; increasing the field, however, decreases the loss of electrons by back diffusion so that the area increases with voltage.

From the experiment v_e is obtainable in two ways,

$$v_e=i_eX/A \quad \text{or} \quad v_e=X/T_e, \tag{6}$$

where T_e is the time measured to the midpoint of the current break. Measurements of v_e in helium are presented in Fig. 7, and for comparison the theoretical curve of Allen[10] and the older experimental data of Townsend[11] are shown. The results obtained with the pulse method agree with the results of the more indirect experiment within the error of the pulse experiment, which may be as large as 10 percent. Patterns similar to

[9] J. A. Hornbeck and G. H. Wannier, Phys. Rev. **82**, 458 (1951). contains an example of these measurements.

[10] H. W. Allen, Phys. Rev. **52**, 707 (1937).

[11] J. S. Townsend and V. A. Bailey, Phil. Mag. **46**, 657 (1923).

those in Fig. 6 have been obtained for neon and argon except at the very lowest E/p, i.e., a few volts applied potential. Under these conditions a sharp spike is observed at the beginning of the pulse. Increasing the voltage increases the amplitude of the pulse and rapidly eclipses the spike effect. Thereafter, the pulses behave like helium. The origin of the spike has not been investigated.

Experimental data from other applications of the experiment are now being obtained and will be reported later. These include (1) the measurement of the drift velocity of molecular ions in the parent noble gases, (2) the semiquantitative determination of the cross section of formation of molecular ions in a collision between an excited gas atom and a neutral atom, (3) a semiquantitative study of the diffusion of ions under high field conditions, i.e., when thermal energy is small compared with the energy derived from the field.

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It is a great pleasure to acknowledge the very considerable assistance, advice, and consultation of many of my colleagues during the course of this investigation; in particular, J. P. Molnar, who was instrumental in initiating the work, H. D. Hagstrum, W. C. Herring, G. H. Wannier, and A. H. White. H. W. Weinhart designed the experimental tube and supervised its construction. A. A. Tartaglia was invaluable as a technical assistant.

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Small Angle Scattering of Neutrons*

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The differential and total scattering cross sections have been calculated for slow neutrons impinging on crystalline spheres whose radii are very much greater than the neutron wavelength. The results for the differential cross section show that when the difference, ρ, between the neutron phase shift in traversing the particle diameter and the phase shift in traversing the same distance in vacuum is small, the result agrees with the Born approximation, while if ρ is large, the result agrees with that obtained by geometrical optics. Also, the total cross section for ρ small is $\pi R^2\rho^2/2$ and for ρ large is $2\pi R^2$, where R is the particle radius.

Using the Oak Ridge reactor, the broadening of a neutron beam in traversing finely divided materials was measured as a function of neutron wavelength, particle size, and coherent scattering cross section, and the results verified these considerations.

A new method for determining coherent cross sections of nuclei and the phases of slow neutron scattering was demonstrated through the use of a liquid of known index of refraction into which the finely divided materials were immersed. In this manner, the phases of Mo, Cb, Pd, Ru, Si, P, and Te were shown to be positive.

I. INTRODUCTION

WHEN a well-collimated beam of thermal neutrons or x-rays (of an angular width in minutes of arc) is passed through finely divided material, the beam is found to diverge.[1,2] This is attributed to diffraction and refraction occurring at each individual particle. The theoretical interpretation of the broadening of the beam has been the subject of much discussion, and a great deal of x-ray work has been done in this field.[3] Two "conflicting" theories dominated the field—that of Rayleigh-Gans[4,5] (diffraction only) and that of von Nardroff[6] (refraction only). As late as 1949, papers appeared which refuted one theory or the other on the basis of experimental results, even though a thesis by Van de Hulst[7] had appeared in 1946 which showed that for electromagnetic radiation the Rayleigh-Gans and von Nardroff theories were different limiting cases of the correct approach to the problem. The important consideration, as was pointed out by Van de Hulst, is the difference, ρ, between the phase change in traversing the particle diameter and the phase change intraversing the same path length in vacuum. If $\rho \ll 1$, the Rayleigh-Gans theory is valid, while if $\rho \gg 1$, the von Nardroff theory is valid. A re-check into some experimental results has shown that this, indeed, was the case and only the accidental choice of particle size determined the magnitude of ρ.

These considerations are here extended theoretically and experimentally to neutrons, the essential difference being that we deal with a scalar wave equation

* Research carried out under contract with AEC.
[1] Krueger, Meneghetti, Ringo, and Winsberg, Phys. Rev. **75**, 1098 (1949); **80**, 507 (1950) (neutrons).
[2] D. L. Dexter and W. W. Beeman, Phys. Rev. **76**, 1782 (1949) (x-rays).
[3] J. H. Donnay and C. G. Shull, Am. Soc. X-Ray and Electron Diffraction (March 1, 1946).
[4] Lord Rayleigh, Proc. Roy. Soc. (London) **84-A**, 25 (1911).
[5] R. Gans, Ann. Physik **76**, 29 (1925).
[6] R. von Nardroff, Phys. Rev. **28**, 240 (1926).
[7] H. C. Van de Hulst, *Optics of Spherical Particles* (N. V. Drukkerij J. F. Duwaer en Zonen, Amsterdam, 1946).

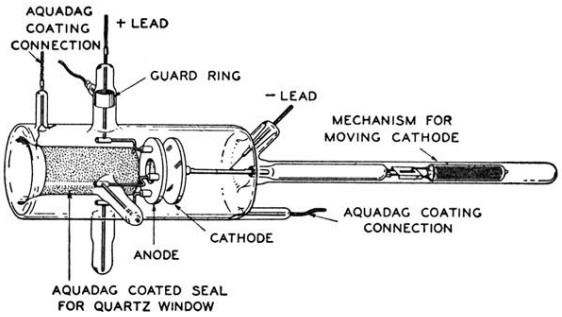

FIG. 3. The experimental tube. The Aquadag coating on the inside of the tube envelope is not shown.

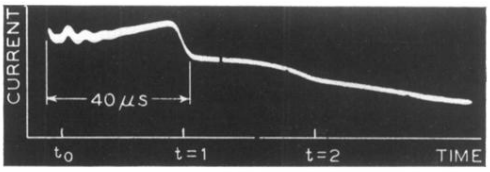

FIG. 5. Oscillogram showing the experimental transient current-time pattern in argon. The time scale indicated is the same as Fig. 4. The photopulse has been bucked out and therefore is not seen.

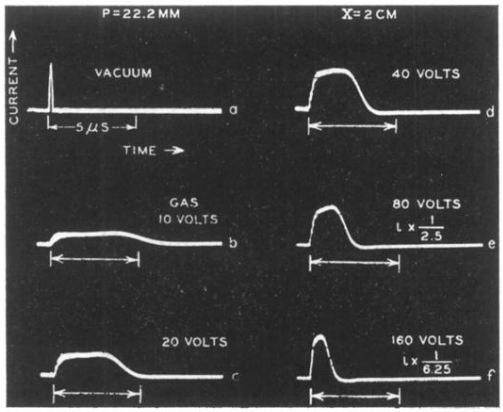

FIG. 6. Oscillograms showing the photoelectric pulse in vacuum and in helium at constant plate separation and constant gas pressure. For traces *b* through *f* the applied voltage is increased, as indicated. The scale of the horizontal time axis is the same for all traces as is the scale of ordinates excepting traces *e* and *f*, for which the scale change is indicated.